

11th ECPC
and
NOKOBETEF 16

European **S**ociety of **P**rotective **C**lothing

11th European Conference on Protective Clothing

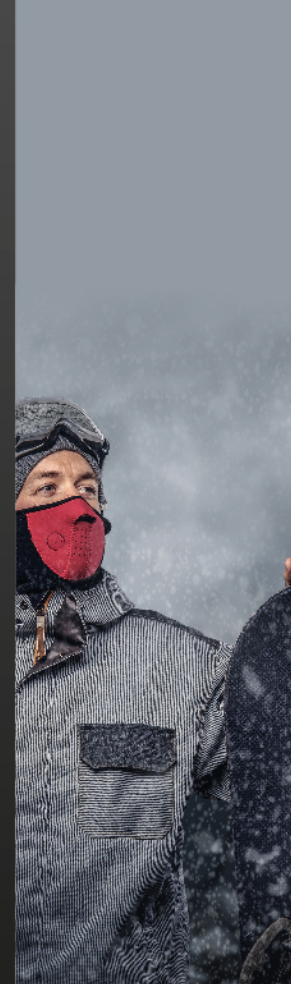
Protective, Smart, Sustainable

20-23 May 2025

Pine Bay Holiday Resort, Kuşadası/Aydın - TURKIYE

www.ecpc2025.com

BOOK OF ABSTRACTS



“Protective, Smart, Sustainable”

**PROCEEDINGS of the 11th EUROPEAN CONFERENCE ON PROTECTIVE CLOTHING
and NOKOBETEF 16**

20 - 23 May 2025 in Kuşadası-AYDIN, Türkiye

Editors:

Bengi KUTLU

Gülşah Ekin KARTAL

Gizem Ceylan TÜRKOĞLU

İZMİR, 2025

FOREWORD

The 11th European Conference on Protective Clothing (ECPC 2025) - NOKOBETEF 11 was held from 20 to 23 May 2025 at the Pine Bay Holiday Resort in Kuşadası, Türkiye. It was organized by the European Society of Protective Clothing (ESPC) ([European Society of Protective Clothing](#)) and hosted by Dokuz Eylül University Textile Engineering Department ([Dokuz Eylül Üniversitesi Tekstil Mühendisliği Bölümü](#)).

ESPC was founded in 1997 in Denmark. Since 2000, the ESPC has co-organized the European Conference on Protective Clothing (ECPC) every two to three years. However, there is a considerably longer history to the protective clothing conference that is bound to the tradition of research and information exchange in the Nordic countries on the subject. The NOrdisk KOrdineringsgruppe om BEskyttelseskläder som TEknisk Forebyggelsesmiddel (Nordic Coordination Group on Protective Clothing as a Technical Preventive Measure) was founded in 1984 and started then with the symposia on this topic.

This year's conference embraced the theme "Protective, Smart, Sustainable" and welcomed participants from 20 countries. It brought together leading researchers, industry professionals, and end-users in the field of protective clothing. Throughout the conference, participants engaged in vibrant discussions and knowledge exchange on the latest advancements in protective textiles, ranging from smart technologies and functional finishing to user-centered design and comfort.

The 11th ECPC also emphasized sustainability and green solutions, explored developments in thermal, chemical, biological, ballistic, and cold weather protection, and highlighted innovative testing methods, material evaluation strategies, and public procurements, reflecting the evolving priorities of academic, public, and industrial communities.

We are sincerely grateful to all those who made ECPC 2025 possible, participants, our sponsors, and supportive organizations, whose collaboration and encouragement were invaluable in shaping this international platform.

İzmir, May 2025

Assoc. Prof. Dr. Bengi KUTLU
Chair

Scientific Committee

Edith Claßen	Hohenstein Laboratories GmbH & Co	Germany
Inga Dāboliņa	Riga Technical University	Latvia
Anna Dąbrowska	CIOP – PIB	Poland
Patricia Dolez	University of Alberta	Canada
Emiel den Hartog	North Carolina State University	USA
Kirsi Jussila	Finish Institute of Occupational Health	Finland
George Havenith	Loughborough University	United Kingdom
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Kalev Kuklane	Netherlands Institute for Public Safety	The Netherlands
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Hyeshin Yoon	Korea Apparel Testing & Research Institute	South Korea

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Bengi KUTLU (Chair)

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Day 1 - 20 MAY 2025

TIME	TOPIC	SPEAKER
12:00 - 13:00	Check-in and Registration	
12:30 - 13:30	Conference Opening -Welcome speeches: • Conference Chair - Assoc. Prof. Dr. Bengi KUTLU • Chair of ESPC - Gilda SANTOS • Head of Department - Prof. Dr. Tuba ALPYILDIZ • Deputy Chairman of the Türkiye Exporters' Assembly - Ahmet Fikret KIŞLECI • Vice Dean - Assoc. Prof. Dr. Sadık Can GİRGİN- Presentation of the Sponsors	
13:30-13:50	Posters, exhibition, and coffee break	
13:50- 14:45	SESSION 1 - Cold Protective Clothing Chair: Prof. Dr. Tuba Alpyıldız	
13:50-14:00	Kıvanç Group Company Presentation	<u>Oscar Cerrada Lopez</u>
14:00 - 14:15	Standards and Measurement of Sweating and Cooling in Multi-Layer Cold Weather Clothing Systems	<u>Emiel DenHartog</u>
14:15 - 14:30	Multi-Level Heating Design for Electrically Heated Clothing Based on Pressure Distribution	<u>Lin Shao</u> , Fuxiang Wang, Jun Li, Yunyi Wang
14:30 - 14:45	Study on Optimization of Heat and Moisture Transfer Performance of Aerogel Foam Materials for Cold Protective Clothing	<u>Wen Cui</u> , Lulu Jiang, Yunyi Wang, Jun Li
14:45 - 15:05	Posters, exhibition, and coffee break	

15:05 – 16:20	SESSION 2 - Physiological Impact and Comfort Chair: <i>Prof. Dr. Emiel DenHartog</i>	
15:05 – 15:20	The Effect of Bulky Protective Clothing on Energy Requirements in Walking Activity	George Havenith , Patrick Ellis
15:20 – 15:35	A Coupling Method for Transient Human Thermoregulation Model and Wearable Monitoring System	Mengyao Huang , Ming Fu, Shifei Shen, Yayun Li
15:35 – 15:50	Heat Stress Prediction for Simulated Technical Rescue Activities	Amber M.H. Klomp, Lotte M.G. Jacobs, Hein A.M. Daanen, Kaley Kuklane
15:50 – 16:05	Experimental Testing of Military Protective and Ballistic Clothing with Active Ventilation in Extreme Heat	Consuelo Latorre-Sánchez , Ignacio Espiritu García-Molina, Juan Carlos González, Gemma Romualdo, Arantxa Díaz
16:05 – 16:20	Influence of Ambient Conditions on the Measurements of Water Vapour Resistance with a Sweating, Thermal Manikin	Bianca-Michaela Wölfling, Edith Classen
16:25 – 18:00	ESPC Board Meeting (Board members only)	
19:00	Welcome Cocktail	

Day 2 - 21 MAY 2025**FIREFIGHTERS' DAY**

TIME	TOPIC	SPEAKER
09:45 – 10:35	POSTER SESSION 1 (5 min/poster) Chair: <i>Assoc. Prof. Dr. Gülşah Ekin Kartal</i>	
P1	Protecting Rescuers in the North: Challenges from the Green Transition Chemicals and Climate Change	Kirsi Jussila , Erja Mäkelä, Piia Taxell, Heli Kähkönen, Eero Lantto, Jenni Kaisto, Tiina Santonen
P2	Investigation of Mechanical Performance of Fluorocarbons Treated Aramid Fabrics	Neda Demir, Nihan Demir, Ayşe Merih Sarıışık, Simge Özkayalar, Sinem Öztürk , Ozan Onuktav
P3	Development of UV-Stabilized, Flame Retardant, Recycled PET Yarns for Outdoor Applications	Esra Okay , Özge Serra Çetin, Dilek Kut
P4	Do Trunk and Thigh Cooling using Wet Sheets and Ice Packs Effectively Reduce Body Temperature in a Hot and Humid Environment?	Yoon Jeong Baek , Ho-Yeon Jeong, Maria Stenkina, Kayoung Cho, Ho-Joon Lee, Joo-Young Lee
P5	Testing of Functional Characteristics of NBC and Firefighter Protective Clothing	Kamila Lunerová , Lukáš Králík, Jakub Vaněk, Michal Mašín, Markéta Weisheitelová, Jan Fišer, Jan Pokorný
P6	An Improved Thermoregulation Model for Predicting Physiological Response to Occupational Heat Exposures	Mengyao Huang , Shifei Shen, Ming Fu, Xuanchao Huang
P7	A New Method for Evaluating the Impact Resistance of Protective Garments Based on Body Injuries	Xuanchao Huang, Ming Fu, Shifei Shen, Mengyao Huang , Yayun Li, Liangchang Shen, Youping Zhu, Xuefan Wang
P8	Mobility and Thermal Comfort Assessment of Personal Protective Equipment for	Do-Hee Kim , Youngmin Jun, Ho-Joon Lee, Gyeongri Kang, Cho-Eun

	Female Healthcare Workers: Impact of Protective Levels and Body Physique	Lee, Yoon Jeong Hur, Joo-Young Lee
P9	A Focus on Superhydrophobic and Oleophobic Textiles	Hanna Houssel-Garcia , Christine Campagne, Claire Longuet, Fabien Salaün, Rodolphe Sonnier, Belkacem Otazaghine
P-14	Mechanical Performance and Caffeine Release of Bi-Layered Polyvinyl Alcohol/Polycaprolactone Nanofibers for Wound Dressing Applications	Elif Alakaş, Rukiye Yiğit, Filiz Altay
10:35 – 10:50	Posters, exhibition, and coffee break	
10:50 – 12:05	SESSION 3 - Thermal Protective Clothing & Evaluation Chair: <i>Prof. Dr. George Havenith</i>	
10:50 – 11:05	Heat Stress Under Simulated Technical Rescue Activities	Kalev Kuklane , Koen Levels, Lyda Kistemaker, Inge Tanck, Eric Mol, Maurice Kemmeren, Ronald Heus
11:05 – 11:20	Predictive Models to Assess Thermal and Evaporative Resistances of Innovative Thermal Protective Clothing	Soraia Ferreira Neves , Luana Valente, Margarida Silva, João Mário Miranda, João Moreira Campos, Patrícia Fernandes, Adriana Moreira, Gilda Santos
11:20 – 11:35	Predicting the Effectiveness of Technical Rescue Gear with Thermal Modelling Software	Savannah Page, Mark Hepokoski, Timofey Golubev , Kalev Kuklane
11:35 – 11:50	Enhanced Thermal Protection for Wildland Firefighters: Integrating 3D Spacer Fabric into Protective Clothing Systems	Elena Kosareva , Stephen Paskaluk, David Torvi, Jane Batcheller
11:50 – 12:05	Development and Standardization of a Flash Fire Cylinder Test Method	Richard Burke , Joshua Ingram, Diane Hess
12:05 – 13:10	Lunch break	

13:10 – 14:25	SESSION 4 - Physiological Impact and Comfort Chair: Gilda Santos	
13:10-13:25	Heat Strain while Working Indoors under High Relative Humidity and Temperature with Cooling Vests	Kirsi Jussila , Jenni Kaist
13:25-13:40	The Path from a Product to a Certified PPE Product – Using PPE with a Cooling Function as an Example	Edith Classen
13:40-13:55	Investigation and Simulation of the Impact of Personal Protective Coveralls on Human Thermoregulation	Simon Annaheim , Ladina Cathomen, Agnes Psikuta, Stéphane Nowak, Aldjia Begriche, René Rossi
13:55-14:10	Heat Stress in Simulated Structural Firefighting Scenarios Utilizing Two Types of Dressing Strategies	Egle Ambo, Märt Reinvee, Priit Purge, Kalev Kuklane
14:10-14:25	Physiological Impact of Rescue Workers Protective Clothing on Heat Stress Development During Simulated Wildland Firefighting Activities	Siim Kaaver , Kalev Kuklane, Priit Purge
14:25 – 14:45	Posters, exhibition, and coffee break	
14:45 – 16:15	SESSION 5 – Smart Protective Products & Innovative Materials Chair: Assoc. Prof. Dr. Kalev Kuklane	
14:45 – 15:00	Technological Solutions for The Design of Intelligent Military Equipment for Combatants Rescue in Emergency Situations	Cristina Grosu , Emilia Visileanu, Georgeta Popescu, Marian Catalin Grosu, Alina Florentina Vladu, Maria Felicia Dondea
15:00 – 15:15	Water Aging of Fire-Protective Polybenzoxazole (PBO) Fabric	Rajitha S. Botheju , Md. Saiful Hoque, Patricia Dolez

15:15 – 15:30	Graphene-Based End-of-Life Sensors for Fire-Protective Clothing	Patricia Dolez , Nadeesha Samaraweera, Diana Yehia, Aashna Husain, Md. Saiful Hoque, Jemma Forgie, Bernardo Araujo Souto, Dan King
15:30 – 15:45	Textile Gloves Reinforced with 3D-Printed Structures Intended for Anti-Cut Protection	Olga Olejnik , Emilia Irzmańska, Paulina Kropidłowska, Jakub Saramak
15:45 – 16:00	Military Stealth: Next-Generation of Camouflage Enhancing Technologies	Gilda Santos , Flávio Ferreira, André Barbosa
16:00-16:15	Design and Performance Evaluation of Flame-Resistant Protective Fabrics	Dilek Şarapnal, Mehmet Aykut Çam, Ahsan Habib, Osman Babaarslan, Ahmet Berkay Barman
16:15 – 16:30	Posters, exhibition, and coffee break	
16:30 – 17:30	ESPC General Assembly for all participants	
17:30	Ancient City of Ephesus Tour (EXTRA)	
Day 3 - 22 MAY 2025		
TIME	TOPIC	SPEAKER
09:00 – 10:20	SESSION 6 - New Evaluation Methods Chair: <i>Prof. Dr. Joo-Young Lee</i>	
09:00 – 09:15	A New Methodology to Assess the Safety of Modifications to Fire Protective Clothing	Jemma Forgie , Patricia Dolez
09:15 – 09:30	Bench-Scale Assessment of Physical and Thermophysiological Properties of Sportswear Fabrics Influenced by Garment Fit and Human Dynamic Anthropometry	Farzan Gholamreza , Rupali Dhiman, Behnam Memarmaher, Mohammadamin Amindehghan, Bulmaro Valdes Benavides, Adrian Lai, Sian Allen, Rob Gathercole, Abbas Milani
09:30 – 09:45	Ergonomic Impacts of Ballistic Vests on the Mobility of Firefighters	Reza Kamali Miab , Roger Barker, Emiel Denhartog

09:45 – 10:00	A Novel Method for Measuring Air Gap Thickness under the Turnout Gear During Walking	Shitan Wang , Yunyi Wang, Shu Jiang, Wenxin Niu, Wen Cui
10:00 – 10:20	Posters, exhibition, and coffee break	
10:20 – 11:50	SESSION 7 - Sustainability in Protective Clothing and Equipment Chair: Dr. Edith Classen	
10:20 - 10:35	Para-Aramid Mechanical Recycling and Valorisation Opportunities	Gilda Santos, Adriana Pereira, Liudmila Basilio , João Ferreira, João Medeiros, André Barbosa, Marisa Silva
10:35 – 10:50	Towards Sustainable Personal Protective Equipment: Exploring Material Separation and Recycling Methods	Felix Kunzelmann, Yordan Kyosev , Alice Schwab
10:50 – 11:05	Special-Purpose Clothing Public Procurements in Latvia: Situation and Perspectives	Inga Dabolina , Eva Lapkovska, Liene Silina, Jelizaveta Bulenkova
11:20 – 11:35	Development of High-Performances Military Fabrics: Silent, Lightweight and Sustainable	Serena Rimoldi
11:35 – 13:00	Lunch break	
13:00 – 13:45	POSTER SESSION 2 (5 min/poster) Chair: Assist. Prof. Dr. Gizem Ceylan Türkoğlu	
P10	Cutaneous Thermal Sensation According to Clothing Fabrics and Footwear Types During Radiant Heat Exposure to The Leg in a Car	Sang-Hyun Roh , Suhyeon Yeom, Joo-Young Lee
P11	Evaluating the Impact of Wearing Protective Gloves on Hand Sweating in a Hot and Humid Environment	Maria Stenkina , Kayoung Cho, Suhyeon Yeom, Ho-Yeon Jeong, Joo-Young Lee

P12	Psycho-Physiological Effects of Industrial Respirator Designs in a Hot Environment: A Pilot Study	Suhyeon Yeom , Sang-Hyun Roh, Joo-Young Lee
P13	Temperature Variations in Different Foot Areas Depending on Toe Heating Levels for Smart Shoes During Exercise	Heeyoung Ju , Suhyeon Yeom, Joo-Young Lee
P15	Sustainability in Protective Clothing Through Comparative Analysis of Conventional and Eco-Friendly Denim Finishing Processes	İsmail İvedi
P16	Ecofriendly Production of Functional Face Masks	Gülbahar Saat , Ali Demir
P17	Evaluating Total Heat Loss of Turnout Gear and Ballistic Vests on Firefighter Heat Strain	Mushfika Tasnim Mica, Roger Barker, Emiel DenHartog
P18	Physiological and Psychological Responses to Immersion Suits for Republic of Korea Air Force Pilots	Minhee Lee , Gyeongri Kang, Joo-Young Lee
P19	Assessment of the Service Life of Firefighter Protective Gloves with Polymer Coatings containing Carbon Fillers on the Example of Chemical Degradation Test.	Emilia Irzmańska, Klaudia Halicka, Olga Olejnik , Magdalena Jurczyk-Kowalska, Tomasz Spólnicki, Julia Jakubaszek
13:45 – 14:15	Posters, exhibition and coffee break	
14:15 – 15:15	SESSION 8 – Chemical Protective Clothing Chair: Prof. Dr. Kamila Lunerová	
14:15 – 14:30	Influence of Beta and Gamma Radiation on The Properties of NBC Protective Clothing	Elżbieta Pawełczyk , Magdalena Płocińska, Klaudia Halicka, Emilia Irzmańska, Małgorzata Okrasa
14:30 – 14:45	Evidence of the Critical Role of the First Layer in Regulating Microclimate and Improving Thermal Comfort	Solène Champigny , Fabien Salaün, Cedric Cochrane, Cyprien Bourrilhon, Pierre-Emmanuel Tardo-Dino

14:45 – 15:00	Chatbot as an Information Support in The Field of Protective Clothing Selection, Use, Care, And Maintenance	Monika Kobus, Agata Kmiecik , Sylwia Krzeminska, Agnieszka Greszta, Anna Dabrowska
15:00 – 15:15	Reviewing Integrated Ergonomics of PPE Textiles	Paula Veske-Lepp, Ada Traumann , Teele Peets, Merje Beilmann, Margit Kuusk, Jane Kivistik
15:15 – 15:50	Posters, exhibition, and coffee break	
15:50 – 16:50	SESSION 9 - Thermal Protective Clothing & Physiological Impact Chair: <i>Prof. Dr. Inga Dāboliņa</i>	
15:50 – 16:05	Structural Integrity of Firefighter Suits and Protection Against Combustion Products	Lukas Kralik , Kamila Lunerova, Jakub Vanek, Marketa Weisheitelova, Pavel Castulik, Jiri Chrastek, Michaela Serakova, Jiri Kozeluh
16:05 – 16:20	Effects of Sleepless and Alcohol on Thermal Strain While Wearing Firefighters' Protective Clothing in a Hot Environment	Ho-Joon Lee , Ho-Yeon Jeong, Joo-Young Lee
16:20 – 16:35	Integrating a Liquid Sweat Diffusion Model into Human Thermal Simulation	Timofey Golubev , Mark Hepokoski, Kevin Ward
16:35 – 16:50	Cooling Clothing Based on Thermoelectric Phenomenon - Evaluation of Functionality and Ergonomics	Anna Dąbrowska, Monika Kobus , Agata Kmiecik, Agnieszka Greszta, Łukasz Starzak, Bartosz Pękosławski
20:00	Gala Dinner is at Panaroma Restaurant	

Day 4 - 23 MAY 2025		
TIME	TOPIC	SPEAKER
09:00 – 10:30	SESSION 10 – Functional Finishing Treatments & Smart Protective Clothing Chair: <i>Assoc. Prof. Dr. Patricia Dolez</i>	
09:00 – 09:15	Improvement of Flame Retardancy Properties of Textile Surfaces Coated with Cellulose Solution by Coagulation with Silane and Phosphate-Based Nano-Sol	Çetin Aka , Aysun Akşit
09:15 – 09:30	High Performance Fabrics, Nanomembranes and Lamination Process Improvements for Firefighters Hoods Sustainability	Fabien Michel
09:30 – 09:45	An Effective Strategy for UV Protection of Aramid Fibers: Layer-by-Layer Nanocoating	Yeşim Ünvar , Merih Sarıışık, Şule Uğur, Aylin Albayrak
10:00 – 10:15	Incorporation of Phase Change Materials onto a Textile Fabric: A Comparison Study	Maria António, Ana Barros, André Barbosa, Gilda Santos
10:15 - 10:30	Designing and Evaluating Smart Thermal Insulation Channel Layout Using MPCM in Thermal Protective Clothing	Miao Tian, Zhili Wang, Lin Shao , Yunyi Wang, Yun Su
10:30 – 10:50	Posters, exhibition, and coffee break	
10:50 - 11:50	SESSION 11 - Innovative Protective Products & New Materials Chair: <i>Dr. Kirsi Jussila</i>	
10:50 -- 11:05	Flexible Composites Containing WO₃/BN Particles for Ionising Radiation Protection	Nebahat Aral , Sağanak Yağmur Arslan

11:05 – 11:20	An Optimized Inherently Flame Retardant Fiber - Part 1 Undergarment	Aras Mutlu , Doğukan Akşim Tekiner, Yusuf Yeşilay, Asli Ertan, Selen Gökçe Selçuki
11:20 – 11:35	3D-Printed Structures on Fabrics for Soft Knee Orthoses: Design and Pressure Evaluation	Ozan Abut , Muhammet Müslim, Murat Demir
	Closing of the conference (poster awards, next conference)	

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ORAL PRESENTATIONS

STANDARDS AND MEASUREMENT OF SWEATING AND COOLING IN MULTI-LAYER COLD WEATHER CLOTHING SYSTEMS

Emiel Denhartog¹

¹NC State University

Abstract: In this study, we used the new dynamic hot plate test methods to evaluate the effects of multi-layer clothing systems on the measured heat loss on the sweating hot plate and thermal manikin. The results showed that there were significant differences between the base layer fabrics on the dynamic plate test on the hot plate, but these differences were much reduced when measuring on a multi-layer system. This would be in line with limited effects found in cold weather clothing systems with human subject experiments. Furthermore, thermal manikin effects on base layer and two-layer systems also showed very little differences, due to the difference in measurement technology and setup. These results suggest that the new dynamic plate protocols as adopted by ASTM and ISO should be used with caution when the fabrics tested are designed to be used in multi-layer clothing systems such as used in cold environments in general and specifically with cold protective clothing.

Keywords: Hot Plate, Thermal Manikin, Dynamic cooling test. Thermal comfort, cold

1. INTRODUCTION

Thermal comfort is important to maintain in extreme cold weather conditions and is directly correlated to thickness and air permeability of a fabric [1,2]. Military ensembles for cold weather combat are often thick multi-layer clothing systems that generally consist of base layers, middle layers, and outer layers to protect against cold weather conditions [1]. The purpose of this study was to evaluate whether 100% wool fabrics would perform the same as polyester base fabrics and to evaluate the effects of underwear layers on standard sweating hot plate technologies, including the artificial manikin “skin” layer, to explore whether they provide accurate results.

2. MATERIALS AND METHODS

2.1. Materials

In these experiments, three sets of fabric samples were evaluated: fabrics from current cold weather winter ensembles, fabrics knitted at NC State, and commercially available fabrics. Table 1, seen below, is a comprehensive list of every fabric sample used in the evaluations.

2.2. Physical Properties

Table 1: A comprehensive list of the fabric samples and their parameters that were used in the evaluations

Fabric Sample	WN-2	WN-1	W-1	W-2	Cold Reference Base	Cold Reference Outer	Manikin “Skin”	Commercial Wool	Commercial PP
Fibers	Wool/Nylon	Wool/Nylon	Wool	Wool	Polyester	Nylon/Spandex	Nylon	Wool/Polyester	Polypropylene
Blend Ratio	80/20	80/20	100	100	100	91/9	100	80/20	100
Fabric Construction	Fishnet	Fishnet	Fishnet	Fishnet	Jersey Knit	Woven	Knit	Fishnet	Fishnet
Thickness	1.91 mm	1.46 mm	1.33 mm	1.28 mm	0.45 mm	0.49 mm	0.6 mm	1.28 mm	0.95 mm
Experiment	HP, M	HP, M	HP	HP	HP, M	HP, M	HP, M	HP	HP

HP: Hot Plate, M: Manikin

The fishnet constructions (WN-2, WN-1, W-1, W-2, Commercial Wool and Commercial PP) all resemble an open mesh/net structure. This structure is very porous and breathable.

2.3. Sweating Hot Plate and Manikin

The Small Sweating Guarded Hot Plate evaluation was performed similar to the requirements of ASTM-F1868 (Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate).

The evaluation conditions were: Environment set to 22°C and 62% RH, Sweat rate of the plate was 1800 mL/hr/m² (or mL/min/pore). The Sweating Thermal Manikin evaluation was performed in adherence to the requirements of ASTM-F1291 (Standard Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin).

The evaluation conditions were: Environment set to 22°C and 62% RH, Sweat rate of the plate was 1000 mL/hr/m² (or mL/min/pore), there were 113 pores distributed over the torso, arms, and legs

3. RESULTS AND DISCUSSION

The three evaluation segments can be seen in the figures. In the hot plate experiments, the first 10 minutes was conditioning, and the next 5 minutes was sweating. During this sweating segment, the curves showed an increasing correlation until the sweating stopped at 15 minutes. The fabrics then dried out and there were very clear differences between the base layer fabrics, cf. Figure 1.

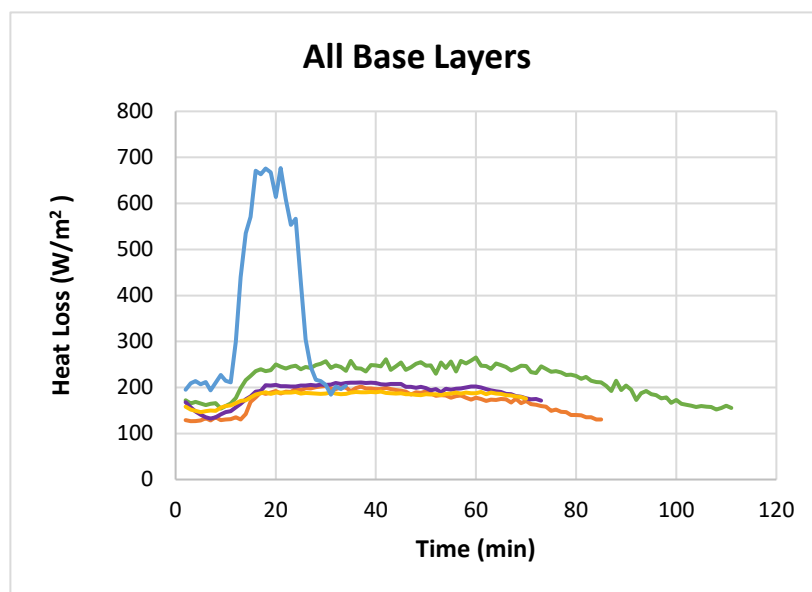


Figure 1: Single layer base layer tests on hot plate, fabrics as follows: Green: Commercial PP; Yellow: WN-2 7.5; Orange: Commercial Wool; Blue: Cold Reference Base; Purple: WN-2 6.0

The tests with multiple layers on the hot plate as well as the tests on the manikin showed very similar trends. In both cases the addition of layers significantly reduced the differences between the base layers. Furthermore, if a strong spreading (wicking) layer was present underneath the base layer, such as in standard sweating thermal manikin experiments, the differences between base layers in the tests disappeared. Reference measurements on the manikin without its “skin” layer confirmed its impact on the test results.

From the results it was clear that the wool-based base layers showed a significant delay in cooling but also a much reduced after-chill effect, which may suggest beneficial effects in the cold but less so in warm conditions. The large difference in heat loss between the polyester jersey knit fabric and the wool/nylon fishnet fabric can be seen in figure 1. Cold Base Layer cooled and dried very quickly while WN-2 dried slowly and had lower heat loss. This starts a discussion as to which fabric is better for a cold weather base layer. It depends on what type of exercise the wearer is

doing, whether that be stationary work or active work. The Cold Base Layer will perform better if the wearer is doing very active work and needs to be cooled and dried quickly once finished. WN-2 will perform better if the wearer is doing stationary or low activity work where it is more desirable to stay warmer during the exercise. During the hot plate evaluations, both PP and Wool Commercial fabrics behaved as very hydrophobic fabrics and only absorbed some of the water but rather sat on top of the water. The Wool Commercial fabric had a very similar curve to the fishnet fabrics which is likely because all three of these fabrics are composed of at least 80% wool. The results from the manikin experiments showed very similar qualitative trends, but the differences between base layer fabrics were very much reduced due to the standard "skin" layer used that provided a high wicking performance. Removing that layer showed similar trends as the hot plate. Thus, the manikin may not always be an appropriate tool to evaluate differences between fabric base layers, in protective clothing systems. Furthermore, the difference between all these tools and true human sweat patterns needs to be studied further.

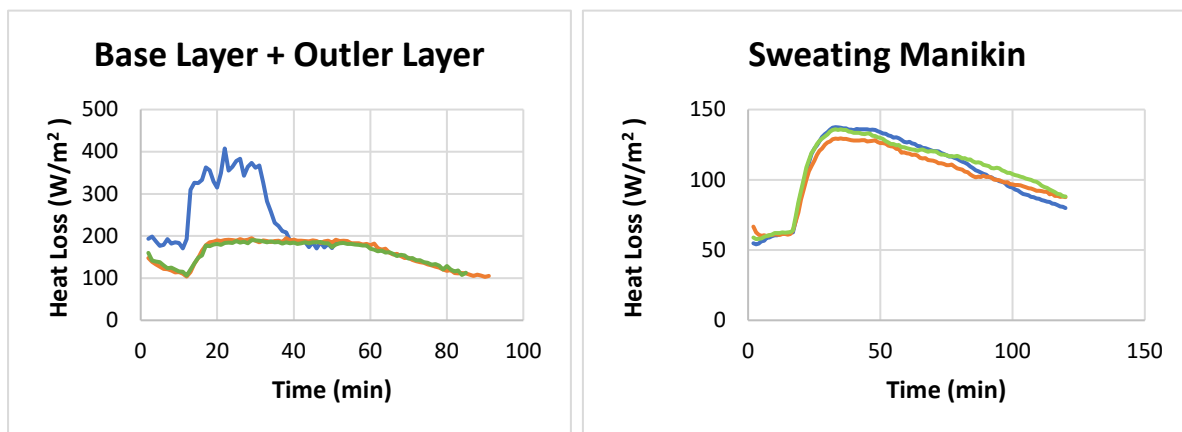


Figure 2: Graphs of the two-layered comparisons on the hot plate. The left graph shows the base layer (Cold Base Reference [blue], WN-2 6.0 [green] and 7.5[orange]) with the Cold reference Outer layer as the second layer. The right graph shows the manikin "skin" layer test results compared to two-layered systems (manikin "Skin" underneath the base layer), with the same color codes, and it can be seen that this layer negates differences that were previously seen between the layers.

4. CONCLUSION

This study showed that during and after exercise, wearing a base layer with wool would provide sufficient insulation to prevent after chill, while the current polyester base layer would provide rapid and strong cooling and garment drying. Neither of these conclusions is better than the other but they both provide the potential for options in different forms of exercise in cold weather, with a buffering effect from the wool-based fabrics. The manikin "skin" layer that is required in ASTM F2370 for sweating thermal manikin evaluations spread the water so productively that it negated any differences in the fabric samples that had been previously seen. This is likely an artifact of that test system. Future research is recommended into the human physiological response while wearing either base layer and performing exercise-rest protocols in cold weather conditions. Specifically, the effects of fabric construction and fiber content should be studied with respect to their thermal sensation with multi-layers in cold conditions.

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MULTI-LEVEL HEATING DESIGN FOR ELECTRICALLY HEATED CLOTHING BASED ON PRESSURE DISTRIBUTION

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Abstract: Electrically heated clothing is typically designed based on thermal requirements in a standard standing posture. However, occupational tasks frequently requiring prolonged static postures (e.g., sitting or squatting) induced a 14.8% reduction in heat transfer efficiency per 1 kPa pressure increment ($p < 0.01$), fundamentally altering thermal equilibrium in the human-clothing-environment system and compromising thermal comfort. This study quantifies clothing pressure distributions across three postures (standing, sitting, squatting) and evaluates the thermal transfer performance of multilayer fabric assemblies under varying pressures (0–6 kPa) and heating levels (38°C, 43°C, 48°C, 53°C) using a sweating guarded hot plate apparatus. A pressure-adaptive multilevel heating strategy is proposed to optimize zone-specific power allocation based on postural pressure patterns. This research establishes a theoretical framework for dynamic thermal regulation in heated garments and advances foundational insights for next-generation smart thermal management systems.

Keywords: Electrically heated clothing, thermal comfort, pressure distribution, multi-level heating, human posture.

1. INTRODUCTION

Thermal protection is crucial in extreme cold environments. While traditional garments rely on passive insulation, active heating—especially electric heating—has emerged to address the issues of bulkiness and reduced mobility associated with passive methods. Despite advances in heating performance, safety, and energy consumption, the impact of clothing pressure on thermal comfort has been largely overlooked.

Most studies on electrically heated clothing focus on the standard standing posture, but real-world work often requires workers to maintain specific postures, such as standing, sitting, or squatting (Li & Cao, 2006). Posture changes significantly influence heat transfer in the “body-clothing-environment” system, affecting insulation and convective heat transfer (Gao, Ooka, & Oh, 2019). For example, insulation in a sitting posture can decrease by up to 20% compared to standing, and convective heat transfer varies with posture and wind speed (Li & Zhang, 2003). This highlights the need to consider posture in the thermal management of electrically heated clothing. Since active and passive heating transfer heat in different directions, this study investigates the effect of posture on heating performance and thermal comfort, aiming to develop a posture-based heating zone design for improved comfort.

This study addresses three critical gaps through interdisciplinary integration:

- Interface pressure mapping across 12 anatomical zones (modified ISO 20344 protocol)
- Thermal hysteresis characterization under cyclic compression (0–6 kPa)
- Development of a sensor-driven heating algorithm using machine learning

2. MATERIALS AND METHODS

2.1 Fabric Assembly and Heating Configuration

A multilayer fabric assembly mimicking commercial cold-weather garments was constructed, comprising:

- Outer shell: 75% polyester/25% polyurethane (230 g/m²)
- Insulation layer: 100% polyimide aerogel (6 mm thickness)
- Base layer: 92% polyethylene/8% spandex (150 g/m²)

Carbon nanotube heating elements ($21\text{ cm} \times 13\text{ cm}$, $3.2\ \Omega/\text{m}^2$) were integrated between the insulation and base layers. Temperature regulation ($\pm 0.4^\circ\text{C}$) was achieved through a programmable DC power supply (Korad KWR102, 0–30V).

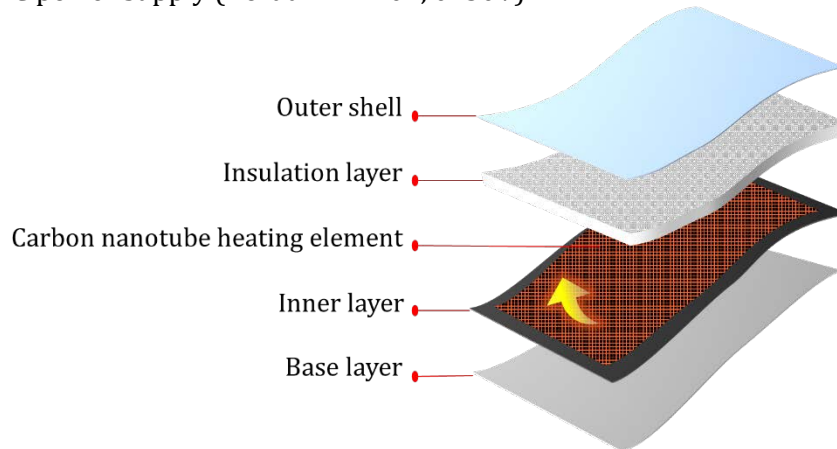


Figure 1. Schematic diagram of multi-layer heating fabric combination

2.2 Pressure Simulation and Experimental Conditions

Calibrated weights (0 kPa, 0.5 kPa, 1 kPa, 1.5 kPa, 2.5 kPa, and 6 kPa) were applied vertically via modular iron blocks, with acrylic barriers minimizing conductive interference. Thermal characterization was conducted in a climatic chamber ($10 \pm 0.5^\circ\text{C}$, $55 \pm 5\%$ RH, $< 0.4\text{ m/s}$ airflow) using a sweating guarded hot plate (SGHP 306-200/400, surface temperature 35°C). iButton sensors (DS1922L, $\pm 0.1^\circ\text{C}$) logged base layer temperatures at 1-min intervals across 120 experimental trials.

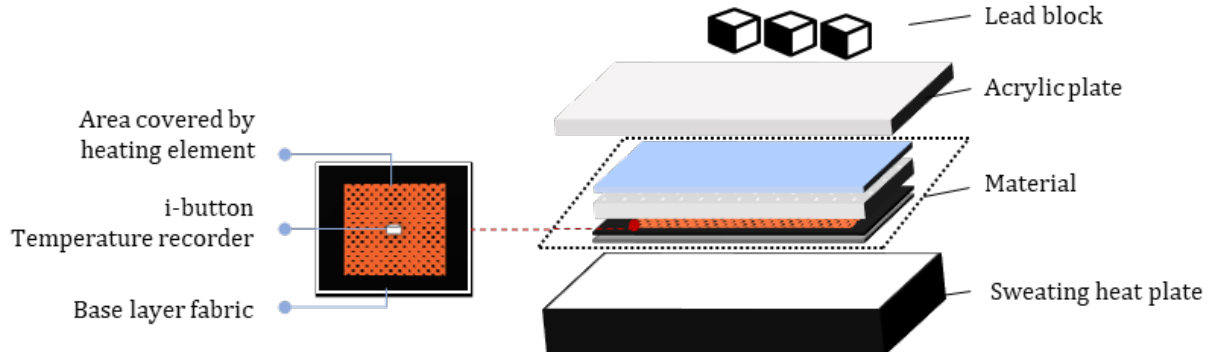


Figure 2. Schematic of multilayer fabric under simulated clothing pressure

3. RESULTS AND DISCUSSION

A nonlinear relationship emerged between applied pressure and thermal plate temperature (Figure 3). Below 1.5 kPa, decreasing fabric thickness dominated heat transfer processes, resulting in a 14.8% temperature drop per 0.5 kPa pressure increment ($p < 0.01$). Above this threshold, partial thermal recovery (3.2% per kPa) occurred due to enhanced interfacial contact conductance.

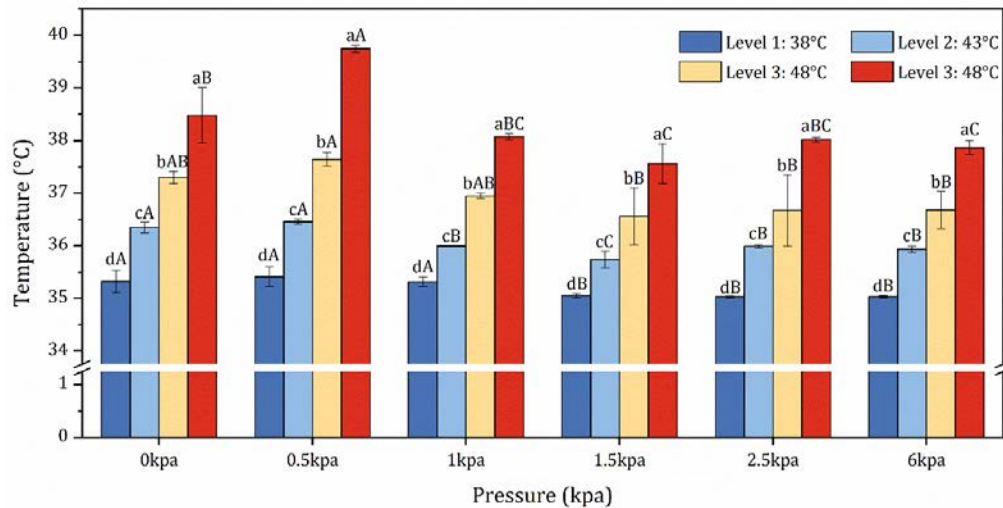


Figure 3. Surface temperature of hot plate under different heating gear and clothing pressure

Note: Different uppercase letters in the figure indicate a significant temperature difference between different pressure levels at the same heating setting ($p < 0.05$); different lowercase letters in the figure indicate a significant temperature difference between different heating settings at the same pressure level ($p < 0.05$).

4. CONCLUSION

4.1 Adaptive Heating Strategy

The proposed framework allocates heating intensities through three operational modes:

- Low-pressure zones (0–1.5 kPa): Level 1–2 (38–43°C)
- Medium-pressure zones (1.5–3.5 kPa): Level 3 (48°C)
- High-pressure zones (>3.5 kPa): Level 4 (53°C)

This hierarchical approach reduced energy consumption by 22% compared to uniform heating in posture-switching scenarios ($p = 0.007$).

4.2 Limitations and Recommendations

- Methodological constraints: Static plate measurements may underestimate convective effects during movement.
- Sensor limitations: Current iButton thickness (3.2 mm) perturbs pressure distribution; microelectromechanical (MEMS) sensors (<0.1 mm) are recommended.
- Validation needs: Human trials under realistic working conditions are essential for physiological validation.

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STUDY ON OPTIMIZATION OF THERMAL AND MOISTURE TRANSFER PERFORMANCE OF AEROGEL FOAM MATERIALS FOR COLD PROTECTIVE CLOTHING

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Abstract: *Despite the excellent thermal insulation properties of aerogel foam used in cold protective clothing, it suffers from poor air and moisture permeability, leading to stuffiness and discomfort when worn. This study explores how hole design affects thermal and moisture transfer performance of aerogel foam based on fabrics and clothing experiments. It is aimed at improving efficacy of structure design on optimizing the performance of aerogel foaming material. The results indicated that changes in porosity within a certain range had minimal impact on the thermal insulation properties of fabrics. However, air and moisture permeability were significantly improved, whose improvements were correlating positively with increased porosity. A high-intensity running test verified that increasing hole diameter of aerogel fabrics could enhance moisture comfort. Specifically, aerogel foam fabric with a 2.8mm hole diameter demonstrated superior performance in improving thermal and moisture comfort among different exercise intensities.*

Keywords: *Aerogel foam fabrics, cold protective clothing, thermal and moisture comfort, hole design.*

1. INTRODUCTION

Aerogel is an exceptionally lightweight nanoporous material characterized by its high specific surface area, superior thermal insulation, and other attributes (Thapliyal & Singh, 2014). Its minimal thickness makes it suitable for lightweight cold protective clothing. However, aerogel foam exhibits poor moisture absorption and air permeability, leading to suboptimal thermal and moisture comfort in clothing (McNeil & Gupta, 2022). Laser drilling was employed to address these issues, proved to be effective in improving moisture transfer performance (Shaïd et al., 2021). Nonetheless, existing research primarily focus on performance of fabrics rather than clothing. Moreover, given that substantial still air within aerogel significantly enhances its thermal insulation, increasing pores will not only improve the material's air permeability and moisture permeability but may also compromise its thermal insulation capacity. Therefore, this paper investigated the optimal design parameter when utilizing aerogel foam in cold protective clothing.

2. MATERIALS AND METHODS

2.1. Preparation of Aerogel Textile and Clothing

To enhance the permeability and moisture transmission of the material, this study used laser cutting machine to process the hole pattern of each material. Specifically, four fabric samples (A-D) were produced using an equidistant layout scheme, with a spacing of 10 mm and varying hole diameter of 0 mm, 2.0 mm, 2.8 mm, and 4.0 mm, respectively. The characteristics of the samples are detailed in Table 1. Clothes samples comprised the same detachable outer coat paired with 4 different inner clothes. They respectively corresponded to the Fabric A-D, designated as samples I-IV.

Table 1. Information of fabric samples

Fabric code	Hole diameter (mm)	Porosity (%)	Thickness (mm)	Mass (g/m ²)	Schematic diagram
A	0	0	2.407	139.70	
B	2.0	3.14	2.407	133.20	
C	2.8	6.16	2.407	126.00	
D	4.0	12.57	2.407	113.20	

2.2. Thermal and Moisture Transfer Performance Test of Fabrics and Clothing

To evaluate the moisture transfer performance of the materials, the air permeability measured by the YG461 digital air permeability tester, the water vapor transmission rate acquired by the FX 3180 moisture permeability analyzer, and the moisture resistance obtained by the SGHP-10.5 sweating hot plate instrument were considered for performance characterization. To assess the thermal transfer performance of the materials and garments, the thermal resistance of fabrics obtained by the aforementioned hot plate instrument and the thermal resistance of garments obtained by the thermal manikin Newton were considered for performance characterization.

2.3. Validation Experiment of Thermal and Moisture Comfort Performance

The effectiveness of hole pattern design for aerogel material in improving thermal and moisture management was assessed through subjective evaluation. Data were gathered from nine college students. The ambient conditions were set at 0°C, with 50% relative humidity and wind speed of 0.73 m/s. The experiment protocol involved an initial 10-minute seated period, followed by a 30-minute treadmill run at a speed of 8 km/h, which corresponds to the high metabolic level specified in ISO 8996, and concluded with another 10-minute seated period. Subjective responses were obtained every 10 min, including thermal sensation (on a 7-degree bipolar scale from -3 = very cold to +3 = very hot, with 0 = neutral), moisture sensation (on a 7-degree bipolar scale), and overall comfort (on a 7-degree bipolar scale).

3. RESULTS AND DISCUSSION

3.1. Analysis of Thermal and Moisture Transfer Performance Test of Fabrics and Clothing

The effect of different hole pattern on thermal and moisture transfer performance of the fabrics and clothing is shown in Table 2. Fabric exhibits excessively high moisture resistance, causing the test device failing to acquire valid result. Significant differences in air permeability are observed between Fabric A and Fabric B, C, D ($p < 0.01$), indicating that the laser drilling significantly enhances air flow within the material. As porosity increases, so does the air permeability of fabric. However, no significant difference in air permeability is found among Fabric B, C, and D ($p > 0.05$). This suggests that once the porosity of aerogel foamed materials reaches a certain threshold, further increases in porosity contribute less to improving permeability. There is a significant negative correlation between the moisture resistance and porosity (Pearson correlation coefficient = -0.915, $p < 0.01$). The porosity of Fabric B, C, and D is approximately 1:2:4, while water vapor transmission and humidity resistance decrease by approximately 50% from B to C and from C to D. These findings confirm that hole design improves the permeability of aerogel foam,

consistent with the outcomes of air permeability. Regarding thermal insulation, no significant difference in thermal resistance was observed between Fabric A and Fabric B, C, and D ($p>0.05$). This indicates that the laser drilling method does not substantially compromise the thermal insulation performance of aerogel foam materials. Notably, while thermal resistance decreases as material porosity increases, this decrease is not proportional to the increase in porosity. This can be attributed to the fact that the fabric in the material test was in a flat state, whereas the garments worn by the manikin were in a natural, three-dimensional state. As a result, the heat transfer mechanisms under these two testing conditions vary.

Table 2. Thermal and moisture transfer properties of fabrics and clothing

Fabric code	Air permeability mm/s	Water vapor transmission rate g/m ² /day	Moisture resistance Pa·m ² /W	Thermal insulation of fabrics °C·m ² /W	Thermal insulation of clothing Clo
A	0.00	18.43	/	0.1339	3.68
B	20.47	168.70	130.20	0.1277	3.55
C	21.85	248.70	69.87	0.1384	3.50
D	22.14	370.40	26.51	0.1235	3.47

3.2. Validation Experiment on Thermal and Moisture Comfort Performance of Clothing

The changes in the psychological responses of subjects wearing cold protective clothes made of four types of aerogel are illustrated in Figure 2. As the porosity of the material increased, the thermal resistance of clothing exhibited a decreasing trend. Therefore, subjects experienced the highest average skin temperature and overall thermal sensation when wearing experimental samples I and II. The lowest degree of moisture sensation was recorded when subjects wore experimental samples II and IV, which was not entirely consistent with the test results showing that fabric C had better moisture permeability than fabric B. This discrepancy may be correlated with the lower overall wetness sensation degree observed when subjects wore sample II after running. Overall comfort degrees were closely related to thermal and moisture management performance of clothing. When standing in windy environment, subjects wearing sample I reported the highest overall comfort, corresponding to its high thermal resistance and low permeability. During the final rest phase, subjects wearing sample II reported the highest overall comfort, aligning with the lowest overall moisture sensation during this phase.

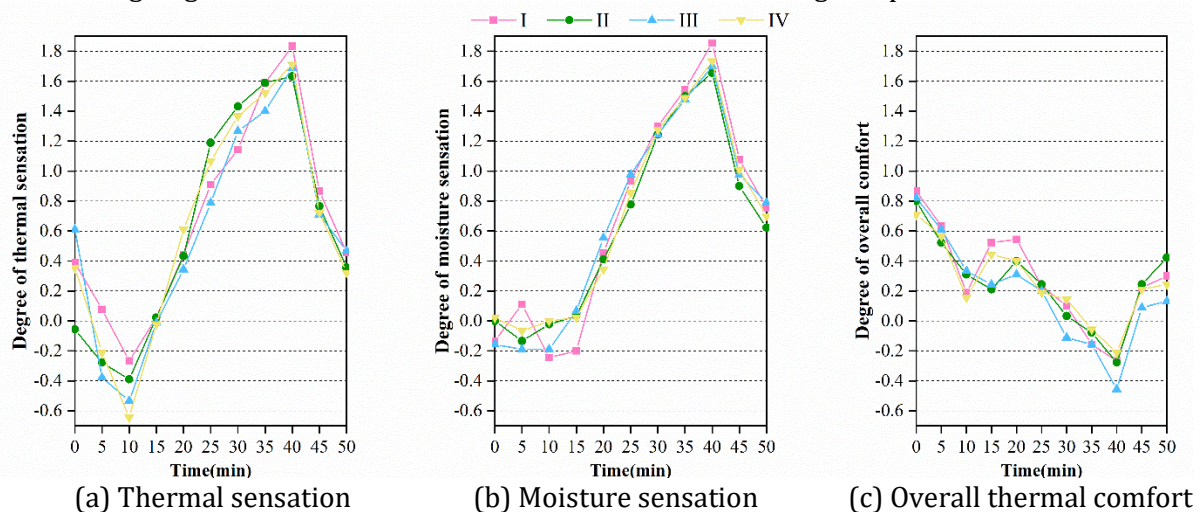


Figure 2. Psychological responses over time

4. CONCLUSION

Focusing on the issues of poor air and moisture permeability in aerogel-foam fabrics, this paper investigated the impact of hole pattern on moisture permeability, thermal insulation and physiological responses. Within a certain range, changes in porosity have minimal effects on the

thermal insulation of fabrics but slightly reduce the thermal insulation of clothing. However, air and moisture permeability are significantly enhanced, with improvements correlating positively with increased porosity. Running test confirmed that increasing the hole diameter of aerogel materials improves moisture comfort under high-intensity exercise condition. A pore diameter of 2.8 mm is suitable for aerogel foam of cold-weather clothing, because subjects reported higher thermal sensation and comfort degrees, along with lower perceived humidity when wearing it.

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THE EFFECT OF BULKY PROTECTIVE CLOTHING ON ENERGY REQUIREMENTS IN WALKING ACTIVITY

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Abstract: *In this study the impact of wind on the metabolic rate ($\dot{V}O_2$, nutritional demands) and cardiovascular load (Heart Rate, HR) of a wearer of bulky Protective Clothing was studied for head- and tailwind in a walking activity. The attenuating effect of tailwind on $\dot{V}O_2$ and HR was shown to be greater than the amplifying effects of headwind. This is consistent with recent publications on the impact of head- and tailwind on semi-nude runners. The increase of the projected area due to the selected Protective Clothing showed decreases up to 9.6 and 4.6% in $\dot{V}O_2$ and HR for tailwind and increases of 5 and 4.1% for $\dot{V}O_2$ and HR in headwind. In order to develop a relation between projected area and metabolic impact of wind additional ensembles need to be tested in the future.*

Keywords: wind, projected surface, metabolic rate, nutritional demands.

1. INTRODUCTION

Testing protective clothing indoors on a cycling ergometer or treadmill in still air conditions does not replicate the complete conditions of walking or cycling outdoors. When exercising outdoors there is the potential presence of wind and self-generated air speed caused by the individual's movement through the air, together producing a relative air speed to the wearer. Air movement relative to the person has impacts on energy expenditure [1,2,3,4], convective and evaporative cooling [5], clothing insulative properties [6] and the person's perception of the exercise [7]. The impact of protective clothing on metabolic rate is substantial (8) and an important factor to consider. When working in windy environments it is expected that the wind may further raise metabolic rate when moving against the wind, or reduce metabolic rate when moving with the wind. As such effects are related to the surface area of the windward body profile (4), the bulkiness of the clothing will have an effect. The present study considers the impact wind has on metabolic rate and its interaction with the clothing bulkiness. A single, bulky ensemble will be tested to get an impression of the effect size. Such data are relevant to the evaluation of PPE for windy conditions and contribute to our understanding of nutritional needs during expeditions where protective clothing and high winds are present.

2. MATERIALS AND METHODS

Oxygen consumption ($\dot{V}O_2$) and heart rate (HR) of 10 healthy participants (age 21-28 years, body mass 62-83 kg) were measured during steady state treadmill walking (5km/h) in various wind velocities. A custom made wind tunnel was used to generate 7.85 m/s tailwind, and 0.13, 4.17 and 7.85 m/s headwinds. Participants walked in two different clothing ensembles (Light clothing ensemble [LCE], and a Cold Weather Clothing Ensemble [CWCE]).

3. RESULTS AND DISCUSSION

$\dot{V}O_2$ (ml.kg⁻¹.min⁻¹) (see Figure 1) and HR (BPM) significantly ($p < 0.05$) increased with headwind speed and decreased as tailwinds increased, whilst walking in both clothing ensembles. When expressing the data relative to the no-wind walking data for each individual ensemble (effectively removing the effects of clothing weight, friction between layers and bulk), for the CWCE, $\dot{V}O_2$ (ml.kg⁻¹.min⁻¹) and HR (BPM) reduced by 9.6 and 4.63% ($p < 0.05$) at a tailwind of 7.85 m/s, compared to walking in the LCE. For the 7.85 m/s headwind, there was a tendency for $\dot{V}O_2$ and HR in the CWCE to be 4.95 and 4.14% higher respectively compared to when wearing the LCE. The tailwind thus had a stronger attenuating effect on metabolic rate and heart rate than the increasing effect of the headwind. This is consistent with the observations without protective

clothing, where also the tailwind had a bigger effect than the headwind on metabolic rate (4) for the experiments where core temperature was controlled. In the classical data from Pugh and Davies (1,2,3), headwind had bigger effects than tailwind, but a recent analysis by (4) indicated that this was due to the experimental protocol, where core temperatures increased with wind speed. The present data can help predict the impact of PPE on metabolic needs and e.g. help setting ration requirements for expeditions.

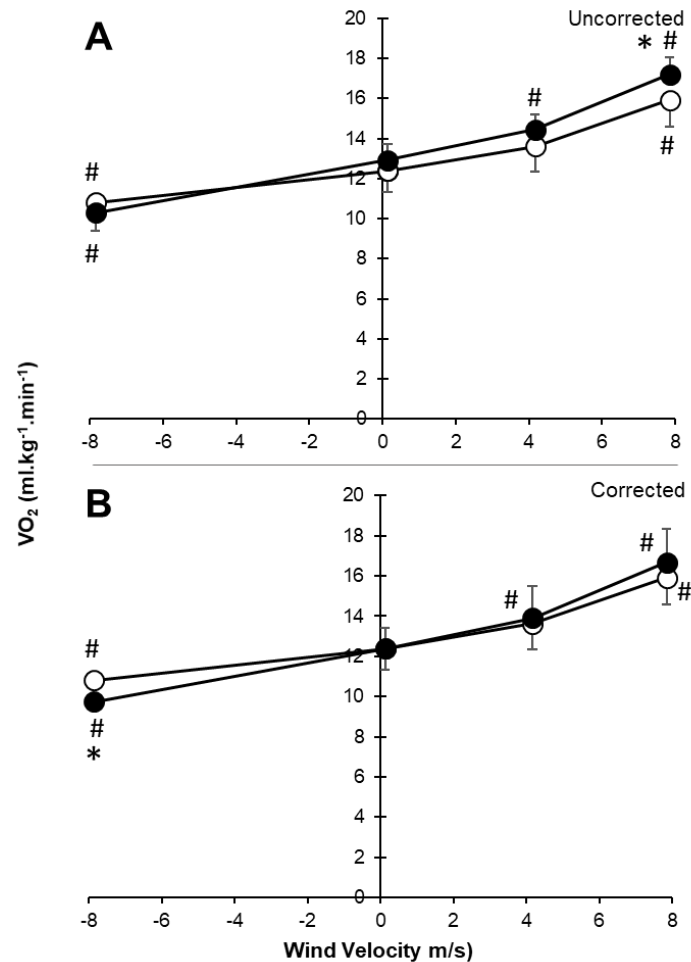


Figure 1 Average $\dot{V}O_2$ (A: Uncorrected; B: Corrected for the no wind difference between ensembles) during walking in various wind velocities in the LCE (○) and CWCE (●). Significant effect (Bonferroni adjusted alpha levels to .008 [.05/6]) vs no wind indicated by #. Significant effect (Bonferroni adjusted alpha levels to .016 [.05/3]) between clothing ensembles at equivalent W_v indicated by asterisk.

4. CONCLUSION

As expected, in this initial study, headwinds and tailwinds significantly increased and decreased energy expenditure respectively, in two different clothing ensembles. The study showed that increases in projected surface area (A_p) due to clothing can increase the changes in energy usage caused by both headwinds and tailwinds. Tailwinds had a bigger impact than headwinds. This study identified the need for further research to explore the relation of projected area and energy requirements whilst working in headwinds and tailwinds wearing Personal Protective Clothing. Further, the impact of surface roughness may be of relevance. With the present clothing having a very smooth surface, the effects observed would be mostly influenced by A_p .

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A Coupling Method for Transient Human Thermoregulation Model and Wearable Monitoring System

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Abstract: In this study, a coupling method for transient human thermoregulation model and wearable monitoring system is proposed. The main work include: 1) An improved thermoregulation model is developed by incorporating dynamic environmental signals (temperature T_a , relative humidity RH) and metabolic-rate (MET) driven by heart rate (HR). 2) The thermoregulation model are further optimized by error feedback of core temperature (T_c, T'_c), skin temperature (T_s, T'_s), and sweat rate (S_w, S'_w). 3) Based on both predicted (T'_c, T'_s, S'_w) and measured data (HR), a thermal-safety evaluation model and accompanying software are established, which estimates possible health risks for occupationally exposures. The presented coupling method contributes to personal protection strategies to avoid occupational injuries.

Keywords: human thermoregulation model, wearable monitoring, thermophysiological indicators, thermal safety.

1. INTRODUCTION

The human thermoregulation model is an effective tool to simulate and predict human thermal response under various environments (Ivanov, K. P., 2006). However, these models often require a number of inputs to ensure the calculation's accuracy, limiting their application. Wearable sensing devices are convenient ways to monitor various physiological and environmental indicators (Bustos, D., et al., 2021) and are expected to be introduced into occupational scenarios. Nevertheless, some important physiological indicators, e.g., body core temperature and metabolic rate (Green, J. A., 2011), cannot be easily measured. In this study, we improve the human thermoregulation model by incorporating real-time physiological and environmental data obtained by the wearable monitoring system. Furthermore, a thermal-safety evaluation model is established to estimate human health risks based on predicted and monitored physiological indicators.

2. METHODS

2.1 Human Thermoregulation Model

The transient human thermoregulation model is developed based on the JOS-3 model (Takahashi, Y. et al., 2021) and then extended to occupational exposure by considering the effects of environmental and clothing conditions on thermal responses, which have been described and validated in our previous works (Chen, F., et al., 2022). The model mainly consists of two parts: the thermoregulation system and the multi-node clothing system. The thermoregulation system describes the passive heat transfer processes inside body tissues, as well as the active regulatory mechanisms. The multi-node clothing system describes the exchange processes of heat and moisture between the body and the environment through personal protective equipments (PPE). The model's inputs involve environmental, clothing, and individual parameters, and the outputs mainly include the core temperature, skin temperature, and sweat rate.

2.2 Wearable Monitoring System

The wearable monitoring system is independently developed (supported by the National Key R&D Program of China, No. 2022YFC3006100) and consists of several units. The monitoring unit is responsible for collecting both environmental and physiological signals. Some physiological signals, including local skin temperature and tympanic membrane temperature, are measured by thermistors fixed at the wrist and the ear, respectively. As for sweating and pulse signals at the wrist, they are measured through skin resistance and photoplethysmography, respectively.

Environmental signals, including ambient temperature and humidity, are approximated and measured by temperature and humidity sensors fixed to the outer clothes' surface, respectively. In addition, all signals are sent and summarized to the communication terminal to become usable data after processing and then be invoked by the thermoregulation model.

3. RESULTS AND DISCUSSION

The scheme of the coupling method is shown in Figure. Firstly, an improved human thermoregulation model is based on our original model and developed by real-time input through the wearable monitoring system, aiming to make dynamic predictions for thermophysiological indicators. The improved model incorporates direct environmental input, e.g., real-time ambient temperature (T_a) and relative humidity (RH), and a metabolic-rate equation, which calculates human metabolic rate (MET) based on real-time heart rate (HR) (ISO 8996: 2004).

Secondly, errors will be obtained by comparing the measured skin temperature (T_s), core temperature (T_c), and sweat rate (S_w) with the model's output (T'_s , T'_c , S'_w). Then, the thermoregulation model's parameters, which control vasodilation (α_1 , β_1), vasoconstriction (α_2 , β_2), sweating (α_3 , β_3) and shivering (α_4) will be modified according to the error feedback, thus improving the model's accuracy.

Finally, by combining the predicted physiological indicators (T'_s , T'_c , S'_w) with measured heart rate (HR), an evaluation model based on deep learning is developed to obtain the human health sequence and evaluate the state of thermal safety. In addition, accompanying software is developed to predict health risks and possible injuries under different working conditions, such as firefighting, cold-weather rescue and chemical-leakage rescue.

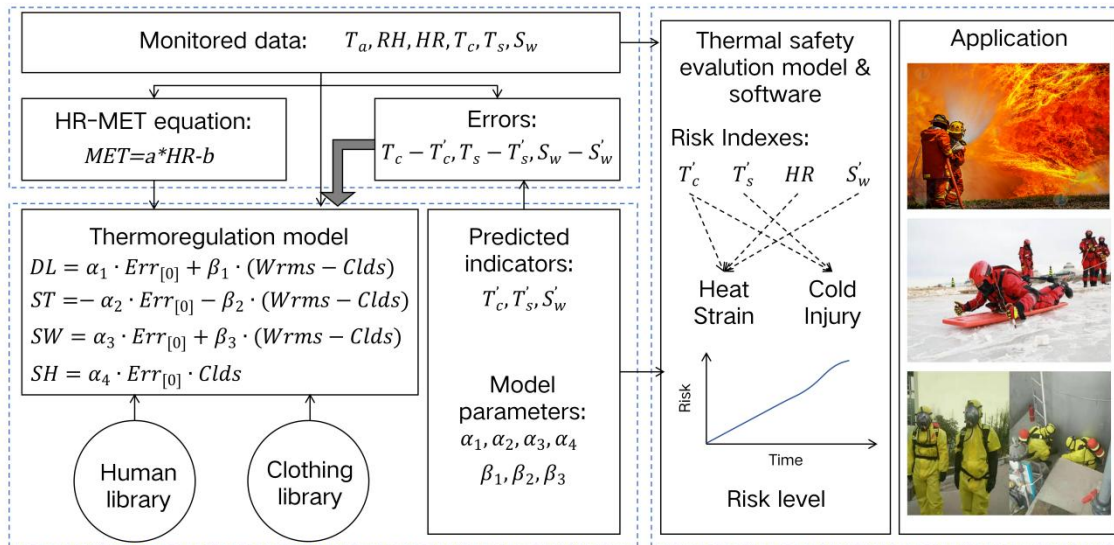


Figure 1. Coupling prediction method for human thermal safety

4. CONCLUSION

This study presents a coupling method that integrates a human thermoregulation model with a wearable monitoring system. By combining real-time environmental and physiological data from the wearable monitoring system, an improved thermoregulation model is developed and expected to predict thermophysiological indicators dynamically. Furthermore, a thermal-safety evaluation model and accompanying software are developed to evaluate health risks associated with

occupational exposures. In our future work, the interaction details between the thermoregulation model and wearable monitoring system will be refined.

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HEAT STRESS PREDICTION FOR SIMULATED TECHNICAL RESCUE ACTIVITIES

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Abstract: Predicted heat strain (PHS, ISO 7933) utilizes clothing, environment and activity data in calculations. Online tool versions from FAME Lab and Lund University allow input of intermittent conditions. The study aimed to validate both algorithms for intermittent firefighter scenarios. This paper addresses technical rescue in warm weather (TRW). Four firefighters dressed in turnout gear performed intermittent activities in a climate controlled room ($T_a=25\pm1^\circ\text{C}$, $\text{RH}=43\pm7\%$, $v_a<0.15\text{ m/s}$). Rectal (T_{rec}) and skin temperatures (T_{sk}), and body water loss (m_{wl}) were compared with PHS predictions. Both tools showed significant differences with the measured data. The discrepancies increased over time and were the largest for T_{sk} ($p<0.05$). T_{rec} showed significant differences towards the exercise end ($p<0.05$), while m_{wl} prediction was similar to measured ($p>0.05$). Neither PHS tool gave a good prediction in TRW. More tests are needed to suggest adjustments of ISO 7933 or a dedicated user standard for intermittent work in protective gear.

Keywords: firefighter, protective clothing, thermal insulation, predicted heat strain, standard.

1. INTRODUCTION

Firefighters often perform heavy work in high ambient temperatures, heat flux from flames and heat radiation and dangerous situations that negatively impact their health and safety (Sandsund et al., 2024). Heavy and semi-permeable protective clothing is commonly used for protection against these hazards. Physiological responses, including increased skin and core temperature may lead to an enhanced risk of heat-related injuries (Carballo-Leyenda et al., 2022). To investigate the effect of clothing on human thermal comfort and thermal stress across various environments, clothing thermal insulation and evaporative resistance should be considered in planning for activities, work organization and selection of optimal protection. For that purpose various thermo-physiological prediction models are available (Havenith & Fiala, 2016). One of these is easily available as a standard on predicted heat strain (PHS, ISO 7933, Malchaire et al., 2001). However, it has been developed mainly for industrial work, and has been shown not to match with measurements outside its validity range (Wang et al., 2013). For advising adjustments of ISO7933, the objectives of this work were to evaluate PHS algorithms for firefighters during simulated technical rescue activities in warm weather (TRW) under changing conditions.

2. MATERIALS AND METHODS

2.1 PHS

Predicted heat strain (PHS, ISO 7933) utilizes clothing properties, environmental parameters and activity levels in calculations. Two online tools for PHS calculations allow input of intermittent conditions: a version from FAME Lab (PHSFL, <https://habitatscience.org/famelabphs.html> based on an ISO 7933 version under revision from 2018) and a Lund University modified PHS version (PHSLU, <https://github.com/Rikuklane/PredictedHeatStrainModel> based on ISO 7933:2004). These tools were utilized on a dataset that was collected during extensive testing on professional firefighters under simulated rescue scenarios and clothing combinations (Kuklane et al., 2024b). The measurements used as input for this work are specifically described in Kuklane et al., (2025).

2.2 Test persons and clothing

For PHS evaluation in TRW scenario the data from four (4) test persons (TP) with traditional turnout gear system was used. Average age of TP was 39 ± 14 years, body mass 86.0 ± 18.3 kg, height of 1.87 ± 0.05 m, body area of 2.10 ± 0.22 m², and body fat $20.6 \pm 7.2\%$. None of TP was smoking and all were in active duty. Used basic clothing insulation was 0.298 and 0.174 m²K/W, clothing evaporative resistance 61.7 and 33.0 m²Pa/W, and clothing moisture permeability index 0.28 and 0.32 for exercise period and recovery, respectively (Kuklane et al., 2024a). The areas with reflective tapes on full clothing set were taken equal to 0.22 m² meaning coverage percent of 8.2% during work and 3.9% during recovery period (no jacket used). Emissivity of the reflective tape was assumed to be at the same level as oxidized aluminium, i.e. 0.20. Rectal (T_{rec}) and skin temperatures (T_{sk}), and body water loss of the human tests were compared with PHS predictions.

2.3 Environment and activity levels

Test person preparation, exercise activities and recovery were all performed in a climate controlled room at $T_a = 25 \pm 1^\circ\text{C}$, $\text{RH} = 43 \pm 7\%$, $v_a < 0.15$ m/s. The activities during exercise were walking at 2.1 km/h (0-30 min), walking at 3.5 km/h (30-60 min), walking at 3.5 km/h with added IR-radiation of 1 kW/m² from right side (60-90 min), and recovery period with seated rest (90-120 min). The measured average metabolic rates for these activities were 142 ± 14 , 187 ± 14 , 193 ± 12 , 68 ± 7 W/m², respectively. The mean radiation temperature during the first 2 activities was $24.5 \pm 0.3^\circ\text{C}$, $62.9 \pm 0.4^\circ\text{C}$ during the period with radiation (assuming radiated area being 32 % of the total body surface) and $26.5 \pm 0.9^\circ\text{C}$ during recovery.

3. RESULTS AND DISCUSSION

Figure 1a shows the skin and Figure 1b rectal temperature development during the experiment and the model, where * marks the experimental periods with significant differences. Figure 2 shows comparison of cumulative body water loss (m_{wl}).

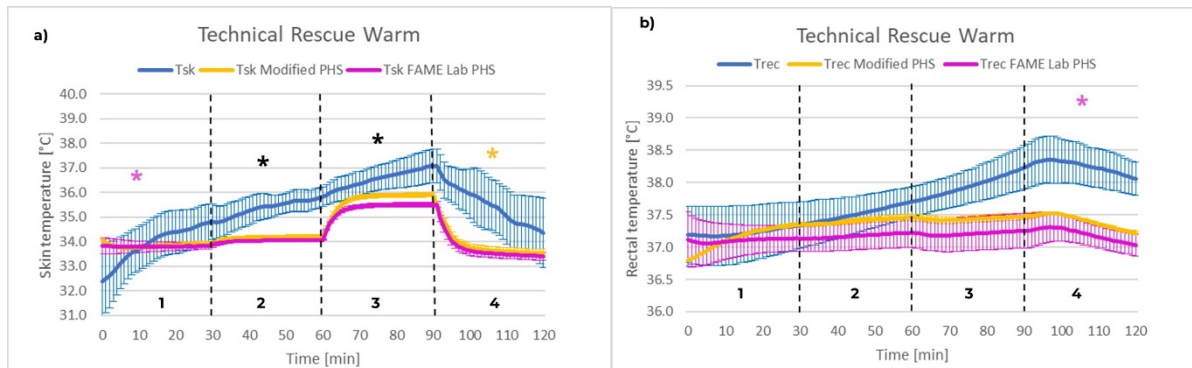


Figure 1. Skin (a) and rectal (b) temperatures during experiment and by the models. * shows significant difference between the experiments and the models within study stages (1-4).

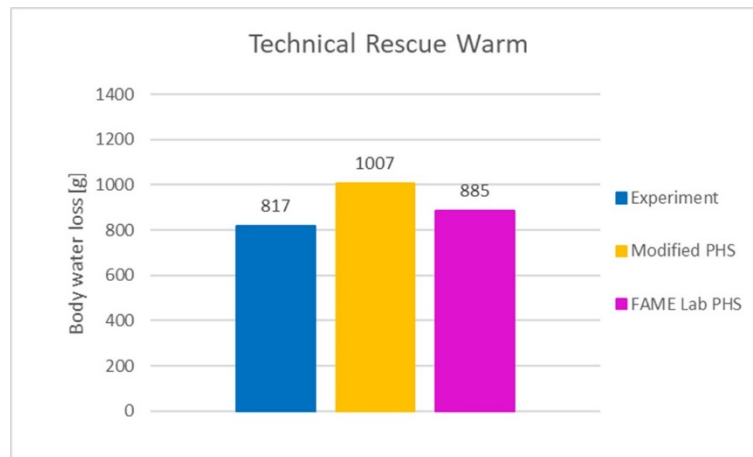


Figure 2. Body water loss.

Standard deviation (SD) of m_{wl} was in all cases ca 200 g, and there were no significant differences observed, although, modelled m_{wl} stayed higher than the experimental values (Figure 2). Mean skin temperature was lower in the model than observed (Figure 1a). Most probably, the higher evaporation expectation in the model leads to lower skin temperature (Figure 1a), and stabilization of the rectal temperature (Figure 1b) in the model compared to measured values.

Another observation is that T_{sk} in the model very quickly reacts to changes in radiation load (1 kW/m², i.e. solar radiation level). Such reaction might be expected when wearing only very light clothing with low insulation and mass or on nude skin. The model calculations include insulation but it seems not to correctly incorporate the evaporative resistance and thermal mass/inertia of the clothing system. PHSFL has no evaporative resistance related input (PHSLU uses moisture permeability index, i_m), and possibly uses the values for normal clothing ($i_m=0.38$) by default. This may explain somewhat higher skin (Figure 1a) and rectal temperatures (Figure 1b) for PHSLU than for PHSFL, that uses measured, considerably lower i_m in prediction.

For a valid prediction RMSD should be less than SD. In the case of TRW RMSD for rectal temperature was 0.51 and 0.67 for PHSLU and PHSFL, respectively, vs. SD of 0.41, and RMSD for skin temperature was 1.20 and 1.35 for PHSLU and PHSFL, respectively, vs. SD of 1.10. I.e. both PHS models were not valid for the exposure prediction under TRW scenario.

4. CONCLUSION

Neither PHS tool gave a good prediction in TRW scenario. However, the study indicated several factors that must be considered for adoption of the model, outside its present validity range. More tests with different clothing and different scenarios are needed to confirm the observations in order to suggest adjustments of ISO7933 or a special user standard for intermittent work in protective gear.

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EXPERIMENTAL TESTING OF MILITARY PROTECTIVE AND BALLISTIC CLOTHING WITH ACTIVE VENTILATION IN EXTREME HEAT

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Abstract: *Extreme missions are a challenge for the army as they require adequate equipment and capabilities to face the associated risks. Understanding the human thermal response allows for modelling and predicting risk situations and adapting solutions to individual characteristics. This study seeks to improve the equipment and strategies of the Spanish Army to face extreme missions in hot conditions, protecting the health and performance of soldiers. The conclusions can be extrapolated to the civilian field, with special interest in Occupational Health, adapted to situations with high thermal stress.*

Keywords: *thermal stress, heat stroke, physiological measurements, active cooling, 3D materials.*

1. INTRODUCTION

The increase in global temperatures is leading to a greater number of heat waves, with record temperatures in different regions. Theoretical and empirical models present gaps in the representativeness of the population, and do not consider the greater or lesser sweating capacity that different thermotypes or different acclimatization could have. It is therefore important to consider the differences in the patterns of thermal regulation and sweating specific to each individual.

Extreme operations in deserts, tropical forests, or with protective equipment, require adequate equipment and capabilities to adapt and face the associated risks. Prolonged exposure to extreme temperatures causes thermal stress in the body, with serious consequences for health.

2. MATERIALS AND METHODS

Based on theoretical data and data from selected users, critical environments and parameters are simulated and then experiments are carried out under controlled conditions with military personnel.

2.1 Objectives

The main objectives of the study were to identify critical areas in the body and in clothing configurations (Latorre-Sánchez et al., 2020) and to identify patterns and variables dependent on thermal regulation and associated with sex, thermal profile or thermotype, and differences between scenarios. From there, to design and incorporate new materials and cooling solutions.

2.2 Clothing and scenarios

Two climates were selected (ARID and TROPICAL) with a temperature > 32°C and with a low relative humidity (20-30%) and high (> 60%) respectively. Three clothing configurations were considered: PPE NBQ configuration, CAMPAIGN configuration (campaign shirt and trousers, storm suit) and COMBAT configuration (light shirt (UBA), campaign trousers and ballistic protection (helmet and anti-fragment-bulletproof vest).

2.3 Experimental design with users

Experimentation with military personnel was carried out throughout the project, A total of 36 sessions of an hour and a half:

- The initial experimental design was carried out considering the factors: sex (balanced), climate (ARID and TROPICAL), clothing and scenario and thermal profile (warm people

and chilly people). The main variables measured were temperature, relative humidity and metabolic expenditure. Temperature was considered A1-extreme dry heat and A2-dry heat and relative humidity: B1- (warm humid) (AECTP 200, s. f.). Metabolic expenditure was divided increasingly into three phases, being moderate in the initial phases I-BASAL and II-BALLISTIC (dressed with the clothing and ballistic protection, bulletproof vest and helmet provided) and high in the last phase III-LOAD (with clothing, ballistic protection and carrying a 10 kg backpack load) (ISO 7243, ISO 8996).

- In a second experiment, an active cooling system incorporated into a breastplate was evaluated. Materials, cooling zones, and usability parameters such as connectors, tubes, air inlets, connections, buttons, and functionalities of the air propulsion electronics were selected. The 1st NBC regiment provided a *Micronel brand NBC* forced breathing apparatus.
- The last battery of tests was with the active cooling prototype and with the clothing with improvements in materials and topologies.

2.4. Thermal comfort laboratory

The experiment was carried out in a thermal comfort laboratory with the main equipment:

- FLIR T650sc thermal cameras. 640 x 480 pixels, 16 bits and 45° lens. LWIR and FLIR A35.
- Modular controlled climatic chamber, with an operating temperature range of -20°C to 60°C and humidity 30% to 80%, 3m x 3m.
- EMPATICA E4© Bracelet (<https://www.empatica.com/research/e4/>) to monitor heart rate, temperature, electrodermal activity (EDA) and photoplethysmography (PPG)
- Portable recording equipment in contact with the user with surface temperature sensor accuracy: $\pm 0.5^\circ\text{C}$, between 10°C and 50°C, and microclimate sensor accuracy: $\pm 0.5^\circ\text{C}$, at 25°C.

2.5. Characterization of new materials in controlled conditions.

New 3D materials (spacer) were characterized, and several test pieces were made with die-cuts and with various air distribution configurations. The test pieces were evaluated in the climatic chamber at 32°C, with the ST2 thermal mannequin that simulates human skin and sweat (<https://thermetrics.com/products/manikin/st-2xl/>) (Figure 1).

3. RESULTS AND DISCUSSION

Objective data from sensors and temperature maps were analysed together with subjective data from surveys. They were grouped by scenario and by sex.

The most critical situations are those that occur in high temperatures, high relative humidity, closed spaces without ventilation and missions with high danger and tension. The areas of the body identified as most critical are in both sexes: armpits, groin and lumbar area. In the case of women, the chest is the area of greatest sweating and in the case of men, the neck and upper back. Regarding sweating, greater sweating is identified in the area of the chest and lower back in women and less in the upper part. In men, sweating is greater in the upper part of the back. In conditions of high ambient temperature, sweating is the most efficient mechanism to reduce body temperature. The evaporation of sweat and heat loss through breathing are key to efficient thermoregulation. Thermographies also show this fact already known from previous experiments and literature (Smith & Havenith, 2011).

The PPE NBQ equipment was the most critical, due to the number of garments, insulation, mask and the use of additional elements such as gloves and butyl boots. The maximum temperature increases in key areas (chest and back) vary between 2°C and 4°C approximately. The maximum temperature increase occurs in the back, in a TROPICAL environment, with 5.9°C. The greatest increase in humidity occurs in the chest, with an average value of 43%. The evaporation resistance and insulation of the storm suit (TROPICAL) and the NBC PPE and Dive Suit limit the evacuation of sweat and its drying, reaching the maximum levels reached for each user during the first phase sooner, and showing few differences in the subsequent phases.

Thermographic studies in a climatic chamber have provided valuable information regarding the limitations of the regulatory equipment and the critical areas of thermal regulation, which have been acted upon to achieve a reduction in the thermal stress of the combatant, mainly in the chest and back.

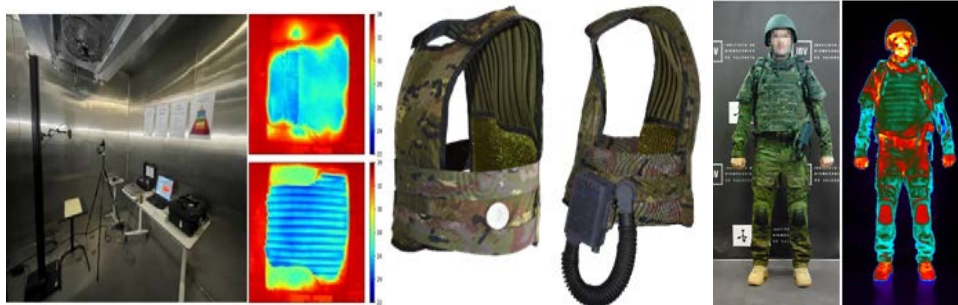


Figure 1. Left. Thermal characterization with ST2 mannequin and thermal cameras over 3D materials. Right: cooling system.

Based on the conclusions obtained in the initial tests, for evaluation under activity and load conditions with the ARID COMBAT configuration, 4 adjustable vests were made as a first design approximation. The materials were previously selected in a characterization under controlled conditions in climate chamber (Figure 1. Left). From the second experiment where the vests were tested, an active cooling prototype was designed (Figure 1. Right).

4. CONCLUSION

The use of temperature maps and records of body humidity, skin temperature, tympanic temperature and the application of thermal comfort models allow complex scenarios to be modelled and solutions to be adapted to the real problems of the combatant. The study has allowed the thermal load of the combatant to be quantified by simulating real operating conditions with the current equipment (clothing and protective equipment) and new technical textile materials have been selected, with the best properties of permeability, absorption and transport of humidity according to the needs of the body area and the clothing layer in question. Furthermore, an active ventilation system has been designed combining the effect of ventilation through 3D fabric channels.

This study and the solutions developed can be transferred to the civil and labour field, in situations with high thermal stress (outdoor work, industrial furnaces, metallurgy, etc.).

The study is part of the COINCIDENTE 2020 program (DN8644) "New technologies for improving comfort and reducing thermal stress of the combatant in conditions of high temperature and humidity" (file NEC 2021/0151E). The experimentation has been carried out with military personnel from the Spanish Army, the NBC (Nuclear, Biological and Chemical) Regiment No. 1 and the Special Operations Command (MOE).

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INFLUENCE OF AMBIENT CONDITIONS ON THE MEASUREMENTS OF WATER VAPOUR RESISTANCE WITH A SWEATING, THERMAL MANIKIN

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Abstract: *This study explores the thermophysiological comfort and water vapour resistance (R_e) of different personal protective equipment (PPE) ensembles using an advanced thermal, sweating manikin named "Sherlock." Experiments were conducted under both isothermal and non-isothermal conditions, adhering to DIN EN 17528 and ASTM F2370 standards. The results illustrate the impact of these conditions on breathability and highlight the importance of comprehensive evaluations to optimize PPE for enhanced thermal comfort and safety. Condensation processes were observed during non-isothermal tests, underscoring the need for realistic testing environments.*

Keywords: *water vapour resistance, thermal sweating manikin, PPE.*

1. INTRODUCTION

Accurate simulation of human thermal behaviour and sweating under different environmental conditions is crucial for a better understanding of human thermoregulation and for improving the design of systems for thermal comfort and safety. Thermally controlled manikins that can mimic human sweating are essential for this research. The present study focuses on the use of these advanced manikins under isothermal and non-isothermal conditions to measure and analyse thermal responses. Isothermal conditions involve a uniform temperature distribution across the entire test environment (manikin and ambient condition), while non-isothermal conditions involve varying temperatures within the test system. While non-isothermal conditions are essential when measuring thermal resistance (see DIN EN ISO 15831), tests to determine water vapour resistance can be carried out under both isothermal and non-isothermal test conditions in accordance with the DIN EN 17528 or ASTM F2370 standards. Both standards do not precisely define the environmental conditions for the measurements but leave room for manoeuvre to reproduce realistic conditions during the measurements. Studying both conditions allows us to gain a comprehensive understanding of the effects on thermal comfort and sweat evaporation rate, which ultimately contributes to the development of more effective climate control systems and protective clothing.

2. MATERIALS AND METHODS

2.1 Materials

Various PPE ensembles (e.g. firefighter jackets, weather protection PPE, welders' PPE, ...) were analysed as part of the investigations (see Table 1). All of them represent the state of the art of German PPE ensembles.

2.2 Thermal, Sweating Manikin

To gain a deeper insight into the thermophysiological comfort of clothing systems, the study employed a thermoregulation model of a human—a sweating, thermal manikin named "Sherlock" (Type Newton, Thermetrics). The measurements accounted for geometric factors like surface coverage, tailoring, and fit, which, along with the functionality of the textiles, influence thermophysiological comfort. Sherlock, the thermal manikin, is anatomically designed to represent an adult male with a standard height of 1.75 meters, a body surface area of 1.85 square meters, and a clothing size of 50. The manikin's skin surface temperature was maintained at a constant 34°C, with the required electrical heating power (H_c) serving as the measurement variable. Thermal insulation measurements were conducted in a climate chamber set at 15°C with a relative humidity of 50% (RH_a) and an air flow of 0.3 m/s according to DIN EN ISO 15831. To simulate realistic clothing situations, tests were performed with the fully clothed Sherlock in both

standing and walking positions. The thermal insulation segments (R_c) were compiled using the parallel method.

Furthermore, to simulate realistic sweating during high-intensity physical activity (heavy, liquid sweating), Sherlock was equipped with a tight-fitting sweat suit and sweat nozzles distributed across the body. The sweat suit's function was to uniformly distribute the sweat water from the nozzles over the body. These nozzles could be individually controlled to set different sweating rates. Preliminary trials adjusted literature-based sweating rates to ensure realistic, reproducible results with the sweating, thermal manikin Sherlock. The tests to determine the water vapour resistance (breathability, R_e) of the clothing systems were carried out under isothermal conditions at a temperature of 34°C and relative humidity of 40%rh. In addition, tests were performed at 15°C, 40%rh for non-isothermal conditions (see DIN EN ISO 17528, ASTM F 2370). The measurements were done with the fully clothed Sherlock standing and walking, and the breathability segments (R_e) were summarised using the parallel method.

Table 1. Material list of PPE clothing systems, - $\equiv$ no data

Field of application	Sample	Product type	Composition	thickness [mm]	Mass per unit [g/m ²]
High temperature range/ metallized heat protection	1	Molding jacket	100% AR with aluminisation	2.22	403
		Jacket	50% CO, 39% MAC, 10% CV, 1% CF	0.66	353
		Overalls			
		Shirt	54% MAC, 44% CO, 2% CF	0.41	198
Welding protection	2	Blouson	89% CO, 10% PA, 1% CF	0.77	396
		Overalls			
		Shirt	54% MAC, 44% CO, 2% CF	0.41	198
Arc flash / Warning weather protection	3	Parka	55% MAC, 43% CO, 2% CF +0.50 Laminate	+0.50	315
		Shirt	54% MAC, 44% CO, 2% CF	0.41	198
		Shirt	63% CV, 16% AR, 13% MAC, 2% EL, 1% CF	-	-
		Jeans	100% CO	-	-
Fire fighter protection	4	Outer shell	-	0.78	224
		Membrane	-	0.90	149
		Lining	-	0.81	201
		Jeans	100% CO	-	-
Weather protection	7	Laminate	-	0.86	313
		Jeans	100% CO	-	-
		Laminate layer	-	0.76	-
		construction			
Additional Clothing	All samples	Jeans	100% CO	-	-
		Socks	100% CO	-	-
		Underpants	100% PES	-	-
		Sports shoes	-	-	-

3. RESULTS AND DISCUSSION

The results, see Table 2, of the characterisation with the sweating, thermal manikin Sherlock show very good reproducibility regarding the water vapour resistance R_e with a standard deviation < 10%.

The results for the water vapour resistance R_e under isothermal test conditions (34°C, 40% r.h.) of the tested clothing systems are in the range 15.83 - 48.19 m²Pa/W. Clothing systems 7 and 9 have low R_e values and therefore good breathability. Clothing system 1 has the highest R_e value. This can be explained, among other things, by the layer structure of the cladding system, which includes the moulding jacket.

Under non-isothermal test conditions (15°C, 40% r.h.), the tested clothing systems have lower water vapour transmission resistances. These are in the range of 14.73 - 17.34 m²Pa/W. So a lower breathability is achieved at lower ambient temperatures, but condensation processes were observed in the layer structure, particularly on the undergarment, even at ambient temperatures of 15°C during the tests.

Table 2. Thermal insulation R_c , water vapour resistance R_e and water vapour permeability index i_m determined with the sweating, thermal manikin Sherlock in a standing position, - $\equiv$ no data

Sample	Thermal insulation R_c [m ² K/W]	Water vapour resistance R_e [m ² Pa/W]	water vapour permeability index i_m [-]	Water vapour resistance R_e [m ² Pa/W]	water vapour permeability index i_m [-]
	Isothermal (34°C, 40% r.h.)			non-isothermal (15°C, 40% r.h.)	
1	0.271	48.19	0.34	-	-
2	0.225	22.93	0.59	-	-
3	0.232	29.98	0.46	17.34	0.80
4	0.242	25.79	0.56	-	-
7	0.205	15.83	0.78	15.11	0.81
9	0.207	21.82	0.57	14.73	0.84

With regard to the water vapour resistance $R_{e,eff}$, values in the range 44.53 - 59.77 m²Pa/W were determined with Sherlock in the standing state. In comparison, values in the range 42.67 - 52.73 m²Pa/W were achieved when walking, whereby the same tendencies can be recognised in the clothing systems. The lower breathability in the walking state can be explained by ventilation effects. Due to the design of the clothing systems, an exchange of air takes place in the microclimate between the person and the clothing when walking, which is reflected in better breathability.

In addition, different zoning was considered in the analyses. It was found that the 'jacket' evaluation method (only upper body segments including arms) results in higher respiratory activities than an evaluation of all segments (complete manikin). This can be explained by the fact that the segments of the upper body and arms are completely covered. Whereas in the complete manikin there are uncovered segments such as the head and hands, as well as lightly clothed segments such as the legs, which are included in the analysis. A comparison of the results also shows that the sequence of breathability of the clothing systems analysed is identical regardless of the evaluation method.

The water vapour transmission index i_{mt} lies in the range of 0.34 - 0.84 for the clothing systems examined.

4. CONCLUSION

The aim of the research was to investigate the effect of different environmental conditions on the results of the measurements with a thermal, sweating manikin.

Non-isothermal test conditions must be selected for the investigations to determine the thermal insulation. The tests to determine the water vapour resistance can be carried out both isothermally and non-isothermally in accordance with the standards. The results show that this results in differences in the values, but that the tendencies of the values are the same. The data therefore show that it is advisable to consider the test conditions and the method of evaluation (evaluation model) when comparing values.

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HEAT STRESS UNDER SIMULATED TECHNICAL RESCUE ACTIVITIES

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Abstract: Rescue activities involve extremely heavy and intermittent activities in extreme environments, and the use of personal protective clothing and equipment. We believe that clothing can be modularly constructed into an integral protection concept so that the protection can be optimized for specific incident scenarios to achieve the best performance with minimal stress. We evaluated two protective clothing systems for thermal impact on the user during warm weather technical rescue scenario (TRW) simulation. A lighter, modular clothing system (M) contributed to lower skin and rectal temperatures and lower body water loss than traditional firefighter clothing system (T). Based on these results expected work could be ~20 min longer in M than in T before reaching a critical rectal temperature of 39°C, and the estimated required recovery period to reach a rectal temperature of 37.5°C before the next work bout would be ~30 min shorter in M than in T.

Keywords: firefighter, protective clothing, heat strain, thermal insulation, evaporative resistance.

1. INTRODUCTION

Rescue tasks often involve extremely heavy and intermittent activities in extreme environments (heat, cold, polluted atmosphere etc.), and require the use of personal protective clothing and equipment. Increased protection increases the bulk and carried weight which results in lower physical performance, higher metabolic load and more internal body heat production (Dorman and Havenith, 2009, Teitlebaum and Goldman, 1972) and restricts the ability to successfully accomplish a task (Son et al., 2022). Significant levels of heat stress develop quickly during hot and high-intensity activities when wearing heavy clothing leading to heat strain and enhanced risk of heat related disorders and injuries (Moran et al., 2003). We believe that the clothing can be modularly constructed into an integral protection concept so that the protection can be optimized for incident scenarios, and in this way best performance can be achieved with minimal stress. In order to develop a long-term vision on protective clothing, it is necessary to develop knowledge about (future) tasks and developments in the field of (modular) protection. This study is a part of a bigger project that aimed to compare different clothing systems for different incident scenarios, and collect data to validate the available thermo-physiological models for firefighter tasks. This presentation aimed to compare two clothing systems in a technical rescue scenario simulation in warm conditions (TRW).

2. MATERIALS AND METHODS

The study was designed in accordance with the Declaration of Helsinki and was approved by the Scientific and Ethical Review Board of VU Amsterdam (VCWE-2023-134R1). This paper focuses on two sets of protective clothing that were evaluated for thermal impact on the user during a TRW scenario simulation. Skin temperature was measured at 8 locations (mean skin temperature calculation by Gagge and Nishi (1977)) and core temperature was represented by rectal temperature. Also, heart rate, metabolic rate, weight loss and subjective responses were recorded.

2.1 Test persons and clothing

8 test persons (TP) participated in this part of the study. All were professional firefighters. We used a prototype of the Dutch firefighter double jacket layer of a modular clothing system with a single jacket (M; set C9A in Kuklane et al., 2022), and a presently used personal protective clothing sets (T; TRW in Kuklane et al., 2024) including station wear (OU) underneath (set C2 in Kuklane et al., 2022) and corresponding personal protective equipment (PPE). Clothing basic insulation (I_{cl}) of M and T were 0.324 and 0.298 m²K/W, clothing evaporative resistance (R_{ecl}) 54.0 and 61.7 m²Pa/W and clothing permeability index ($i_{m,cl}$) 0.36 and 0.28, respectively. During recovery the used clothing properties were approximately the same for both systems: 0.174 m²K/W, 33.0 m²Pa/W and 0.32 (REC in Kuklane et al., 2024). Four persons were using set M and four persons set T. Their mean age was 42.8±14.9 and 39.0±14.4 years, weight 91.8±14.5 and 86.0±18.3 kg, height 1.80±0.06 and 1.87±0.05 m, body surface area (A_{Du}) 2.11±0.20 and 2.10±0.22 m², and body fat (acc. to Durnin & Womersley, 1974) 21.5±6.0 and 20.6±7.2 % for M and T, respectively.

2.2 Environment and activities

TP preparation, exercise activities and recovery were all performed in a climate controlled room. During preparation and activities without radiation, air temperature (T_a) was 24.8±0.4 °C, humidity (RH) 49.1±10.4% and air velocity (v_a) <0.15 m/s. The activities during exercise were treadmill walking at 2.1 km/h (0-30 min), 3.5 km/h (30-60 min), 3.5 km/h with added IR-radiation of 1 kW/m² from the right side (60-90 min), and recovery period with seated rest (90-120 min). The measured average metabolic rates for these activities were 145±11, 187±13, 195±16 and 65±6 W/m², respectively. Addition of radiation made impact, and T_a raised by 1 °C, and RH dropped to 39.0±11.2 and 35.9±11.1 for the last activity and recovery, respectively.

3. RESULTS AND DISCUSSION

Figure 1 shows the change in rectal temperature for clothing systems M and T, Figure 2a skin temperature and Figure 2b thermal sensation. Standard deviation bars are given in the figures.

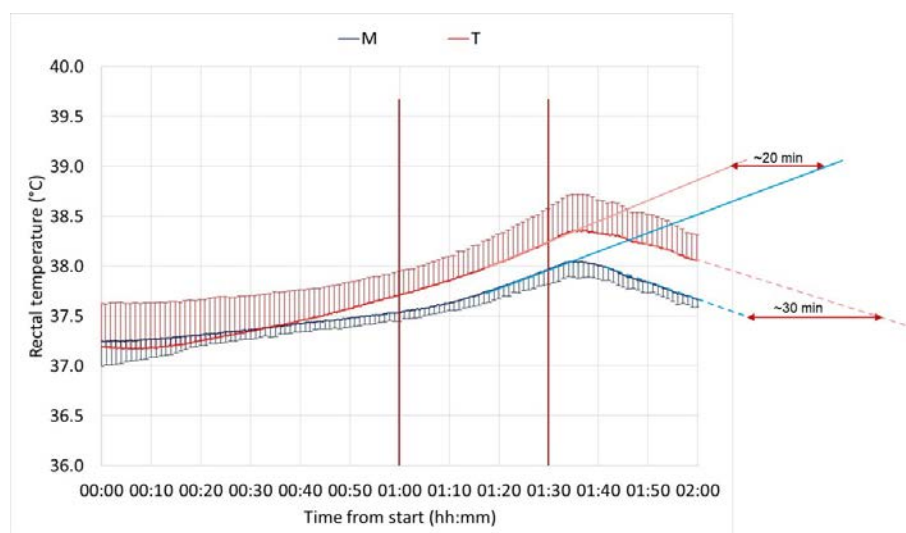


Figure 1. Rectal temperatures and estimations of exposure and recovery time differences for a modular (M) and traditionally used, EN469 (T) clothing systems.

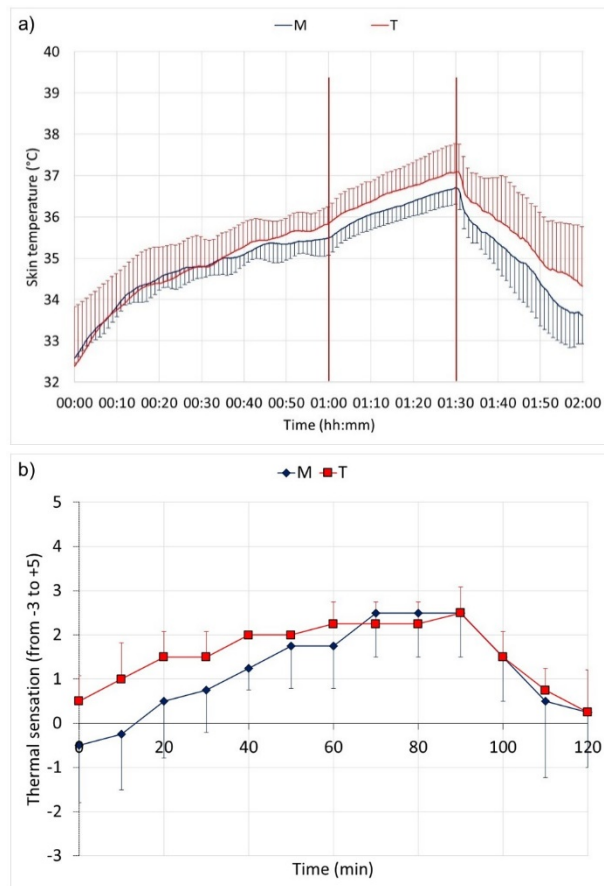


Figure 2. a) Mean skin temperatures; and b) mean whole body thermal sensation. M – modular clothing set using inner jacket of double layer system, T – traditional clothing system.

The mean start temperatures in M and T for rectal and skin temperatures differed minimally. The increasing differences between systems M and T are clearly observable, reaching on average over 0.3 °C in rectal and about 0.5 °C in skin temperature after starting recovery with temperatures higher when using T. Considering rectal temperature of 39 °C as a exposure termination criterion, then following the last 10 min linear regression line of exposures one could work with the same pace in M for 20 min longer than in T. Considering rectal temperature of 37.5 °C as a recovery criterion before the next work bout start, then the required break for T should be ~30 min longer than in M. Considering this limit being 38 °C then in M only a short comfort break is needed for rehydration, while in T still needs 30 min to recover. Body water losses in M were 975 ± 190 g and in T 817 ± 248 g for the whole 2 hour experiment. The subjective responses were at the beginning lower for M, but with body heat gain and radiation these caught up with T and stabilized, and they stayed similar also under recovery. The heart rate stayed on average over 20 b/min higher in T than in M for all experimental periods.

4. CONCLUSION

The temperature differences between M and T were within or close to 1 SD, while they increased with time. This is especially clear for the recovery period. All measured parameters individually and together indicated higher heat stress in traditional firefighter clothing system (T) than in a modular system with single jacket (M) that had somewhat higher I_{cl} and considerably lower R_{ecl} than T. The results showed positive effect of optimizing protective clothing for the task and it reduces firefighter heat stress. This dataset allows validating different thermo-physiological models for firefighter heat stress prediction (Klomp et al., 2025, Page et al., 2025).

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PREDICTIVE MODELS TO ASSESS THERMAL AND EVAPORATIVE RESISTANCES OF INNOVATIVE THERMAL PROTECTIVE CLOTHING

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Abstract: Protection and comfort are critical considerations in the development of thermal protective clothing (TPC), however, achieving optimal performance while maintaining worker comfort remains a significant challenge. For TPC, thermal and evaporative resistance are key properties closely linked to comfort perception and typically assessed using specialized and expensive equipment, such as thermal manikins. Straightforward method to quantify comfort is still needed. In this study, predictive models of varying complexity were developed to address this gap. These models range from simple applications of electrical circuit theorems to numerical analyses employing bi- and tri-dimensional approaches. A case study featuring an original firefighting vest will be presented, highlighting the effect of different properties, dimensions, and configurations of the integrated materials on the overall properties. The circuit theorem provided reasonably accurate estimations of the vest's properties when heat and mass transfer were predominantly unidirectional. More advanced numerical analyses are required to account for bi- and tri-dimensional effects.

Keywords: thermal protective clothing, predictive models, thermal resistance, evaporative resistance.

1. INTRODUCTION

Over the years, numerous innovative solutions have been explored for integration into thermal protective clothing to enhance body protection. These include wearable sensors and active heating/cooling systems, presenting significant challenges for manufacturers and developers to achieve optimal performance while maintaining wearer comfort. In laboratory settings, even basic tests, such as evaluating the impact of different fibre types in a prototype, require a series of resource-intensive and laborious steps: sourcing or producing fibres, textile manufacturing, and assembling the new prototype. While numerical analysis offers an alternative, it is often time-consuming and demands substantial computational resources. Moreover, despite the widespread use of experimental and numerical approaches to assess the thermal performance of protective clothing, a simple and efficient method for quantifying comfort indicators remains lacking. For Thermal Protective Clothing (TPC), the thermal and evaporative resistances of the product are two properties closely related with the comfort sensation, and they are usually evaluated through specialized and costly equipment found in textile/clothing laboratories (e.g., thermal manikins and sweating guarded-hotplate). In this work, predictive models were developed, considering different levels of complexity, relying from simple electrical circuit theorems to numerical analysis (bi- and tri-dimensional approaches). The developed approaches were used to study and optimize the performance of a firefighting vest when subjected to standard tests.

2. MATERIALS AND METHODS

2.1 PCM FIREFIGHTER VEST

The vest consists on a group of pouches with PCMs (phase change materials) alternated with layers of textiles (Santos et al. 2023). The effect of various parameters on the vest properties (thermal and evaporative resistances) was studied, including different dimensions of the pouches (width and thickness), two types of PCMs, different materials (e.g., textiles, cork, impermeable materials used in PCMs pouches), and various configurations of the vest. In all the studies, the goal

was to determine the distribution of pouches on the vest (i.e., fraction of area covered by pouches) that would guarantee the standard requirements.

2.2 CONSIDERED STANDARD REQUIREMENTS FOR TPC

According to ISO 15384, the TPC must meet maximum thermal and evaporative resistance thresholds of $0.055 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ and $10 \text{ m}^2 \cdot \text{Pa} \cdot \text{W}^{-1}$, respectively. For that reason, these parameters were established as relevant requirements for the new vest design.

2.3 MATHEMATICAL MODELS FORMULATION

To evaluate the vest's thermal and evaporative resistances, heat and mass transport through vest samples were model based on the procedures outlined in ISO 11092, i.e., samples evaluated in sweating guarded hotplate apparatus. For thermal resistance determination, the sample is exposed to dry conditions ($RH=0\%$) and a temperature difference (of 15°C). For evaporative resistance determination, a humidity gradient was imposed ($\Delta RH = 60\%$) at isothermal conditions (at 35°C). The surface facing the apparatus plate is labelled as 1 in Figure 1 and the surface exposed to a constant air flow ($1 \text{ m} \cdot \text{s}^{-1}$) is identified as 2, for the three models studied. The models independently account for heat conduction and water vapour diffusion through the different sample elements. They enable the prediction of heat and mass flux under steady-state conditions, replicating the conditions of the standard test and to calculate the thermal (or evaporative) resistance of the sample.

To illustrate the main mathematical assumptions, a vest configuration was chosen consisting of three layers of generic materials, with a PCM pouch placed between the inner and middle layers, as described in Figure 1.

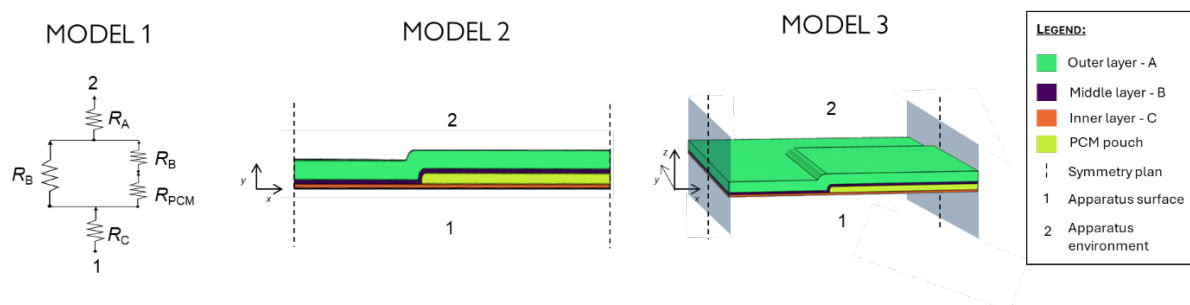


Figure 1. Schematic diagrams of a vest sample with three layers (A, B, and C) and a PCM pouch integrated for the three models developed (model 1, 2 and 3) to predict the (thermal/evaporative) resistance of the vest (R)

Model 1

The temperature/concentration gradients between sample surfaces were treated as unidirectional, from surface 1 to 2, and in series. For partially covering materials (e.g., PCM pouch, Figure 1), a parallel heat/mass transfer arrangement was applied to the specific integrated layer (e.g., Layer B in Figure 1).

Model 2

Heat and mass transfer in the PCM vest's components (air gaps, textiles, insulation, and PCM pouches) was numerically analysed using FEM (Finite Element Method). Due to the vest's matrix structure, consisting of repeating units, the simulation domain focuses on a cross-section of a single unit (Model 2, Figure 1), considering a bi-dimensional approach.

Model 3

Building on Model 2's assumptions, Model 3 predicted phenomena in the vest using a 3D geometry. Simplification was achieved by modelling only $\frac{1}{4}$ of a single unit due to the vest's repetitive structure (Model 3, Figure 1).

Heterogeneous distribution of proprieties

Previous models calculated vests with a uniform pouch distribution. For non-uniform distributions (areas with and without pouches), the total thermal/evaporative resistance was determined using a parallel arrangement of pouch-covered and uncovered areas.

3. RESULTS AND DISCUSSION

Model 1 provided accurate estimates of vest properties when PCM pouches covered less than 8% of the surface area (Table 1). For higher coverage or scenarios with impermeable materials and spatially dependent water diffusion (Figure 2), Model 1 was inadequate.

For larger pouch-covered areas, the two-dimensional approach (Model 2) predicted thermal and evaporative resistances with reasonable accuracy but tended to overestimate compared to the three-dimensional model (Model 3). Nevertheless, computational time is considerably less when Model 2 is used instead of Model 3 (from seconds to hours).

A configuration satisfying both thermal and evaporative resistance standards was achievable only with a heterogeneous pouch distribution on the vest.

Table 1. Comparison between the vest thermal resistance obtained with Model 1 and Model 2 for different configurations of the vest (8 % of PCM coverage area; PCM pouch with a width equal to ~0.06 m)

Case	Observations	Thermal resistance Model 1 / $\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$	Thermal resistance Model 2 / $\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$	ΔR %
32	3 layers + 1 pouch PCM A; 8% coverage	0.0351	0.0355	-1.1
59	2 layers + 1 pouch PCM A; 8% coverage	0.0271	0.0275	-1.5
74	3 layers + 1 pouch PCM B; 8% coverage	0.0454	0.0473	-4.2
96	2 layers + 1 pouch PCM B; 8% coverage	0.0275	0.0293	-6.5

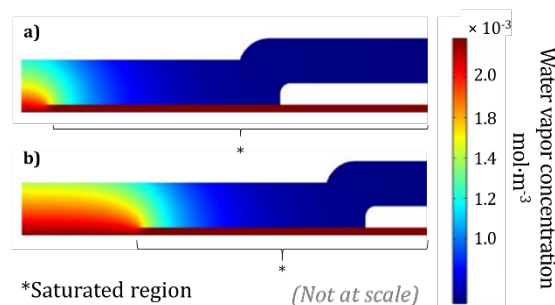


Figure 2. Water vapour concentration maps along the layers of two configurations of the vest (a and b) with impermeable materials integrated with different dimensions, using Model 2.

4. CONCLUSION

The thermal and evaporative resistances of a PCM vest were numerically analysed using three predictive models across various configurations. The most simplified model provided accurate predictions for unidirectional transfer scenarios (e.g., low impermeable material content) but is unsuitable for complex cases. For such scenarios, bi- and tri-dimensional models are recommended. This study highlights the value of simplified models in early TPC development to quickly identify bottlenecks and minimize variables.

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PREDICTING THE EFFECTIVENESS OF TECHNICAL RESCUE GEAR WITH THERMAL MODELLING SOFTWARE

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Abstract: Protective clothing is important for keeping firefighters safe as they work in hazardous environments, and modelling the effectiveness of the clothing can reduce experimental cost and risk. Human subject testing was conducted on two technical rescue ensembles and a significant difference in core temperature rise was observed between them. TAItherm™ was employed to reproduce these test results using a human thermophysiology model, the measured boundary conditions, and the clothing properties of the two ensembles. The predicted core temperature captured the measurement trends and was within one standard deviation of the test data. The thermal capacitance of the clothing had a significant impact on the heat transferred to the skin.

Keywords: firefighter, protective clothing, radiation modelling, thermal insulation, thermal capacitance.

1. INTRODUCTION

Firefighters are frequently exposed to prolonged periods of high thermal radiation while performing strenuous activities in which effective personal protective clothing is essential. The thermal properties of firefighter rescue gear affect the comfort, safety, and efficiency of the firefighter. The effectiveness of protective clothing is commonly evaluated using physical tests employing human subjects or test manikins (Deaton et al. 2020), however these methods can be costly and, depending on the severity of the test scenario, have potential to cause harm to test persons. Human thermal models offer an alternative for assessing the efficacy of protective firefighter clothing via predictive means without exposing humans to danger or incurring the time and cost associated with physical testing. In this study, human subject test results of firefighters in a simulated technical rescue scenario in warm weather (TRW) are compared to predictions from TAItherm™, a thermal modelling software tool (ThermoAnalytics, Inc. 2024).

2. MATERIALS AND METHODS

2.1 Protective Clothing Properties

Two protective clothing sets were considered in this study: a new double layer jacket system, set TRW-D (C9A in Kuklane et al. 2022) and the traditional Dutch firefighter system, set TRW-T (TRW in Kuklane et al. 2024). The properties of the TRW-D and TRW-T sets are summarized as follows, in terms of their whole body values: I_{cl} , 2.09 and 1.92 clo; R_{ecl} , 54.0 and 61.7 m²Pa/W; f_{cl} , 1.49 and 1.41; and $i_{m,cl}$, 0.36 and 0.28, respectively.

2.2 Human Subject Testing

Eight active firefighter test persons were recruited for the experiment. Four test persons wore ensemble D, being of age 42.8±14.9 years, weight 91.9±14.5 kg, height 1.80±0.06 m, body surface area 2.13±0.22 m², and body fat 21.5±6.0%. The other 4 test persons wore ensemble T, being of age 39±14.4 yrs, weight 86.0±18.3 kg, height 1.87±0.05 m, body surface area 2.13±0.22 m², and body fat 20.7±7.2% (Kuklane et al. 2025).

Testing took place in a climate-controlled room with an ambient temperature of 24.8±0.4 °C. Test persons walked on a treadmill and were exposed to radiation by an IR radiation panel on their right side. The radiation panel was set to a heat flux of 4.6 kW/m² when it was turned on. When the panel was off, it was rotated away from the test person to avoid exposure to residual heat. The panel was placed 1.5 m away from the right upper arm of the test person to achieve 1 kW/m²

radiation at that location. The test was comprised of four stages and had a total duration of 2 hours. During the first stage (0-30 minutes) subjects walked at 0.58 m/s, after which the treadmill speed was increased to 0.97 m/s for the second stage (30-60 min). At the start of the third stage (60-90 min), the panel was turned on while subjects continued to walk uninterrupted at 0.97 m/s. For the fourth and final stage (90-120 min), the subjects sat in recovery with jackets, gloves, and helmets removed. Mean skin temperature was recorded using sensors at 8 body locations (Gagge & Nishi, 1977). Core temperature was measured with a rectal probe. Heart rate and oxygen consumption rate (VO_2) were measured, from which metabolic rate (W/m^2) was derived.

2.3 Thermal Model

TAItherm™ was used to simulate the heat transfer associated with a human undertaking physical exertion while wearing firefighter turnout gear. The software contains a complete thermophysiological description of the human body and a capability to model high resolution boundary conditions, which are needed to characterize regional heating by a radiative panel. Metabolic heating, shivering, respiration, sweating, and peripheral vasomotion, etc. are considered in the model to simulate a human body as it attempts to maintain homeostasis.

The radiative panel was treated as a black body and its temperature, which was not measured, was identified based on model calibration to achieve $1 \text{ kW}/\text{m}^2$ incident radiation at the right upper arm. The local clothing insulation, evaporative resistance, and area factor for the TRW-D and TRW-T ensembles were calculated and applied at a body part level. The thermal emissivity of the ensemble, which also was not measured, was approximated as 0.95. Thermal convection around the human was modelled using an empirical formula based on estimated velocities for each body segment depending on the treadmill speed over time (Nishi & Gagge, 1970). Air velocity (0.1 m/s) and air temperature were set to be consistent with measured values.

3. RESULTS AND DISCUSSION

Primary indicators of model performance are core and skin temperature prediction accuracy. Figure 1 compares core temperature predictions to measurements for both TRW ensembles, demonstrating that the model follows similar trends as the measurements and predictions fall within their standard deviations over the duration of the test scenario.

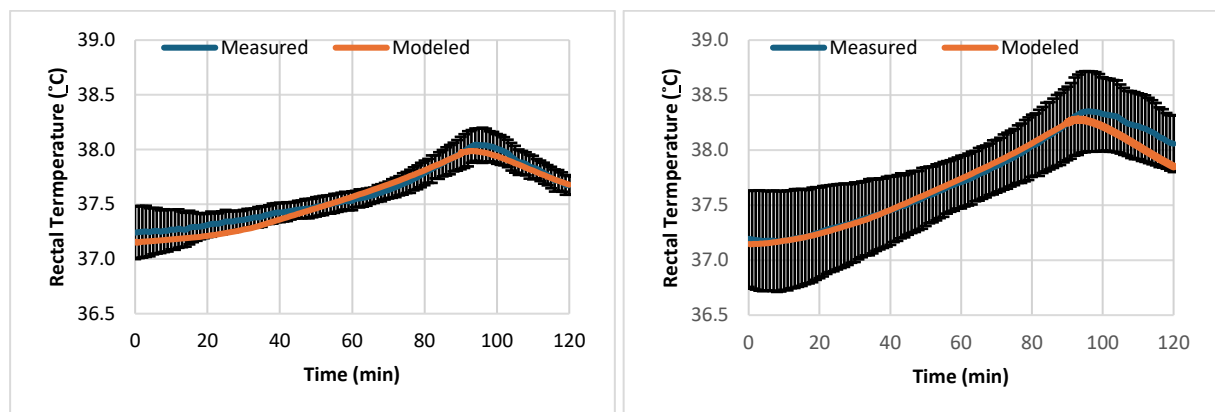


Figure 1. Predicted vs. measured rectal temperatures for TRW-D (a) and TRW-T (b).

The relative accuracy and precision of the model can further be expressed quantitatively in terms of RMSD and bias, which are listed for mean skin temperature, core temperature, and local skin (i.e., right upper arm) temperature in Table 1.

Table 1. RMSD and bias of mean skin, rectal, and right upper arm (RUA) skin temperatures

Ensemble	Mean Skin Temperature		Rectal Temperature		RUA Skin Temperature	
	RMSD (°C)	Bias (°C)	RMSD (°C)	Bias (°C)	RMSD (°C)	Bias (°C)
TRW-D	1.192	0.826	0.094	0.004	1.348	1.047
TRW-T	1.007	0.705	0.195	0.098	1.592	1.299

There was an observable difference in the core temperature rise between the two ensembles, which the model was also able to reproduce. The rectal temperature RMSD values for the TRW-D and TRW-T sets was less than the standard deviation, 0.25 and 0.41 °C, respectively. The mean skin temperature RMSD for the TRW-D ensemble was slightly above the standard deviation of 0.97 °C, and for the TRW-T ensemble it was less than the standard deviation of 1.09 °C. The skin temperature of the right upper arm closest to the radiation panel was slightly higher than the standard deviation of 1.16 and 1.47 °C for TRW-D and TRW-T, respectively.

Clothing thermal capacitance was found to strongly influence core temperature in this particular study. This was evidenced when re-running the model while disregarding it (i.e., setting it to zero), which resulted in much higher core temperatures (RMSD of 0.345 °C for TRW-D and 0.414 °C for TRW-T) than those in Table 1. This suggests that when modelling heavy personal protective equipment like technical rescue gear, the thermal capacitance of the gear must be considered.

4. CONCLUSION

A TAItherm™ model of a firefighter in a TRW scenario was shown to accurately predict transient core and skin temperatures, being consistent with those measured in a test using human subjects. Important elements of the test were reproduced in the simulation, in particular, the difference in maximum core temperature observed between two TRW ensembles. The model was thus able to assess the impact of protective clothing on the thermophysiological state of a firefighter and should prove useful in future studies to identify differences in effectiveness among technical rescue gear without subjecting humans to unnecessary and potentially dangerous test scenarios.

Additional effort will be undertaken to more accurately depict the thermal capacitance and surface emissivity of the clothing ensemble. The thermal capacitance of the firefighter gear can have a significant impact on the heat transferred through the ensemble to the skin, and the properties of the surface have the potential to absorb or reflect high levels of thermal radiation. Standard test methods should be employed to obtain the mass, specific heat, and surface properties of each ensemble.

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ENHANCED THERMAL PROTECTION FOR WILDLAND FIREFIGHTERS: INTEGRATING 3D SPACER FABRIC INTO PROTECTIVE CLOTHING SYSTEMS

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Abstract: *This study investigates the use of three-dimensional (3D) warp-knit spacer fabric in wildland firefighters' protective clothing to enhance thermal protection in high-risk areas. The fabric, composed of flame-resistant aramid fibres and compression-resistant polyetheretherketone (PEEK) fibres, was incorporated into a prototype shirt and tested against a control shirt using a flash fire manikin system. Results demonstrated that the 3D warp-knit spacer fabric significantly reduced predicted burn injuries, with the prototype showing a 6% decrease in total burn area compared to the control. By maintaining air gaps, the spacer fabric effectively impeded thermal energy transfer, particularly in the upper torso, neck, and upper arms, highlighting its potential for improved protective clothing designs.*

Keywords: *Wildland firefighters' protective clothing, thermal protection, heat transfer, flash fire manikin system, spacer textiles.*

1. INTRODUCTION

The number of wildland fires has substantially increased during the last several decades (Tyukavina et al., 2022). There is a need for thousands of wildland firefighters to control these threats. Wildland firefighters' protective clothing is made from high-performance inherently flame-resistant fibres such as aramid, in single-layer fabrics intended to protect against high thermal exposure as well as short-term engulfment by flames, while still allowing for ventilation and evaporation of perspiration to minimize physiological strain (Crown et al., 2002). Previous research using a simulated flash fire/instrumented manikin system to represent a life-like scenario of short-term full-body engulfment in flames, showed that personal protective clothing worn by wildland firefighters is not able to protect upper torso areas of the body that are in direct contact with the garment fabric (Rucker et al., 2000). This research investigated using a three-dimensional warp knitted fabric (3D spacer fabric) made of inherently flame-resistant aramid fibres and compression-resistant monofilament PEEK fibre, in a shirt design for wildland firefighters. The aim was to maintain air gaps in specific problematic areas of the shirt and improve the overall thermal protection provided by the garment.

2. MATERIALS AND METHODS

2.1 Physical Properties of fabrics

Three fabrics were used in the research. Nomex® IIIA with moisture-wicking finish is 212 g/m² 0.6 mm thick plain weave fabric that represents the outer material of wildland firefighters' shirts. It is an inherently flame-resistant fibre blend of 93% meta-aramid, 5% para-aramid, and 2% anti-static fibre. The 100% cotton jersey knit fabric of the t-shirts (Hanesbrands Inc.) is 158 g/m² 0.7 mm thick used for the base layer garment worn under the wildland firefighters' shirts. The 3D spacer fabric with a flame-retardant finish is 380 g/m² 5.3 mm thick Raschel warp-knit that has a mesh with 2.5 x 4 mm apertures at the front and back. It is made of inherently flame-resistant meta-aramid staple fibre for both the face and back fabric, and PEEK fibre for the spacer structure between the face and back fabrics. The 3D spacer fabric was sourced from Heathcoat Fabrics Limited. It was selected for the wildland firefighters' prototype shirts. It was added to specific areas of the shirt (shoulders, upper torso, neck and wrist) to create and maintain an air gap in these areas. The porous structure of the knit fabric and the non-compressive monofilament PEEK

fibre enables still air to be trapped within the 3D spacer fabric and impedes the transfer of thermal energy through the garment system during testing. The mass (g/m^2) and thickness (mm) of the fabrics were determined in accordance with ASTM D3776/ D3776M-20 and ASTM D1777-96 standard tests.

2.2 Methods

A shirt with the design currently used by wildland firefighters in Alberta (control shirt) and a prototype shirt were constructed for performance comparison in a flame engulfment instrumented manikin test following ASTM F1930 standard test. Testing included three replicates of the garment ensemble with the control shirts and three replicates of the garment ensemble with the prototype shirts. Each shirt was tested as part of a whole garment ensemble, which included a shirt, pants, t-shirt, and briefs. Before conducting the full-scale instrumented manikin tests, all garments were washed, dried, and conditioned for at least 24 hours at $21 \pm 2^\circ\text{C}$ and $65 \pm 5\%$ relative humidity in accordance with ASTM D1776 standard. The instrumented manikin with 110 thermal energy sensors at the University of Alberta is designed and constructed to represent the adult-sized male human. The manikin was placed in the flash-fire chamber surrounded by six burner sets, each with two propane jet diffusion burners that generated the flames. The chamber had an ambient temperature of between 15 and 30°C and provided isolation from exterior weather and wind. Each whole garment ensemble was exposed for 4 seconds to flames which produced an average incident heat flux of 84 kW/m^2 ($2 \text{ cal/s}\cdot\text{cm}^2$) on the surface of the manikin. The results were recorded as percentage of the total manikin surface area reaching a predicted burn injury (including predicted second-degree and third-degree burns). Additionally, each sensor collected the information on the value of absorbed heat flux under the garments in kW/m^2 .

3. RESULTS AND DISCUSSION

Burn injury diagrams were generated by the instrumented manikin system when the garment ensembles were engulfed in flames for 4 seconds (Figure 1). Burn injuries were mainly concentrated in the legs, and arms where the garment ensemble with the prototype shirt had only one layer of fabric. In contrast to the garment ensemble with the control shirt, the areas of the upper arms, neck, and upper front and back torso did not indicate predicted burn injuries. Therefore, it would appear that these areas were insulated during the test by the still air trapped in the 3D spacer fabrics. Noticeably fewer third-degree burns were indicated in the arm, and specifically wrist area under the tested prototype shirt compared to the control shirt. Flame engulfment of the garment ensemble with the control shirt showed an average total predicted burn injury of 30.97 % of the manikin surface that included 22.38 % second-degree burn, and 8.59 % third-degree burn. Flame engulfment of the garment ensemble with the prototype shirt showed an average total predicted burn injury of 24.72 % of the manikin surface that included 18.86 % second-degree burn, and 5.86 % third-degree burn.

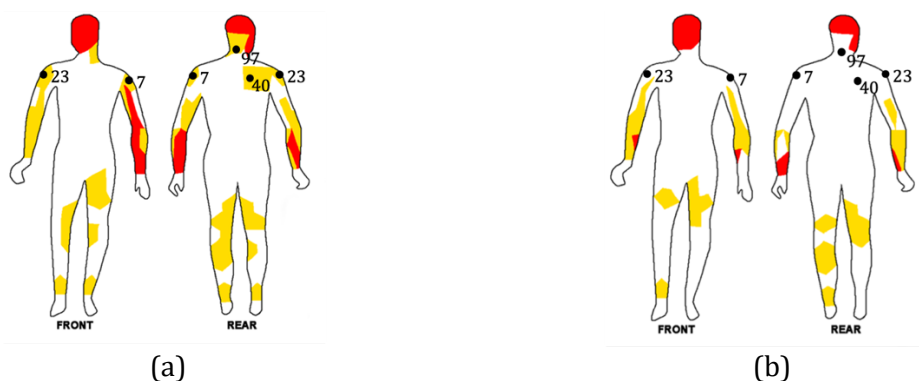


Figure 1. Typical burn injury pattern generated by the instrumented manikin system when the garment ensemble was engulfed in flames for 4 seconds: (a) control, (b) prototype

Absorbed heat flux for selected sensors in areas prone to second-degree burns is presented below (Figure 2). Twenty seconds of the absorbed heat flux data from the control and prototype shirts testing is presented on the graphs. These graphs show the differences in the thermal protection performance of control and prototype shirts. They show how the still air in the three-dimensional fabric incorporated into the prototype shirt can prevent thermal energy from easily passing through the garment system.

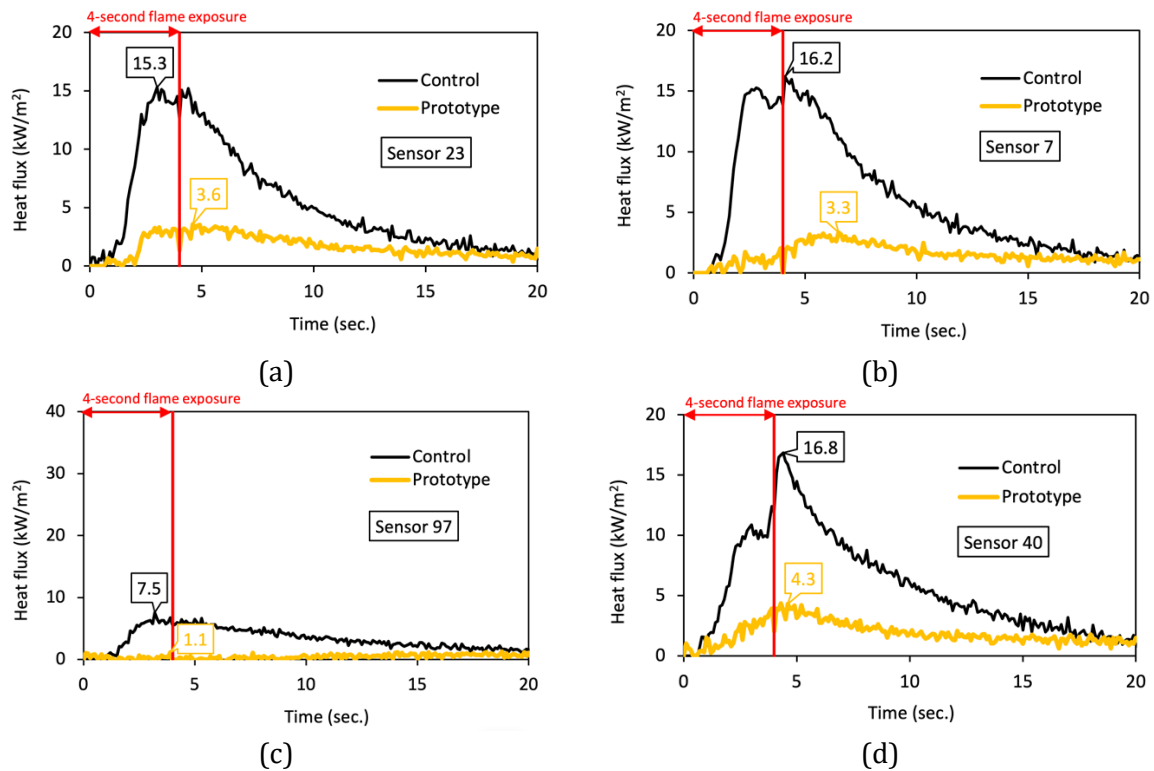


Figure 2. Average heat flux recorded by the skin simulant sensors caused by thermal energy passing through the garment ensemble with control and prototype shirts in different locations on the upper torso area of the manikin: (a) upper left arm, (b) upper right arm, (c) centre neck, and (d) right back

4. CONCLUSION

The prototype shirt design showed significant improvements in thermal protective performance when it was tested. It decreased the total burn area of the manikin surface by approximately 6% compared to the control shirt. The 3D spacer fabric substantially impeded high amounts of thermal energy, generated during the flame engulfment, from transferring through the fabric system in the areas of the upper front and back torso, upper arms, and neck. It maintained the air gap and improved thermal protection in the problematic areas.

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DEVELOPMENT AND STANDARDIZATION OF A FLASH FIRE CYLINDER TEST METHOD

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Abstract: The Flash Fire Cylinder (FFC) instrument was designed for bench-scale evaluation of flame-resistant materials, bridging the gap between Thermal Protective Performance (TPP) testing and full-scale flash fire manikin tests. A draft ASTM test method was developed and approved to guide device use and data analysis, computing Energy Ratio Value (ERV) as the primary performance metric. An intralaboratory study of three materials demonstrated acceptable consistency, and a study with 14 NFPA-certified composites exhibited a weak correlation between ERV and TPP ratings, highlighting the tests' differing insights, presumably due to geometry differences of the sample in the two tests.

Keywords: Flame resistant clothing, heat exposure, protective clothing

1. INTRODUCTION

A cylindrical flame exposure instrument was previously developed to address an unmet need for a bench scale materials test in-between TPP tester and flash fire manikin (Burke, Ingram 2021). Since the original introduction of the device, numerous design improvements were identified and implemented, including replacing the original 9 torch array (3x3 on 120 deg. orientation) with an 8 torch array (2x4 on 90 deg. orientation), physical separation of the controls and burner system, and an integrated sample holder/spacer to provide uniform air gap under the sample.

To demonstrate the utility of this instrument and test method, a comprehensive research study was conducted with two specific goals. First, to quantify the repeatability of the instrument and test method, and second to determine the correlation with TPP results for typical test specimens.

2. MATERIALS AND METHODS

2.1 Test Method

A draft test method (ASTM F3552-25) was developed and approved through the ASTM F23.80 subcommittee to be compatible with the updated instrument. It includes a comprehensive description of the device, sample preparation and conditioning, test procedure, and data analysis and reporting. The primary measurement result is Energy Ratio Value (ERV), computed as

$$ERV = \frac{Q_{transferred}}{Q_{incident} \times \frac{t_{test}}{t_{cal}}}$$

Where

$Q_{transferred}$ = Cumulative thermal energy measured by the sensors during specimen test

$Q_{incident}$ = Cumulative thermal energy measured by the sensors during nude exposure

T_{test}/T_{cal} = Ratio of the exposure duration for specimen and nude exposure duration

2.2 Intralaboratory Repeatability Study

A single-laboratory study was conducted on three different materials to assess repeatability of the draft ASTM test method. Material 1 is a three-layer structural firefighting turnout composite system. Material 2 is a single layer, 90sy (305gsm) FR-treated cotton. Material 3 is a single layer 60sy (205gsm) meta-aramid/para-aramid/carbon antistatic blend. 10 samples comprised of 6 specimens each (3 on warp and 3 on fill orientation) were tested.

2.3 TPP Correlation Study

An additional study was conducted on 14 NFPA-certified structural firefighting composite systems. These composites were all previously tested via ISO 17492 to obtain a TPP rating. The 14 composites were tested on the Flash fire Cylinder in accordance with draft test method, prelaundered, with 3 specimens oriented on warp and 3 on fill direction. Specimens were exposed to 84 kW/m² heat flux for 10 seconds, and resulting ERV was computed.

3. RESULTS AND DISCUSSION

The redesigned instrument (Figure 1) consists of a cylinder assembly with 8 adjustable torches and all fuel supply components, and a separate controller assembly containing the major electrical and process control components. During use, the cylinder assembly is located in a controlled area with suitable exhaust ventilation.

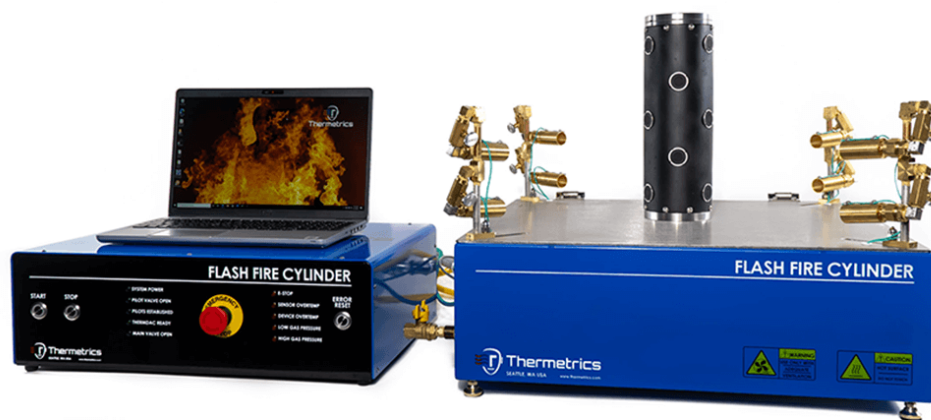


Figure 1. Redesigned FFC System

The intralaboratory repeatability study results including 3 materials, 10 samples, 60 specimens is shown in Table 1. The ASTM F23 technical committee found the consistency sufficient to approve the draft method in March 2025.

Table 1. Intralaboratory repeatability results

	Material1	Material2	Material3
Mean Energy Ratio Value (%)	19.1	31.7	47.1
SD (%)	1.1	3.5	2.9
C.V.	5.7%	11.2%	6.2%

The results of the TPP correlation study are shown in Figure 2. Regression analysis of 14 structural firefighting composites shows only a slight relationship ($R^2=0.35$) between the energy ratio value (ERV) and the TPP ratings, which indicates that there is different information provided by each test. This difference is presumed to be primarily due to sample geometry. Dimensional changes that influence the FFC sample circumference have a strong effect on trapped air and resulting insulation. This effect is less pronounced for the TPP device which uses a flat sample.

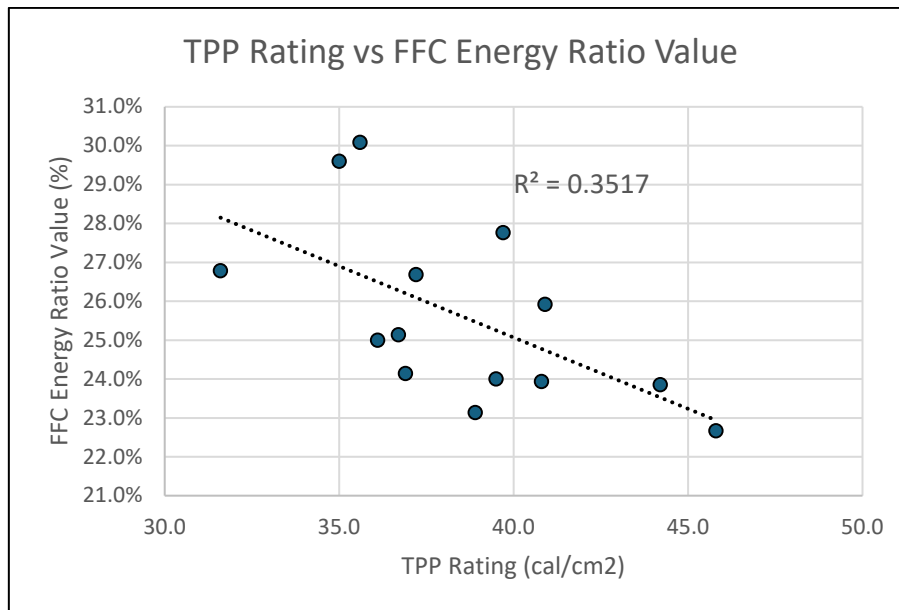


Figure 2. Correlation between TPP Rating and FFC Energy Ratio Value

4. CONCLUSION

The design-optimized Flash Fire Cylinder (FFC) and companion ASTM test method provide a laboratory-scale option to evaluate materials exposed to a simulated fire environment. The calculation of Energy Ratio Value (ERV) is within repeatability limits of similar test methods and provides additional performance data not represented in sample TPP Ratings. An interlaboratory study is proposed to begin later in 2025.

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HEAT STRAIN WHILE WORKING INDOORS UNDER HIGH RELATIVE HUMIDITY AND TEMPERATURE WITH COOLING VESTS

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Abstract: Climate change increase summer air temperatures also in Northern regions, that may lead to elevated indoor temperatures as well. This study aimed to find how much high relative humidity (RH) in hot indoor working conditions effects on heat strain and if it can be mitigated by cooling vest. A 75-min test protocol simulating light work with six test subjects was performed at an ambient temperature of 30°C and RH of 40 and 75%. During the tests was measured heart rate, core and skin temperatures, moisture accumulations, and thermal and moisture sensations were recorded. Fan and hybrid cooling vests were studied. The results showed that skin temperatures, heart rate and sweating increased when RH was higher. The fan-integrated vest was more effective to remove moisture from the clothing and the hybrid vest (fan and phase change material packages) to decrease the skin temperature. Breaks should be taken in cooler recovery room.

Keywords: Phase change material, fan cooling vest, hybrid cooling vest, relative humidity, heat strain.

1. INTRODUCTION

Climate change causes increase in air temperature and extend periods of heatwaves (IPCC, 2022). The ambient temperature above 28°C is the criterium for hot work in Finnish occupations. However, high relative humidity (RH) at hot work environment increases heat stress by decreasing sweat evaporation, which is not considered in the criterium. In indoor workplaces temperature can increase during heatwaves, adding heat stress on top of those ambient factors from the production process (Narocki, 2022). Correspondingly, Rissanen et al. (2022) found a cumulative increment in indoor temperatures during the heat waves in Finland especially in workplaces where heat radiative machines are required, such as in laundries. Heat strain of the workers was shown to be generally moderate. Heat problems in summertime are recognized at indoor workplaces in Finland (Kaisto et al., 2022). It has been shown that thermal comfort can be improved by personal cooling with phase change materials (PCM), air-cooled, evaporative cooling, liquid-cooled and hybrid cooling garments (Golbabaie et al., 2022).

The purpose of this study was to demonstrate how much elevated RH in hot working conditions effects on workers' heat strain and if it can be mitigated by cooling vests.

2. MATERIALS AND METHODS

2.1 Cooling vests and clothing

The study was performed with subjects wearing a vest with two fans at lower back (fans OFF = "No Cooling" and fans ON = "Fan Cooling") and a hybrid cooling vest ("Hybrid Cooling") with the two fans at lower back and packages of PCM on the upper back.

Clothing worn during the study was: T-shirt (cotton), thin working trousers (cotton), socks and running shoes.

2.2 Test subjects

Six volunteer test subjects (5 females, 1 male) participated in the study. Their age was on average 38.2 years (SD±15.3 years) and body mass index (BMI) was on average 23.8 (SD±4.9).

2.3 Ambient conditions

To create realistic working scenario into laboratory conditions, air temperature (T_a) and RH data was collected in real conditions at a laundry located in Southern Finland during summer 2023. The T_a varied from 23 to 30°C at the worksites when outdoor temperature was 25°C or above. RH varied at the same time from 39 to 82% at different work sites. Ambient conditions to laboratory study were selected based on these measurements: T_a was 30°C, the wind speed of 0.5 m/s, and RH was 40 and 75%, the WGBT was 26.0 and 29.4 °C, respectively.

2.4 Thermo-physiological measurements and experimental protocol

Skin temperatures (T_{sk}) from nine sites, core temperature (T_c), and heart rate were measured. Thermal sensation, thermal comfort and skin moisture sensation were asked from the test subjects in every 10 min. Moisture accumulations were measured by weighing the garments separately before and after the measurement. The subjects performed a 75-min trial consisted of rest (standing, 5 min), light work (walking in treadmill at a 1-degree angle 4km/h, 40 min), rest (standing, 10 min), and light work (walking in treadmill at a 1-degree angle 4km/h, 20 min).

3. RESULTS AND DISCUSSION

The results showed that elevated RH from 40 to 75% at T_a of 30°C increased the mean T_{sk} approx. by 0.5°C, average heart rate by 3.4% during working periods, and sweating was increased based on approx. 3.5 times higher moisture accumulations in the clothing (T-shirt and trousers). The T_c was approx. 0.16°C higher at RH 40%. However, the T_c rose 0.1°C more during the working periods at RH 75%. At the end of the tests thermal sensation was “hot” at RH 75% and “very warm” at RH 40%.

The mean T_{sk} was lower when cooling vests were used. When RH was 40% at the end of test protocol the mean T_{sk} were 33.0, 32.5, and 32.4°C with No Cooling, Fan Cooling and Hybrid Cooling, respectively. Correspondingly, when RH was 75% the mean T_{sk} were 33.8, 33.2 and 32.9°C with No Cooling, Fan Cooling and Hybrid Cooling, respectively. The largest variation between the local T_{sk} was found on shoulder blade where also the PCM packages in Hybrid Cooling vest were located. Thermal sensations were slightly cooler when cooling vests were used. However, no differences were found in thermal sensations between the cooling vests.

The moisture accumulations in the T-shirt were the lowest when the Fan Cooling vest was worn (Figure 1). The integrated fans increased the air movement under the vest and thus increased moisture evaporation. In the Hybrid Cooling vest air movement is partly restricted due to the weight of the PCM packages located on the shoulder blade area. The skin moisture sensations were “wet” at RH 75% with No Cooling and “moist” at the end of the other test protocols.

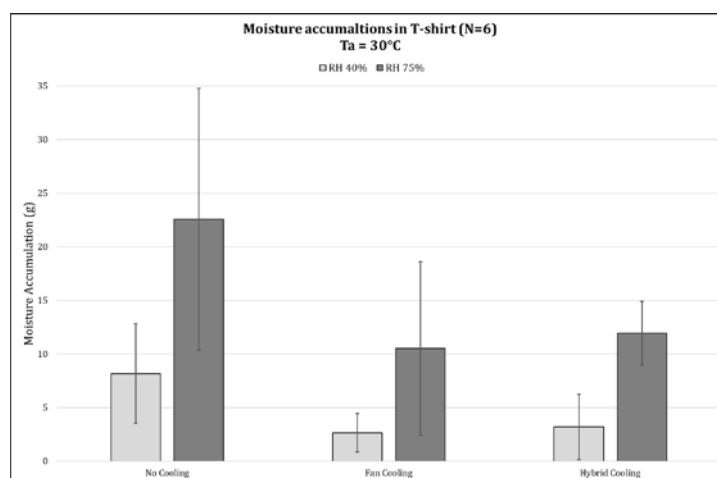


Figure 1. Moisture accumulations in the T-shirt (N=6) with different type of cooling vests at ambient conditions: T_a 30°C, RH 40 and 75% and wind 0.5m/s.

4. CONCLUSION

High relative humidity in hot environment increased heat strain of the test subjects. This is important to consider especially at workplaces where heat radiative machines are used, and moisture is evaporated from the process, such as in laundries. The fan integrated cooling vest was more effective to remove moisture from the clothing and the hybrid vest (Fans - PCM) to decrease the skin temperature. Breaks should be taken in cooler recovery room to provide sufficient recovery from the heat strain.

ACKNOWLEDGEMENT

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THE PATH FROM A PRODUCT TO A CERTIFIED PPE PRODUCT – USING PPE WITH A COOLING FUNCTION AS AN EXAMPLE

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Abstract: PPE with cooling function is an innovative PPE and no European or international standard is available for requirements for such PPE. No standardization group for PPE was responsible for such PPE up to 2024. That was the reason for the decision of the standardization group CEN/TC 162 to expand the scope of the CEN/TC 162 WG 4 for cooling PPE. The talk will give an overview about the integration of new kind of PPE in the European PPE standardization system and the steps in the standardization group to establish standards for PPE with cooling function in the future.

Keywords: PPE with cooling function, harmonized PPE standards, organisation and system of PPE standardization.

1. INTRODUCTION

Personal protective equipment (PPE) is intended to protect workers in the working environment. Due to climate change, high ambient temperatures are reached in European countries in summer, which can cause heat strain on workers. Cooling of the body can avoid overheating during work and will become more and more important. Therefore, PPE with cooling function is in demand by workers. The textile industry and research institutes are working on solutions for high-performance and practical PPE with a cooling function. One important step to bring PPE with cooling function in the market is the development of appropriate testing procedures. In Europe, PPE must be certified according to EU-PPE regulation 2016/425. Harmonized European standard specifies requirements for manufacturing the products for. PPE products are classified in different risk categories from 1 to 3 depending on the protection level. First category PPEs are intended to protect against minimal risks and manufacturers are authorized to test and self-certify their products. Second category PPEs provide protection against intermediate risks and third category PPEs provide protection against high risks that can lead to very serious consequences. Both categories II and III require specific testing and certification by an authorized body issuing the CE mark. PPE certification is preceded by comprehensive material, design, and functional tests in specialized laboratories which are in most cases determined by European standards. For PPE with cooling function, no European or international standard is available.

2. DEVELOPING PROCESS

Harmonized PPE standards are developed in national, European and international standardization group at the national standardization body (e.g. in Germany DIN, Italy UNI, Spain UNE), the European Committee for standardisation (CEN), and the international (ISO). No standardization working group for PPE was responsible for PPE with cooling function up to 2024. Standards for protective clothing are developed in the technical body CEN/TC 162 “Protective clothing including hand and arm protection and lifejackets”. In 2024, the technical body CEN/TC 162 decided that standards for PPE with cooling function can be included in the work of working group CEN/TC 162 WG 4 “Protective clothing against foul weather, wind and cold”. Now the working group has to extend the scope. The previous scope deals only with protective clothing against foul weather, wind and cold and now it is necessary to extend it to include exposure to hot environments and climates. PPE with a cooling function will be used in hot environmental climate situation. After the formal expansion of the working area of the working group CEN/TC 162 WG4 the next steps are the development of specific standards for PPE with cooling function. Such harmonized standards are a valuable tool for manufacturers and notified bodies to certify PPE. The experts of the working group can use the knowledge of the experience gained on measurement methods that determine the comfort of clothing and PPE for the development of

harmonised standard for PPE with cooling function. Since the cooling function is a new function, cooperation with research and development is necessary to improve or develop test methods and, if necessary, test equipment for determining the cooling function. There are test methods on the market which can determine the cooling function of fabrics; the testing of the whole garment of PPE with a cooling function can be principally done with thermal sweating manikins and with subject trials. Testing all PPE garments with cooling functions is, in principle, possible using thermal sweating manikins. However, these tests are currently mostly conducted in research laboratories, and the test conditions are not yet established. This makes comparing results from different laboratories difficult, and standardization of test methods is necessary to facilitate comparison. Furthermore, general requirements for materials and processing must be established, adapted to the respective use. For successful work, it is necessary that experts in PPE with cooling functions share their expertise and collaborate in the development of standards. This work will be done in the future and all experts for PPE with cooling are invited into the standardisation group to share their expertise.

3. CONCLUSION

The talk shows an overview about the integration of new kind of PPE in the European PPE standardization system using PPE with cooling function as an example. The talk describes necessary steps to establish standards for PPE with cooling function together with all stakeholders from industry, authorities, and users in the future. General requirements for materials and processing must be established, adapted to the respective use, in order to bring PPE products with high functionality and high quality to the market.

INVESTIGATION AND SIMULATION OF THE IMPACT OF PERSONAL PROTECTIVE COVERALLS ON HUMAN THERMOREGULATION

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Abstract: Nonwoven coveralls provide high chemical and biological protection but can affect wearing comfort and working performance. A validated simulation approach is presented to assess the impact on human thermoregulation and to identify hazardous working conditions. Three coveralls and a casual reference clothing system were investigated in a human subject trial. The data was used for validation of the simulation approach. Critical components of environmental conditions were identified and the range of the impact on thermoregulation for various coveralls was investigated. Physical activity and radiation revealed the biggest impact on core body temperature. Coveralls increased core body temperature by up to 0.7°C and resulted in an additional sweat loss of up to 2400g compared to casual clothing during a working shift of 8 hours duration. Our new simulation approach provides a new foundation for the evaluation and development of protective clothing for specific applications.

Keywords: protective coverall, wearing comfort, heat strain

1. INTRODUCTION

Coveralls are made of nonwoven materials with their main function to provide high protection against low concentrated inorganic liquids and harmful particles throughout use. They are used in applications, such as pharmaceutical handling, chemical processing or the oil and gas industry, requiring robustness and durability against wear and abrasion. Optimizing protection and robustness affects the thermal properties of the fabric by increasing its thermal and evaporative resistance (Wang & Gao, 2014). This reduces wearing comfort, which potentially impairs working performance. Current developments in the field of personal protective fabrics aim at improving comfort without compromising on the protection and durability properties (Lou et al., 2021).

This study aims to apply a simulation approach to assess the impact of protective coveralls on human thermoregulation. In the first step, a human trial was performed using coveralls and conditions close to end-use, serving as a validation basis for the simulation method. Such a simulation approach allows the identification of hazardous working conditions and environmental factors with a high impact on comfort during use.

2. MATERIALS AND METHODS

2.1 Human Subject Trial

The impact of four different clothing systems, consisting of three different protective coveralls (Clothing A and B protecting against low concentrated inorganic liquids and harmful particles and fibres, and Clothing C providing limited particle protection only) and one casual clothing set with no protection at all (Clothing D), was investigated for their impact on body core temperature (CBT; eCelsius Performance), heart rate (HR; Eq02+ LifeMonitor) and thermal sensation (TS, visual analogue scale). Sweat loss was measured based on differences in body weight measured directly before and after the experiment (Mettler Toledo, KCC150). The environmental conditions consisted of an ambient temperature of 35°C (± 1°C) and relative humidity of 30% (± 5%). The experimental protocol consisted of 60 min of resting followed by three phases of physical activity, such as walking on a treadmill for 20 min (6 metabolic equivalents [MET] during phase 1 and 4 MET during phases 2 and 3) separated by seated breaks of 5 min. Participants chose their preferred walking speed (3.8 km/h – 4.5 km/h), and the inclination of the treadmill was adjusted

accordingly to achieve the required metabolic activity (18.7% - 22.3% and 9.8% - 11.7% for 6 MET and 4 MET, respectively). The metabolic activity was predicted based on body surface area (Dubois), assuming 1 MET equals 58 W.m⁻² (Fiala et al., 1999). The participants were instructed to keep the zippers of the coveralls closed and to keep the hood on throughout the experimental protocol. The casual clothing set consisted of long-sleeved jeans and a long-sleeved cotton shirt. No water intake was allowed throughout the exercise. 4 people (2m/2f) participated in the study.

2.2 Simulations

For the simulation of the thermoregulatory responses, the Fiala physiological comfort model FPCm (V 5.3) was used (Fiala et al., 1999, 2001). Local thermal clothing properties (thermal and evaporative resistance obtained from thermal manikin measurements, clothing area factor) were considered for the head, thorax, abdomen, hips, upper and lower arms, upper and lower legs, and feet. A sensitivity analysis was done using Clothing B to investigate the impact of various environmental factors compared to standard working conditions ($T_{env} = 30^{\circ}\text{C}$, relative humidity = 30%, physical activity of 4 MET during two working shifts of 4 hours duration separated by 1-hour break). The factors included an increased environmental temperature (35°C), the presence of irradiation (500W.m^{-2}), the impact of a highly humid environment (70%) and increased working intensity (6 MET).

3. RESULTS AND DISCUSSION

3.1. Human Subject Trial

The casual clothing (Clothing D) affected CBT the least (Fig. 1, left). Protective clothing had a different impact on CBT, with Clothing C (lowest protective performance) resulting in the lowest increase in CBT. Clothing A outperformed Clothing B in the second part of the wearing trial despite both fabrics showing the same protective and durability performance. Heart rate represents the overall load on the cardiovascular system, which increases due to the reduced ability for thermoregulation. The cardiovascular load was lowest for Clothing D, while differences in protective clothing systems became apparent during ongoing exposure (Fig. 1, right). The highest cardiovascular load was exerted when wearing Clothing B. Clothing A, and C resulted in a similar cardiovascular load.

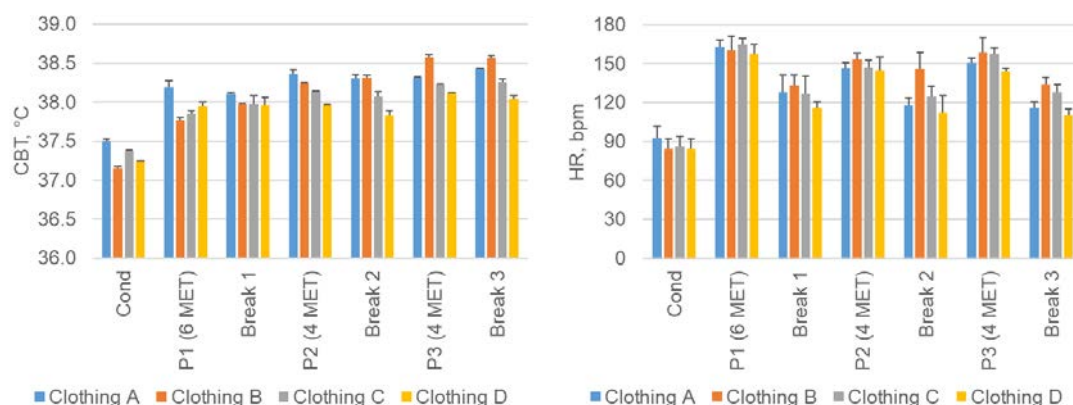


Figure 1. Core body temperature (CBT, left) and heart rate (HR, right) for each separate activity phase (P1 – P3). Conditioning phase (Cond).

3.2. Validation of Simulation Method

The simulation of the human subject exposure revealed a bias (indicating the systematic error of prediction) for CBT simulation of -0.14°C , 0.01°C , 0.15°C and 0.10°C , for Clothing A, B, C and D, respectively. The root mean square deviation (RMSD, indicating the random error of prediction) for CBT simulation was 0.24°C , 0.09°C , 0.16°C and 0.11°C for Clothing A, B, C and D, respectively. Factors that might have contributed to this bias were differences in the predicted and the actual

metabolic activity and differences in the effective insulation of the clothing due to slight differences in clothing fit. However, the accuracy for the simulation of CBT was well within 0.3°C, corresponding to the accuracy for real measurements of human CBT, and, thus, simulations were considered valid.

3.3. Effect of Ambient Conditions and Activity Level

An increase in the ambient temperature by 5°C and an increase in relative humidity by 40% had a similar effect on CBT (Fig 2, left) and accumulated sweat loss (Fig. 2, right). The presence of radiation surpassed these thermoregulation responses, while the biggest impact was found with an increase in the working intensity from 4 MET to 6 MET. Hence, working conditions must be well characterized, and protective clothing and the work regime must be adapted to avoid health hazards due to heat stress.

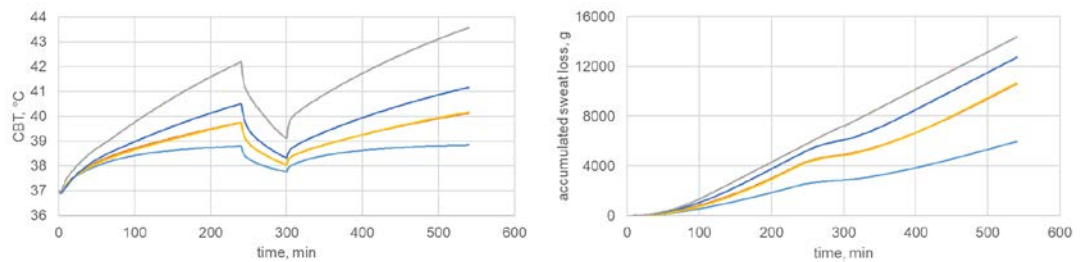


Figure 2. Sensitivity analysis for core body temperature (CBT) and accumulated sweat loss to various conditions differing in ambient temperature, relative humidity, radiation and work intensity when wearing Clothing B.

3.4 Effect of Coverall

The simulation of the impact of various protective coveralls revealed that protection inevitably results in an increased thermal burden due to a reduced ability for thermal regulation of the human body. An increase in CBT and an increase in accumulated sweat loss was observed when comparing the effect of overalls to a casual clothing set (Clothing D, Fig. 3). Furthermore, the simulation results indicate that the initial thermal burden (e.g. during the first 30min of wearing protective coveralls) was quite similar irrespective of the protective performance of coveralls. Differences in thermal and evaporative clothing resistance became apparent after an exposure of 2 hours and were reversible by work breaks. Coveralls with very high protective performance reduce the effectiveness of thermoregulation and, thus, require an adaptation of working regimes to avoid heat stress.

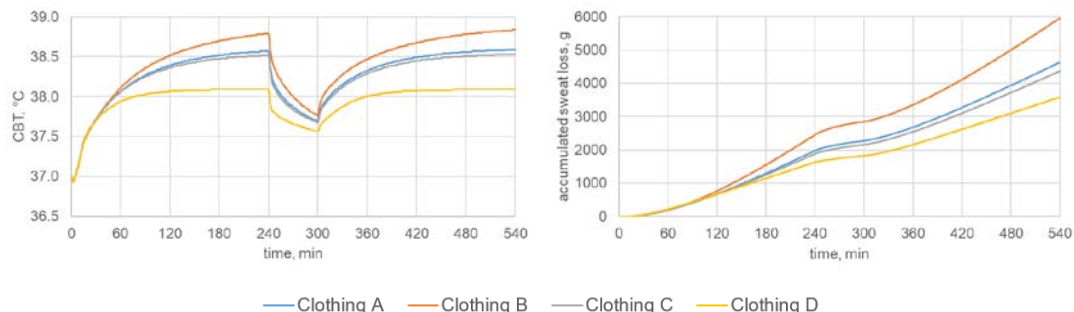


Figure 3. Impact of various protective clothing systems (Clothing A – C) and casual clothing (Clothing D) on core body temperature (CBT, left) and accumulated sweat loss (right).

4. CONCLUSION

In conclusion, we detected differences in the thermoregulatory impact of personal protective clothing systems based on wearing trials. An accurate simulation setup enabled the investigation

of the thermoregulatory impact of different environmental conditions and protective clothing systems. This knowledge allows for developing recommendations for the proactive clothing system selection for specific tasks and conditions and adaptation of the working conditions accordingly. This should enable high working performance without putting workers at health hazards.

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HEAT STRESS IN SIMULATED STRUCTURAL FIREFIGHTING SCENARIOS UTILIZING TWO TYPES OF DRESSING STRATEGIES

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Abstract: The study aimed quantifying firefighters' heat stress when moving out and doing pre-work in station wear, and adding turnout gear only before entering building (Strategy1) compared to performing all tasks in full gear (Strategy2). Estonian firefighters' station wear and protective clothing "TAURUS" were used. Eight (8) firefighters followed both strategies, and their skin and rectal temperatures, heart rate and weight loss were recorded. Pre-work was performed on a bicycle ergometer outside the climate chamber (20 min, $T_a=23\pm2^\circ\text{C}$, $RH=33\pm5\%$). Test continued with treadmill walking in heat (30 min, $T_a=45\pm1^\circ\text{C}$, $RH=26\pm5\%$), and concluded with recovery outside the chamber (30 min). Air velocity in both rooms was low (0.12 to 0.13 m/s). The results indicated reduction of firefighter heat stress in Strategy1 expressed in lower temperatures and pulse. It is recommended performing pre-work in station wear, whenever possible, and adding protective clothing with the necessary equipment before entering the hot environment.

Keywords: firefighter, protective clothing, dressing strategy, body temperature, heat strain.

1. INTRODUCTION

Clothing thermal insulation protects the firefighter from extreme temperature changes, at least in the short term. Greater protection results from the larger volume and mass of the garment, which, however, inhibits the physical performance of the person, increases the metabolic load and the amount of heat stored in the body (Dorman & Havenith, 2007). Reduced mobility and flexibility can also limit the successful performance of the task (Son et al., 2022). The minimum level of functionality and protection of firefighter clothing is established by standards, such as EN 469, ISO 11999-3, ISO 15384 etc. Most of the requirements arising from these standards are related to materials, and do not take into account the ergonomics of the clothing and how the clothing system as a whole affects the user. The occurrence of heat stress depends on the temperature of the environment, humidity, the thermal insulation and vapor resistance of the clothing, the type of work being done and for how long. Selecting optimal protection for specific incident scenarios and avoiding overdressing for tasks that do not require protection against extreme hazards allows reduction of heat stress and in long term may diminish the risks for cardio-vascular and other occupational disorders. This study evaluated the impact of heat stress reduction for a situation where turnout gear is dressed only just before the tasks requiring entering the hot environment.

2. MATERIALS AND METHODS

2.1 Ethical considerations

This study focused on two dressing strategies for protective clothing. In one strategy prework was carried out in station wear (Strategy1; S1), and in another in full turnout gear while no breathing apparatus (SCBA) nor gloves were used (Strategy2; S2). In both strategies full turnout gear with SCBA was used during the exposure to heat, and helmet, gloves and jackets were removed for recovery period. The strategies were evaluated based on thermal impact on the user during exposure. The study was approved by TAI Human Research Ethics Committee, Estonia (decision nr. 1296, 26.02.2024). The participants were able to end the test at any point in time without giving any reason. The tests were obliged to be terminated if rectal temperature (T_{rec}) of participants reached 39.0°C or if skin temperature in any measurement point reached 43.0°C . If

the study leader observed unsafe behaviour such as unclear communication or abnormalities in gait, they had the authority to stop the test.

2.2 Test persons and clothing

Eight (8) firefighters volunteered to participate in the study as the test persons (TP) on two days (once per strategy). Minimally one day without exposure had to stay between two test occasions. TP average age was 34 ± 7 years, body mass 93.2 ± 14.0 kg, height 1.83 ± 0.07 m, and body area 2.14 ± 0.18 m². No TP was smoking and all were in active duty. The basic clothing insulation was 0.132, 0.376 and 0.195 m²K/W, clothing evaporative resistance 14.1, 89.9 and 33.0 m²Pa/W, and clothing moisture permeability index 0.52, 0.24 and 0.32 for station wear, full turnout gear with SCBA, and recovery period, respectively. The full turnout gear system without SCBA had a basic clothing insulation of 0.365 m²K/W, clothing evaporative resistance of 79.2 m²Pa/W and clothing moisture permeability index of 0.26.

2.3 Objective and Subjective Measurements

Rectal temperatures (T_{rec}) and skin temperatures at 4 body sites (chest, upper arm, thigh and calf) and heart rate were recorded each 10 seconds. Mean skin temperature (T_{sk}) was calculated according to Ramanathan (1964). TP was weighed before and after work (bicycling and in heat) and rest periods with clothes, and nude before and after the experiment for body water loss (m_{wl}) and evaporation. Subjective responses (thermal, comfort, skin wetness and pain sensation, and perceived exertion) were recorded at the end of each task but at least at 10 min intervals.

2.4 Environment and activities

Test person preparation, pre-work period on bicycle ergometer (20 min at 50 W) and seated recovery period (30 min) were done at air temperature of $T_a = 23 \pm 2^\circ\text{C}$ and a relative humidity of $\text{RH} = 33 \pm 5\%$. Exposure to heat (30 min in total) occurred at a temperature of $T_a = 45 \pm 1^\circ\text{C}$ and a relative humidity of $\text{RH} = 26 \pm 5\%$ and consisted of walking on treadmill at 3.1 km/h for 10 min, 4.0 km/h, 5.4 km/h, 4.0 km/h, 5.4 km/h for á 5 min. The air velocity outside and inside the climate chamber stayed at 0.12-0.13 m/s, i.e. heat exchange with environment was dominated by body motion (activity) or natural convection (seated recovery).

3. RESULTS AND DISCUSSION

Changes in rectal temperature and mean body temperature (reflecting change in body heat storage) are shown in Figure 1a, and skin temperature change in Figure 1b. All test persons finished full exposure time to the experimental conditions. The mean maximal rectal temperature in S1 and S2 were 38.37 and 38.71 °C, respectively, and these temperatures were reached in average 8 and 12 minutes after exiting the heat, respectively. Maximum mean skin temperatures reached 38.10 and 38.46 °C, respectively. Taking rectal temperature of 39 °C as a mission termination criterion, and assuming the same temperature rise as during the last minutes of exposure then one could work in heat 5.5 min longer in S1 than in S2

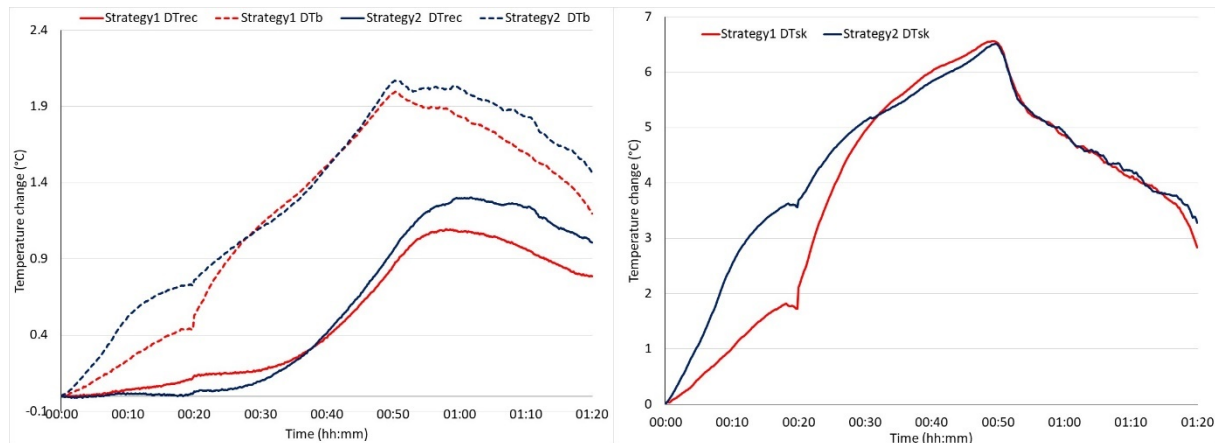


Figure 1. Change in a) rectal (DTrec) and mean body temperature (DTb), and b) mean skin temperature (DTsk) for Strategies 1 and 2.

Figure 2a shows body weight loss and evaporation for S1 and S2. In a condition with full turnout gear from the start (S2) the body water loss was in average almost 200 g higher than in S1. Also, evaporation is commonly higher in S2 (Figure 2a). Thermal and comfort sensation followed the skin and mean body temperature curves reaching in average maximally to 3.1 ± 0.4 and 1.8 ± 0.9 for S1, 3.6 ± 0.5 and 2.1 ± 0.8 for S2, respectively, and dropped quickly after exit from chamber and removal of jacket. Skin humidity sensation reached to 2.3 ± 0.3 and 2.6 ± 0.4 for S1 and S2, respectively. Perceived exertion reached in average to 12.6 ± 1.4 and 13.8 ± 1.3 by the end of heat exposure for S1 and S2, respectively, and heart rate (Figure 2b) was in S2 on average 6 beats/min higher than in S1 throughout the whole test period. Increase in heart rate reflects activity change and increase in rectal temperature, i.e. heat stress (compare heart rate differences of 4 and 5.4 km/h walks at the last minute of each 5 minute period of the test in Figure 2b). Both higher perceived exertion and heart rate indicated higher total physical load in S2 than in S1. Considering health effects then chronically higher heart rates in occupational setting may mean higher risk for cardio-vascular disorders (Meade et al. 2025).

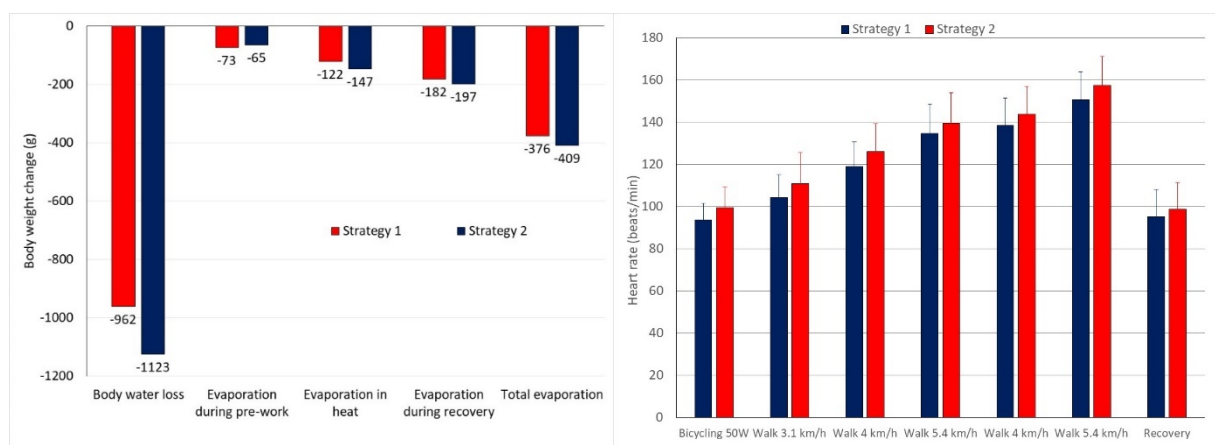


Figure 2. a) Body water balance (g) and b) heart rate (beats/min).

4. CONCLUSION

All measured parameters show that traditional dressing strategy (S2), with wearing continuously full protective clothing set from the alarm start, leads to higher physiological strain in firefighters even if the differences with S1 are not statistically significant in all timepoints and parameters. Heat strain can be considerably reduced by organizational measures, e.g. utilizing measures similar to dressing Strategy 1.

ACKNOWLEDGEMENTS

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PHYSIOLOGICAL IMPACT OF RESCUE WORKERS' PROTECTIVE CLOTHING ON HEAT STRESS DEVELOPMENT DURING SIMULATED WILDLAND FIREFIGHTING ACTIVITIES

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Abstract: Wildland firefighting presents significant physiological challenges due to extreme conditions and prolonged operations. Firefighters wear full protective clothing, which increases heat stress and affects performance. This study examined the thermal impact of the Taurus protective clothing system with and without station wear during a simulated wildland firefighting scenario. Wearing station wear led to higher rectal, body, and skin temperatures, slower cooling, and greater heat gain than wearing only underwear and a T-shirt under turnout gear. While work duration and recovery time remained similar, firefighters in station wear experienced greater thermal strain and discomfort. These findings emphasize the need to optimize protective clothing configurations to improve heat dissipation and endurance in extended wildland firefighting operations.

Keywords: wildland firefighting, protective clothing, heat strain, thermal insulation, physiological strain.

1. INTRODUCTION

Wildland firefighting (WLF) presents challenges due to rapid fire spread and extensive risk areas. Its physical demands result from prolonged operations requiring sustained exertion (Mol & Heus, 2023). Firefighters wear personal protective equipment (PPE) in all incidents, including WLF, which exacerbates heat stress, impairs performance, and increases heat-related injuries such as heatstroke and heat exhaustion (Holmer et al., 2006). Heat stress leads to reduced work capacity and fatigue-related accidents (Mol & Heus, 2023; Pons et al., 2023). Elevated core temperature affects cardiac function and triggers metabolic changes, impacting endurance (Carballo-Leyenda et al., 2021; Ghiyasi et al., 2019). Undergarments influence heat stress development. Studies show that in low-intensity work, replacing long pants with shorts reduces heat stress and extends exposure time by 10–15%, though no difference is observed in high-intensity tasks (McLellan & Selkirk, 2007). This study evaluates the physiological impact of PPE compliant with EN 469, focusing on undergarment effects in simulated WLF conditions in Estonia.

2. MATERIALS AND METHODS

The study was designed in accordance with the Declaration of Helsinki, as outlined by the World Medical Association's 2024 guidelines, and was approved by the Research Ethics Committee on Human Studies of the National Institute for Health Development, Estonia (decision no. 1335, 2024). This paper evaluates the thermal impact of the Taurus PPE system, with and without station wear, during a WLF scenario simulation. Skin temperature was measured at four locations, and core temperature was represented by rectal temperature. Additionally, heart rate and subjective responses were recorded.

2.1 Test subjects and clothing

Six professional male firefighters participated in this study. The experiment consisted of two test series using the Taurus PPE system, which is used in all common rescue tasks in Estonia. In the first, participants wore station wear under PPE (H), while in the second, they wore only underwear and a T-shirt under turnout gear (L). There was minimally one full day between the two tests. Each participant was scheduled to complete both conditions, but tests were terminated if rectal temperature exceeded 39 °C or if the participant withdrew voluntarily. The mean age of

the participants was 36.3 ± 10.0 years, with a body weight of 87.4 ± 10.7 kg, height of 1.83 ± 0.06 m, body surface area (A_{Du}) of 2.09 ± 0.08 m², and body fat percentage of $17.7 \pm 5.2\%$ (acc. to Durnin & Womersley, 1974). In the L condition, two subjects discontinued testing at 63 and 71 minutes, respectively, while in the H condition, three subjects terminated participation at 60, 64, and 79 minutes.

2.2 Environment and activities

The experiment was conducted in a climate chamber with controlled air temperature (T_a) and relative humidity (RH). During the heat exposure period, T_a was 35.7 ± 1.2 °C and RH $37.5 \pm 1.4\%$. In the recovery period, T_a was 23.3 ± 0.3 °C and RH $43.5 \pm 2.5\%$. Air velocity (v_a) remained below 0.15 m/s throughout the experiment. Participants walked at 2.1 km/h (0–10 min), 3.5 km/h (10–25 min), 4.5 km/h (25–40 min), 3.5 km/h (40–55 min), 4.5 km/h (55–70 min), and 2.1 km/h (70–80 min), followed by seated rest (80–110 min), during which they removed their gloves, helmet, balaclava, and firefighting jacket. The last activity 2.1 km/h (70–90 min) was excluded from analysis due to multiple test discontinuations, leading to an insufficient sample size.

3. RESULTS AND DISCUSSION

Figure 1 illustrates rectal temperature (T_{rec}) development in clothing systems L and H. Figure 2a presents changes in rectal (ΔT_{rec}) and body temperatures (ΔT_b), while Figure 2b shows change in skin temperatures (ΔT_{sk}). Standard deviation bars are included in all figures.

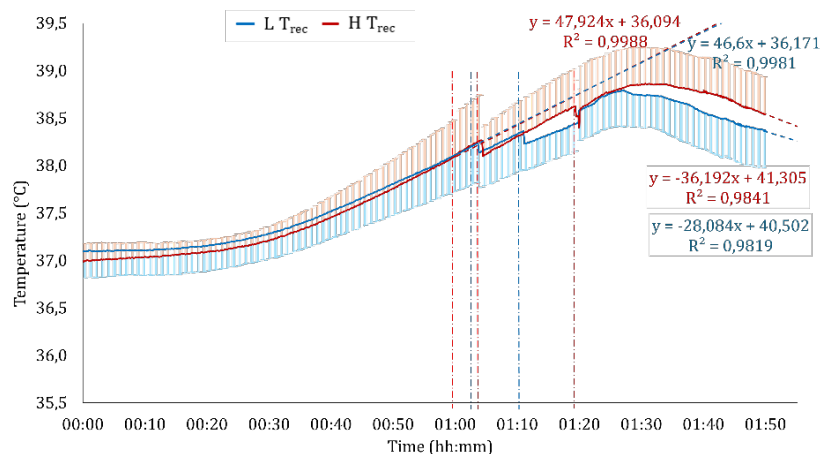


Figure 1. T_{rec} development and regression-based estimations of exposure duration and recovery time. Vertical markers indicate test terminations.

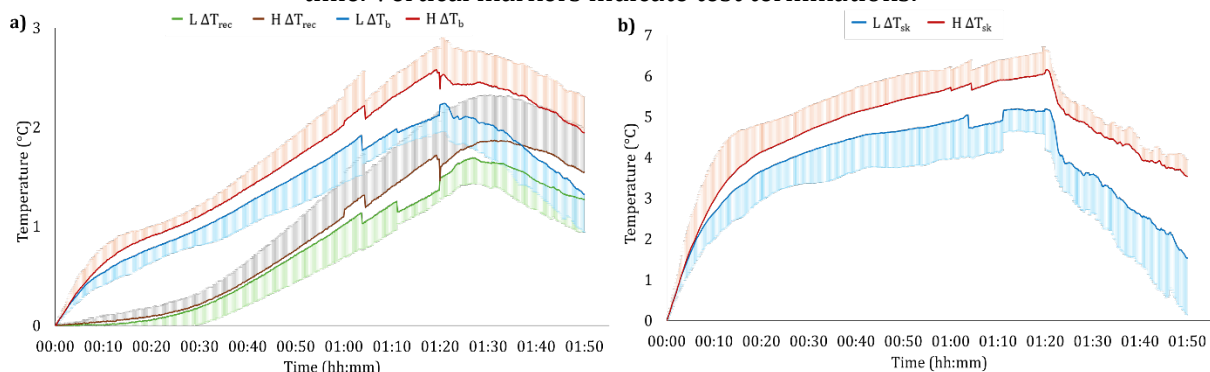


Figure 2. a) Change of ΔT_{rec} and ΔT_b ; b) change of ΔT_{sk} .

The mean initial T_{rec} differed minimally. There were no statistically significant differences in T_{rec} during heat exposure (Figure 1 and 2a). The largest change in temperature from the start of recovery observed at the 100th minute, in ΔT_{rec} in H was 0.20 °C more pronounced than in L. A considerable difference was also noted at the 110th minute, where ΔT_{rec} in H was 0.16 °C higher than in L ($p > 0.05$). The PPE systems did not significantly influence rectal temperature dynamics,

indicating a comparable overall thermal effect. To assess the efficiency of heat loss in the protective clothing systems, differences in temperature change during recovery were analysed (Figure 2). A statistically significant difference in ΔT_b was observed for 100th minute, with a decline from recovery start by 0.5 °C in L and 0.3 °C in H, leading to a difference of 0.2 °C ($p < 0.05$). The greatest difference was reached during the final recovery phase (100–110 min), where ΔT_b had dropped by 0.9 °C in L and 0.6 °C in H, resulting in a 0.3 °C difference between the sets ($p < 0.05$). These results indicate that heat exchange was less efficient in H, leading to prolonged body temperature elevation due to higher heat gain and slower heat dissipation in this PPE system, ultimately reducing the body's heat loss capacity. A similar trend was observed in ΔT_{sk} during recovery. By 100th minute, ΔT_{sk} had decreased by 2.6 °C in L and 2.0 °C in H from the start of the recovery and was significant with a difference of 0.6 °C ($p < 0.05$). The most pronounced change occurred in the final recovery phase by the end of which (110th min) ΔT_{sk} had further decreased up to 3.6 °C in L and 2.5 °C in H, leading to a 1.1 °C difference ($p < 0.05$). The smaller reduction in H for both body and skin temperatures suggests that this PPE system contributed to higher heat accumulation while impairing heat loss capacity compared to L. Regression lines, based on the last ten minutes of recorded temperatures and accounting for test terminations, was used to estimate maximum work duration up to critical T_{rec} of 39.0 °C and minimum recovery time down to 37.5 °C. Under test conditions, the estimated maximum work duration was 87.4 minutes in L and 87.3 minutes in H, while the average recovery time required to lower T_{rec} to 37.5 °C after heat exposure was 73.9 minutes in H and 71.4 minutes in L ($p > 0.05$). Although recovery time was shorter in L, the cooling rate may have been influenced by clothing differences, with participants in H wearing station wear under PPE, while those in L wore only a T-shirt and underwear under PPE. The higher number of test terminations in H suggests that the additional clothing layer caused greater discomfort and earlier cessation during heat exposure, likely hindering heat dissipation.

4. CONCLUSION

The initial T_{rec} differed minimally between L and H, with no statistically significant differences observed during heat exposure. However, H accumulated more heat, leading to a slightly higher peak T_{rec} . Although ΔT_{rec} did not differ significantly between the systems, values were slightly lower in L, but this did not indicate a meaningful reduction in heat strain. H exhibited greater heat gain, particularly seen in ΔT_b and ΔT_{sk} during the final recovery phase. Maximum work durations and recovery times were similar, but the higher number of test terminations in H suggests that actual endurance may have been affected by increased heat strain, with variability in thermoregulation, evaporative resistance, and heat gain in H likely contributing to greater thermal discomfort and prolonged recovery.

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TECHNOLOGICAL SOLUTIONS FOR THE DESIGN OF INTELLIGENT MILITARY EQUIPMENT FOR COMBATANT RESCUE IN EMERGENCY SITUATIONS

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Abstract: *Soldiers are exposed to multiple risks, in the most unexpected ways, but blood loss is a major cause of death for combatants in armed conflict areas. A major challenge in the design of military protective equipment is the complicated problem of auto hemostasis of wounded people on the battlefield. The current paper proposes 3 technological solutions to solve this problem by integrating an innovative autonomous system of primary hemostasis in the structure of the military equipment, ensuring both the functionality, respectively the automatic activation of the pneumatic tourniquet upon detection of bleeding in the limbs, for the induction of hemostasis, as well as the comfort of the combatant, in conditions of armed conflict. For the virtual visualization of the clothing components of the combat protective suit, 3D modeling and simulation solutions of the products were used, using the OptiTex software suite. The fabric used for the undergarment was antibacterial treated and the IR camouflage for the combat suit was obtained through the screen-printing method.*

Keywords: *pneumatic tourniquet, auto hemostasis, smart textiles, 3D simulation.*

1. INTRODUCTION

The smart textiles market is in continuous expansion, especially in the Military and Defense sector, due to the ability of these materials to monitor both the wearer and their environment, so that they can react adequately to stimuli triggers. It is estimated that the conductive textiles market will triple globally, from the value of 2.3 billion dollars recorded in 2023 to 7.3 billion dollars, by 2032, growth supported by the continuous modernization of the Army (Research and Market, 2024).

The first smart commercial product consisted of a jacket, equipped with a mobile phone and an MP3 player, but the removal of all the smart elements before each washing process was a large disadvantage. The next generations of smart textile products were improved in terms of compatibility between parts until they were integrated into textile structures or became textile structures themselves (Molliflex®, 2024). The first intelligent product for protection was the Reima suit, intended for people driving snowmobiles, whose intelligent system asks the victim if needs help, in which case the GPS signal is automatically triggered, allowing the rescue team to track the location of the victim (The Textile Institute, 2013).

Smart textiles have a wide range of military applications, with soldiers being exposed to multiple dangers, in the most unexpected ways, but blood loss is a major cause of death for combatants in armed conflict areas. Giving first aid can be difficult due to poor localization of the victim and achieving self-hemostasis by applying conventional tourniquets is often difficult due to the impossibility of movement, opening and applying the tourniquet with one hand, while pressure must be applied with the other hand on the injured area (China Patent No. CN210631265U Emergency tourniquet and military camouflage clothes thereof, 2020), (Patent No. US10874152B2_Wearable device for reducing fluid loss, 2021). The designed military equipment solves this shortcoming by integrating an innovative autonomous system of primary hemostasis, with an automatic trigger system upon detection of the wound, without the intervention of the human factor (Romania Patent No. RO133698B1 Autonomous System for Primary Haemostasis, 2021).

2. MATERIALS AND METHODS

Starting from the requirements that military protective equipment must meet, 3 technological solutions for the integration of the automatic primary hemostasis system were identified, which have in common with the production of auto hemostasis, through the automatic inflation of the pneumatic tourniquets (5), actuated by the pneumatic circuit (4), based on the signal received from the central unit (3) and triggered by the interruption of the electrical circuit of the textile material (2), by shooting or cutting (fig. 1).

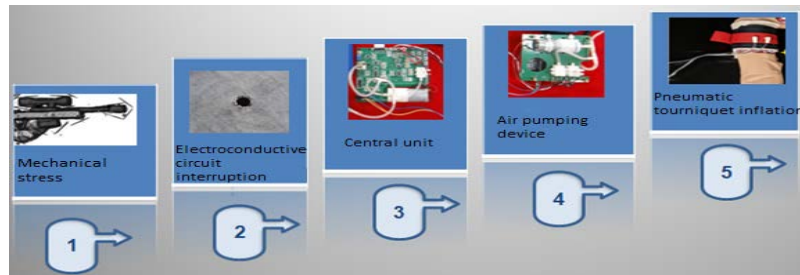


Figure 1. Activation of the automatic primary hemostasis system

To ensure the survival of combatants in operational conditions, the intelligent equipment was designed to be a compound of 2 modules, respectively: *the undergarment ensemble*, consisting of a long-sleeved blouse and long trousers, made of knitted textile structures with special antibacterial and electroconductive properties, and *the IR camouflage combat suit*, consisting of a jacket and trousers, made of woven fabric printed in IR camouflage colors.

3. RESULTS AND DISCUSSION

The technological solutions (T.S.) are based on different configurations of the automatic primary hemostasis system, respectively: T.S.1) 4 pneumatic tourniquets: 1 tourniquet for each member, 4 control units: 1 unit for each member, 4 electroconductive circuits: 1 circuit for each unit of command; 4 pneumatic circuits: 1 circuit for each tourniquet; T.S.2) 8 pneumatic tourniquets: 2 tourniquets for each member, 4 control units: 1 unit for each member, 8 electroconductive circuits: 2 circuits for each control unit; 8 pneumatic circuits: 1 circuit for each tourniquet (fig.2).

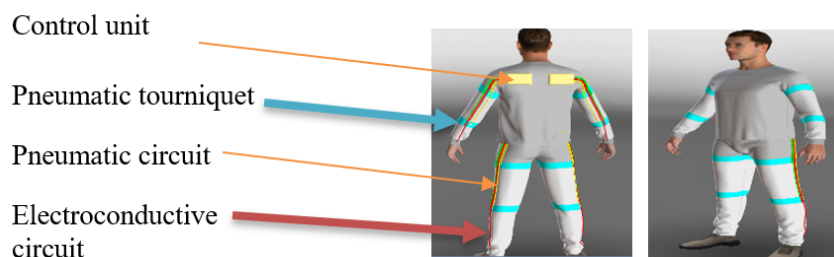


Figure 2. Technological solution T.S.2

Technological solution T.S.3 is similar to T.S.2, having as particularity a modular structure of the electroconductive areas (fig.3).

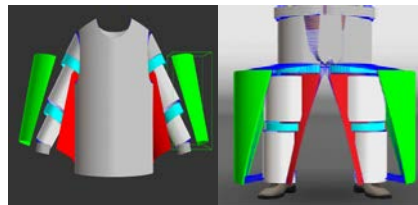


Figure 3. 3D simulation of the T.S.3

The undergarment ensemble, consisting of two components * blouse and *pants is made from a knitted textile structure composed of 90% BBC and 10% Elastane. This textile is treated using a

scarfing technology with essential pine oil and collagen hydrolysate, following these steps: 1) Prepare a 1.5% hydrolyzed collagen solution and 2) Prepare a solution of 450 µL of essential pine oil in 15 mL of ethyl alcohol. 3) Mix the collagen solution and pine oil solution, adding 4.5 g of zeolite and 4.5 g of β-cyclodextrin (in a 1:10:10 ratio of pine oil: zeolite: β-cyclodextrin). After treatment, the textile structures were air-dried at room temperature for 24 hours. The degree of loading with the active substance was 1.33%. The GS-MS method identified specific chemical compounds in both the essential pine oil and the treated textile structures. Resistance testing against *Staphylococcus aureus* ATCC 6538 (gram-positive) and *Escherichia coli* ATCC 10536 (gram-negative) showed satisfactory results for antibacterial effectiveness.

The IR camouflage suit consists of a jacket and combat pants made from fabric printed with IR camouflage colors to ensure effective concealment of the combatant in the operational field (Fig. 4). The fabric was printed using NEWTEX TRANSPARENT HD 10 screen printing ink and Chromatex HD-10 pigments. The camouflage print includes five colors: navy blue, brown, yellow, green, and black. Vector images were edited using the CorelDRAW program. The IR reflection values and corresponding reflection curves were determined. A comparative analysis of the reflection values reveals slight differences between the original textile structure and those subjected to friction, washing, and light resistance tests. All reflectance values are below 75%.

4. CONCLUSION

The major challenges of the design for military emergency rescue equipment are given by the need to find optimal technological solutions for the integration of the automatic primary hemostasis system, to obtain the functionality for which the intelligent equipment was designed, namely the automatic activation of the pneumatic tourniquet upon detection of bleeding in the limbs, simultaneously with ensuring the comfort of the combatant, in conditions of armed conflict. To define and visualize the pieces for the intelligent military equipment component, for all of the developed technological solutions, several 3D simulations were carried out, on a parametrized mannequin, using the OptiTex software suite.

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WATER AGING OF FIRE-PROTECTIVE POLYBENZOXAZOLE (PBO) FABRIC

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Abstract: This work aims to understand the ageing behaviour of PBO fibres when exposed to water in liquid and vapour form. The residual load at the break of a PBO fabric was measured after exposure to hydrothermal and hygrothermal ageing between 21°C and 90°C. Samples were also exposed to thermal ageing at 90°C. The effects of the water state, temperature, and exposure time were analysed using ANOVA and the combination of the time-temperature superposition (TTS) and Arrhenius models. Contact angle measurements, scanning electron microscopy (SEM), and electron dispersive X-ray spectroscopy (EDX) were also conducted as complementary analyses. The results show no effect of the water phase, while the exposure time and ageing temperature controlled the reduction in strength due to hydrothermal and hygrothermal ageing. A surprisingly significant reduction in strength after 50 days of thermal ageing at 90°C was recorded.

Keywords: PBO fibres, hydrothermal ageing, hygrothermal ageing, fire-protective fabric, force at break.

1. INTRODUCTION

High-performance fabrics made of fibres such as para-aramid, meta-aramid, polybenzimidazole (PBI), and PBO are used to make firefighter garments (Hoque & Dolez, 2023). These garments are exposed to harsh conditions during their lifetime, which impacts the useful life span of the fire-protective garments. In the case of PBO, a shooting incident at Forest Hills, Pennsylvania, in 2003 exposed a potential safety issue in bulletproof vests used by police officers due to premature ageing. An investigation led by the US Department of Justice attributed the unexpected failure of the bulletproof vest to degradation by moisture (US Department of Justice, 2004). Even though PBO was banned from being used as a material for bulletproof vests after this incident, it is still used in fire-protective garments. As the knowledge of the mechanisms and kinetics of PBO water ageing is still limited, this study investigated the effect of hydrothermal (exposure to liquid water) and hygrothermal (exposure to humid atmosphere) ageing at different temperatures on the mechanical strength of a PBO fabric.

2. MATERIALS AND METHODS

2.1 Material

Zylon fabric with 100% PBO AS regular staple yarns was obtained from TOYOBBO CO. Its characteristics were: plain twill structure, weight of 320 g/m² and thickness of 0.5 mm.

2.2 Accelerated aging protocol

Six replicates with a size of 15 x 3.5 cm were prepared for each condition. The length of the specimen was aligned to the fabric's warp direction. Replicates had different warp and weft yarns. The specimens were unravelled to 2.5 cm (65 warp yarns) before ageing. Hydrothermal ageing was applied by immersing the specimens in a jar filled with reverse osmosis (RO) water and placed in a convection oven at temperatures of 60, 80 and 90°C. The specimens were maintained in a 100% humidity environment for hygrothermal ageing at temperatures of 60, 80 and 90°C. The hydrothermal and hygrothermal ageing were also conducted at 21°C. The thermal condition was created by keeping the fabric specimens in the oven at 90°C. Ageing lasts for up to 50 days.

2.3 Testing

The residual load at break of the aged specimens was measured according to the ASTM D 5035 standard test method (ravelled strip) and compared to the values for unaged specimens. Complimentary SEM imaging, EDX analysis, and contact angle measurements were also performed.

2.4 Data analysis

The ageing duration, ageing temperature, and ageing environment were taken as the explanatory variables for the ageing study. The ageing duration and temperature are quantitative variables: duration had six levels (0, 10, 20, 30, 40, and 50 days), and the temperature had four levels (21°C, 60°C, 80°C, and 90°C). The ageing environment is a categorical variable with three levels: thermal, hygrothermal, and hydrothermal. The responsive variable was the load at the break. A factorial design method was used for the experiment. Two separate ANOVA analyses were conducted to determine the statistical significance of the variables. The first ANOVA focused on the effect of ageing temperature, duration, and water state (liquid with hydrothermal and vapour with hygrothermal). The second ANOVA compared the hydrothermal, hygrothermal, and thermal ageing data at 90°C. IBM SPSS Statistics software (Version 29.0.1.0(171)) was used for the statistical analysis. The Bonferroni pairwise test was performed as a post hoc test. The α value was selected as 0.05 with 95% confidence level. The ageing data were modelled using the Arrhenius and the time-temperature superposition (TTS) models.

3 RESULTS AND DISCUSSION

3.1 Comparison of the effect of hydrothermal and hygrothermal ageing

The results of the measurement of the effect of hydrothermal and hygrothermal ageing on the PBO fabric load at the break at different ageing temperatures are illustrated in Figure 1. It shows a decrease in the residual load of a break with ageing duration and temperature. This decrease reached 48% after 50 days of hydrothermal and hygrothermal ageing at 90°C. The three-way ANOVA showed a significant statistical difference with strong evidence between the ageing temperature levels on one side and the ageing duration on the other side ($P < 0.001$). The post hoc Bonferroni test on the ageing duration levels showed a significant difference between the initial and each ageing duration (10, 20, 30, 40 and 50 days) with strong statistical evidence ($P < 0.001$). Post hoc test on the temperature levels also showed a significant difference between the data at 21°C and the other levels (60°C, 80°C, 90°C) with strong evidence ($P < 0.001$). On the other hand, there was no significant difference between the data for the two different water states (hydrothermal and hygrothermal) with strong evidence ($P = 0.911$).

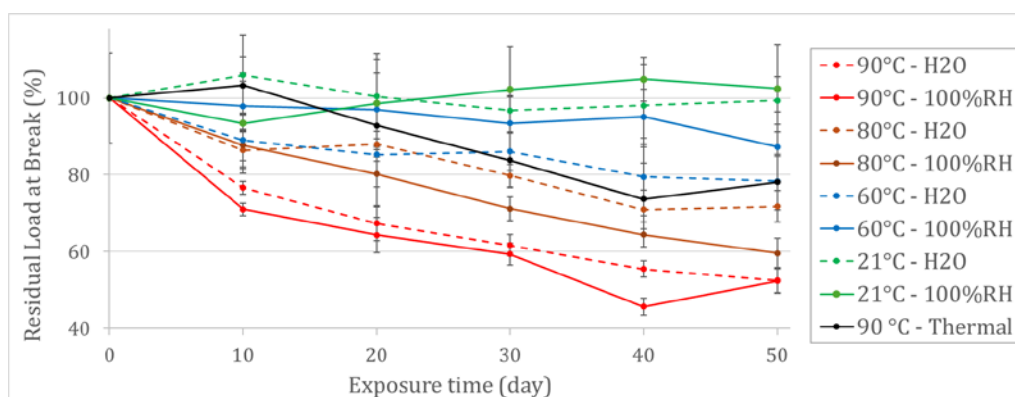


Figure 1. Residual load at break after hydrothermal, hygrothermal and thermal ageing

3.2 Comparison of the effect of hydrothermal, hygrothermal, and thermal ageing at 90°C.

Figure 1 also shows the residual load at the break of the PBO fabric after thermal ageing at 90°C. The residual load at break value after thermal ageing decreased with ageing time, reaching 22% after 50 days. This result is surprising given that the temperature of continuous operation of PBO has been reported to be 310°C (Bourbigot & Flambard, 2002). The two-way ANOVA showed a significant difference between each level of the considered factors, ageing conditions and ageing duration, with strong evidence ($P < 0.001$). The thermal ageing data showed a significant difference with the hydrothermal and hygrothermal data with strong statistical evidence ($P < 0.001$). This result demonstrates the accelerating effect of water in the liquid and vapour phases on the ageing experienced by the PBO fabric.

3.3 Effect of temperature on hydrothermal and hygrothermal ageing

TTS master curves were constructed using the 60°C, 80°C, and 90°C strength data for both hygrothermal and hydrothermal conditions. The shift factors provided by the TTS transform were satisfactorily described by the Arrhenius model (R^2 value of 0.99 for both hydrothermal and hygrothermal ageing). The activation energies provided by the Arrhenius plots were 69 and 80 kJ/mol for hydrothermal and hygrothermal ageing, respectively. These values are slightly higher than the activation energies reported by Hoque et al. (2022) for a series of para-aramid/polybenzimidazole firefighter outer shell fabrics exposed to hydrothermal ageing.

3.4 Microscopic analysis and water repellency.

Observations by SEM revealed no morphological difference between the unaged and aged PBO fabric samples. Contact angle measurements did not reveal any changes either in water repellency after ageing. EDX analysis showed the presence of phosphorus in the fabric, which may have contributed to the strength reduction observed when the fabric was exposed to moisture (Kanbargi et al., 2017).

CONCLUSION

The mechanical strength of the PBO fabric was significantly reduced after exposure to hydrothermal and hygrothermal ageing conditions at temperatures between 60 and 90°C. The reduction increased with ageing time and ageing temperature. The presence of phosphorus in the fabric may have contributed to this reduction in strength upon water exposure. There were no significant differences in the residual load at break between the hydrothermal and hygrothermal ageing conditions. The effect of thermal ageing at 90°C was significantly lower than the effect of hygrothermal and hydrothermal ageing behaviours. However, it still produced a surprisingly high reduction in strength of about 20% after 50 days at 90°C considering the continuous operation temperature of 310°C reported for PBO. Both moisture and heat showed an accelerating effect on the hydrothermal and hygrothermal ageing process of PBO.

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GRAPHENE-BASED END-OF-LIFE SENSORS FOR FIRE-PROTECTIVE CLOTHING

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Abstract: Graphene-based end-of-life sensors have been developed to allow monitoring the condition of fire-protective clothing during service. The sensors combine a sacrificial polymer sensitive to the same aging condition as the fabric of the fire-protective clothing with a layer of graphene prepared at the surface of the polymer by laser engraving. The degradation of the sacrificial polymer creates a disruption in the graphene track, whose electrical conductivity increases. Three polymers have been selected as the sacrificial layers for the different types of sensors: polyetherimide for the thermal sensor, polyimide for the moisture sensor, and two-pack polyurethane for the UV sensor. The manufacturing process was optimized within the context of industry production. The decoupling of the heat, UV, and moisture sensing functions of the end-of-life sensor is currently being investigated. The sensor will soon be field tested at a firefighter training school.

Keywords: Fire-protective fabrics, end-of-life sensors, firefighter protective clothing, degradation, graphene.

1. INTRODUCTION

Although the materials used in fire-protective clothing exhibit exceptional performance when new, the various conditions they are exposed to during the lifetime of the clothing reduce their performance over time (McQuerry et al., 2015). In addition, these large losses in performance may occur before any sign of damage is visible to the naked eye (Rossi et al., 2008). Moreover, fire-protective clothing's laundering frequencies are being increased following the discovery that smoke particles and combustion-generated carcinogenic chemicals can penetrate firefighters' protective clothing (Keir et al., 2017); these harsher laundering conditions will accelerate the aging of the protective clothing, making the current retirement directives obsolete.

To tackle this critical issue, a graphene-based end-of-life sensor was developed to monitor the condition of the fire-protective clothing over its lifetime. It relies on polymers that are sensitive to the same aging conditions as high performance fibres: polyetherimide for heat (Cho et al., 2022), polyimide for UV (Khémir et al., 2022), and two-pack polyurethane for moisture (Braun et al., 2022). These polymers are combined with a graphene-based conductive track (Dolez et al., 2022). Upon reaching a certain level of exposure to one of these aging agents sufficient to cause the fire-protective fabric to enter an unsafe range, the sacrificial polymer degrades, causing a disruption in the graphene conductive track and a change in its electrical conductivity. The end-of-life sensor is secured on a fabric substrate that is stitched as a patch at a few strategic locations on the fire-protective clothing.

2. MATERIALS AND METHODS

2.1 Sensor Fabrication

The first step is preparing the graphene track on the polymer strip by laser engraving. In the case of the thermal and moisture sensor, the laser engraving is performed on the corresponding sacrificial polymer. At the same time, holes are created on each side of the graphene track to house the electrical contacts (Fig. 1.a). A layer of epoxy is applied on the sensor for encapsulation. For the UV sensor, the graphene track is formed on a polyimide strip (Fig. 1.b). The electrical contacts extend on each side of the graphene track, which is covered by the sacrificial polymer.

The sensor is laminated on a narrow fabric made of Nomex IIIA (93% meta-aramid, 5% para-aramid, 2% antistatic fibre) so that it can be stitched to the outer shell of the firefighter bunker suit (Yehia et al., 2023).

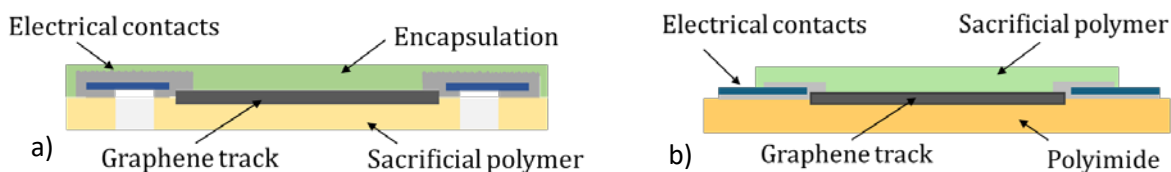


Figure 1. Design of the sensor: a) thermal and moisture sensor; b) UV sensor

2.2 Aging Program

Different accelerated aging conditions are applied to the sensors to assess their ability to monitor the aging sustained by the fire-protective fabrics during service. These accelerated aging conditions were selected to produce significant changes in the performance of fabrics used as outer shell in firefighter protective clothing when exposed to thermal (Hoque and Dolez, 2024a), hydrothermal (Hoque et al., 2022), and UV aging (Hoque and Dolez, 2024b) while remaining relevant to the conditions encountered in the field. Thermal aging is conducted using an air-circulating oven at temperatures between 70 and 300°C corresponding to the hazardous exposure range. UV aging is applied by exposing the sensors to UVA radiation using fluorescent lamps at an irradiance of 1W/m² (at 340 nm) with the chamber at temperatures of 40 and 80°C. Moisture aging is simulated by keeping the sensors in water at temperatures between 40 and 90°C. Aging programs also test the decoupling of the heat, UV, and moisture sensing functions of the sensor.

2.3 Characterization of the Sensor Performance

The sensor performance in the initial state and after exposure to aging is characterized by measuring the residual electrical resistance of the graphene track using a multimeter with its two probes placed on the sensor's electrical contacts.

3. RESULTS AND DISCUSSION

3.1 Thermal Sensor

Prototypes of the thermal sensor (Figure 2.a) were exposed to 270°C for up to 29 days. A gradual and reproducible increase in their resistance, by 10 times after 29 days, was observed, demonstrating the ability of the sensor to monitor fabric degradation due to thermal aging (Cho, 2022). On the other hand, water immersion at 90°C for 28 days did not produce any changes in the sensor resistance. Repeated bending was also applied to the sensor to simulate the mechanical stress experienced during use. No significant change in resistance was recorded after 5000 bending cycles (Chhetry et al., 2022).

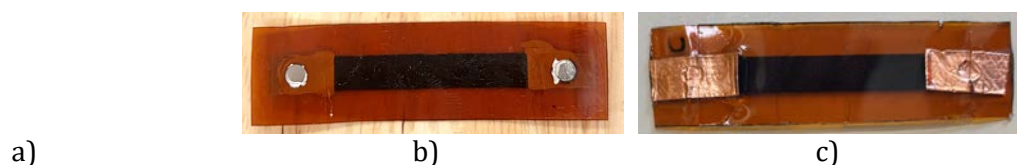


Figure 2. Prototypes of the thermal sensor (a), moisture sensor (b), and UV sensor (c)

3.2 Moisture Sensor

Figure 2.b shows a picture of moisture sensor prototypes that were subjected to the aging program. Exposure to water at 90°C for 28 days produced an increase in the resistance of moisture sensor prototypes, showing the ability of the moisture sensor to monitor fabric degradation due to hydrothermal aging. On the other hand, no significant increase in the resistance of the moisture sensor was measured after UV exposure under an irradiance of 1W/m² at 40°C for 25 days.

3.3 UV Sensor

The UV sensor is shown in Figure 2.c. The resistance of the UV sensor was not significantly affected when it was subjected to accelerated hydrothermal aging at 90°C for 28 days. The effect of UV radiation on the resistance of the UV sensor is currently being assessed under 1W/m² at 40°C for up to 25 days to quantify its ability to monitor fabric degradation due to UV aging.

4. CONCLUSION

A graphene-based end-of-life sensor with thermal, moisture and UV modules has been developed to monitor the degradation that would be experienced by fire-protective fabrics when exposed to heat, moisture, and UV. The manufacturing process has been scaled up for industry-scale production and commercialization. Tests are being performed to quantify the change in electrical resistance upon exposure to the aging conditions known to affect fire-protective fabrics as well as verify the absence of cross effects between the different aging conditions. The next step of the work involves field testing the sensors in accelerated yet realistic conditions at a firefighter training school.

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TEXTILE GLOVES REINFORCED WITH 3D-PRINTED STRUCTURES INTENDED FOR ANTI-CUT PROTECTION

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Abstract: The aim of the study was to obtain novel anti-cut gloves using innovative hybrid composite materials consisting of a textile carrier and polymer reinforcement. In this research, 3D-printing technique was applied in order to obtain mentioned reinforcement in the form of novel structures, such as openwork ones, with the aim of improving cut-resistant properties of textile gloves. The prepared thermoplastic structures, made of commercially available thermoplastic filaments, including poly(ethylene terephthalate)-glycol (PET-G) and polyamide with glass fibres (PA-GF), were implemented in the textile using contact welding process. The obtained gloves were tested in terms of mechanical properties with special regard to cut resistance and tear resistance. The results confirmed that implementing 3D-printed structure made of PA-GF improves anti-cut properties of commonly used textile gloves, where the highest performance level is achieved. Furthermore, the tear resistance was also improved and all the materials were characterised by the highest (5th) performance level.

Keywords: 3D-printing, cut resistance, protective gloves, polymer reinforcement.

1. INTRODUCTION

Cut resistant gloves are of great importance in personal protective equipment (PPE) and are mostly used in the workplace to prevent hands from injuries such as cuts inflicted by blades, broken glass and other different objects with sharp edges. Furthermore, anti-cut textiles can also be applied outside work, for instance sport activities. To give one example, mountaineering clothes are worn to prevent the human from being cut by a crushed stone during rock climbing or other activity, where similar risk may occur (Wang et al., 2018). Nowadays, there is a growing interest in creating innovative cut-resistant materials to increase human safety (Zhai et al., 2021; Mao et al., 2024). In our researches, we are focused on obtaining novel protective gloves by designing new textures and structures, where well-known polymers and fibres are applied but with the use of nonconventional processing methods (for instance 3D printing (Żyłka et al., 2024), ultrasonic welding (Irzmańska et al., 2024) and laser texturing (Kropidłowska et al., 2023)). In this study, the results of improving textile gloves by implementing 3D-printed thermoplastic reinforcement on the surface by means of contact welding process are presented.

2. MATERIALS AND METHODS

2.1 Preparation of Textile Gloves reinforced with 3D-printing Structures

In order to obtain textile gloves characterized by improved cut-resistant properties, the designed thermoplastic structures were printed using 3D technique applying different available thermoplastic filaments, including poly(ethylene terephthalate)-glycol (PET-G) and polyamide filled with fibre glass (PA-GF). The 3D-printed structures (SMK 3D Jakub Saramak, Poland) were implemented in the synthetic fibre textile gloves (S.I. Zgoda, Poland) by means of contact welding method using optimized parameters, including T=160°C and t=40s for textile/PET-G samples and T=190°C and t=40s for textile/PA-GF samples.

2.2 Cut Resistance (TDM test)

Cut resistance was tested under variable load according to EN ISO 13997:2023 (TDM test, P.I. Kontech, Poland). The performance level was determined according to EN 388:2016+A1:2018.

2.3 Tear Resistance

Tear resistance measurement was carried out according to EN 388:2016+A1:2018 using a testing machine (4465 INSTRON, Great Britain) applying a head speed of 100 ± 10 mm/min. The performance level was also assessed according to EN 388:2016+A1:2018.

3. RESULTS AND DISCUSSION

According to the results depicted in Figure 1., implementing novel 3D-printed thermoplastic structures applying contact welding process caused an increase in cut resistance of the tested textile gloves from 2.7 N to 17.2 N in the case of the PET-G thermoplastic and to 33.7 N for the PA-GF material. Based on the results, the tested textile gloves reinforced with PET-G polymer were classified as effective at level D and the gloves with PA-GF were characterized by the highest performance level (F) according to EN 388:2016+A1:2018. Moreover, such reinforcements contributed to tear resistance enhancement from 128.3 N in the case of the referential textile to 145.8 N for textile reinforced with PET-G structure and to 156.4 N for gloves with PA-GF reinforcement. However, all tested samples were characterised by the highest 5th performance level according to EN 388:2016+A1:2018.

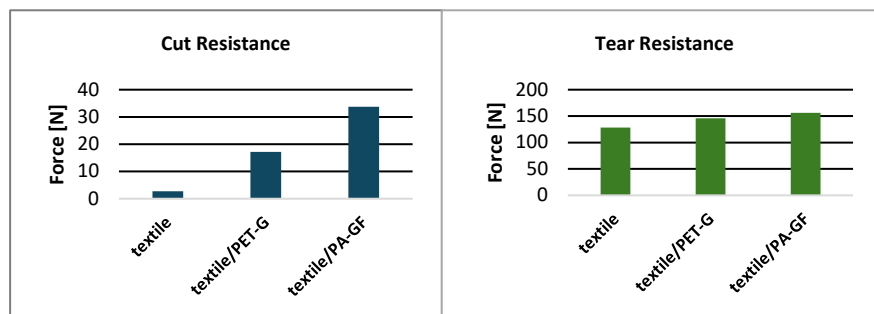


Figure 1. Cut resistance and tear resistance of reinforced textile gloves.

4. CONCLUSION

The implementing of novel 3D-printed reinforcement into commonly used textiles is a simple, low cost and effective way of creating new anti-cut gloves. The obtained results confirmed that designed advanced and complex thermoplastic 3D-printed structures are able to improve cut resistance and tear resistance of textile gloves, but such enhancement depends on polymer filament selection. The highest cut resistance was achieved for textile reinforced with PA-GF, where the parameter was increased by approximately 96% in comparison to textile with PET-G and was characterised by the highest performance level (F). Moreover, an application of PA-GF structure caused an improvement in tear resistance of about 22 % compared to the referential textile sample. However, all the tested materials were characterised by the highest (5th) performance level.

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MILITARY STEALTH: NEXT-GENERATION CAMOUFLAGE ENHANCING TECHNOLOGIES

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¹Citeve

Abstract: *This study utilizes additive manufacturing (AM) to enhance visual camouflage by creating 3D structures on textile substrates through layered material deposition. By transforming traditional camouflage patterns into the third dimension, AM improves concealment effectiveness. The research incorporates digitization, 3D modelling, and AM techniques to develop advanced camouflage solutions. In addition to colour patterns and combinations, 3D effects were integrated using regular FDM polymers, photopolymers, UV light, and inkjet heads. The process begins with a CAD model, which is converted into a printable format to ensure precision and rapid production. This approach enables the fabrication of highly detailed and customized camouflage patterns with enhanced visual disruption capabilities. By leveraging AM technology, the study demonstrates an innovative method for producing next-generation camouflage solutions applicable to military, tactical, and outdoor environments. The findings highlight AM's potential to revolutionize traditional camouflage by adding depth, complexity, and improved adaptability to various operational settings.*

Keywords: *Camouflage, AM, military patterns, 3D printing, textiles.*

1. INTRODUCTION

Current operational environments can be characterized as volatile and uncertain, with high complexity. These characteristics are accentuated by new technologies and the phenomena of globalisation, digitalisation, and pervasive connectivity. Therefore, a dangerous, competitive environment is defined and is not limited only to the traditional domains of land, sea and air but also extends to the domains of space and cyberspace. This will also influence the ability to employ forces of different sizes and capabilities, from large scale manoeuvres to special operations involving small forces, possibly unmanned. Traditional battlefield has, thus, evolved into a combat situation based on persistent and multi-domain threats, enhanced by hybrid warfare techniques and new high-tech weapons, to produce interconnected effects across all five domains (Air, Land, Maritime /Sea, Space and Cyberspace) presenting complex conditions for the military to perform proficiently. (Cannon, 2024) More importantly, they need to avoid enemy sensors' detection and stay safe. Here, camouflage efficiency crucial, where the soldiers or the platforms' signature should go unnoticed. The higher the blending into the surrounding background the better is camouflage efficiency. Camouflage nowadays is applied in a multispectral level, extending from visible spectrum to the radar spectrum. Nonetheless, visual signature remains the first line of concealment. (Hossain, 2024)

Improvements on visual camouflage can be achieved by additive manufacturing (AM), which consists in creating 3D objects by layering materials, bottom-to-top orientation. Therefore, traditional camouflage patterns, among other elements, can be brought to the 3rd dimension and improve visual camouflage efficiency.

Herein is described the use of digitization techniques, 3D modelling and AM to produce visual camouflage solutions, where besides colours (camouflage patterning or simple colour combination), 3D-effects were added with quickly creating precise parts by using photopolymers, UV light, and inkjet heads. This was done starting with a CAD model, which is then transformed into a printable format.

2. MATERIALS AND METHODS

2.1 CAD MODELLING

3D models were developed and optimized using Fusion 360, GrabCAD, Blender and 3D imaging STRATASYS proprietary software. These models were constructed taking into consideration forest and urban environments previously studied.

2.2 AM MANUFACTURING

3D printing was performed by means of STRATASYS Polyjet and ULTIMAKER S6 FDM printers. The materials used in prototyping can be listed as follows:

- Stratasys photopolymer;
- PLA, from filament2print.

2.3 TEXTILE SUBSTRATES

The most suitable textile substrates were studied, in terms of printing material adhesion, and the most relevant ones were selected. Textile substrates used can be described by 2 types of blends, such as WO/PES/PU and AR/VIS as well as a single-material substrate like PA.

3. RESULTS AND DISCUSSION

Several 3D models were developed for visual camouflage. Parameters such as type and colour of patterns, as well height of printed elements were carefully studied and integrated into the designs to optimize their effectiveness. These parameters played a crucial role in achieving a balance between visual disruption and material efficiency. The most relevant models, which showcase the impact of these design choices, are depicted in Figure 1.

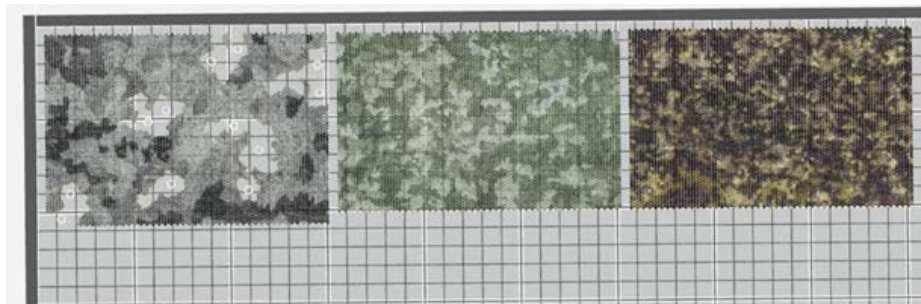


Figure 1. Some examples on 3D models created for visual camouflage.

Parallel to modelling development, various textile substrates were studied. Several samples, containing varied blends were collected, analysed and preliminary printing tests were performed to assess material adhesion. All the blends tested showed promise. To achieve a more stable and adherent print without significantly increasing the total printing time, adjustments were made to printing parameters, such as material time deposition and curing time.

3D printing of the developed models onto the textile substrates was performed and some examples are shown in Fig. 2.



Figure 2. Examples of the 3D models for visual camouflage printed on fabric.

Moreover, the pattern on the left (both in Figure 1 and Figure 2, right) was optimized by isolating part of the coloured spots and adding a snap-like system to be able to customize the missing

colours on the pattern, thus improving blending to the surroundings. The “spots” counterparts were modelled (Figure 3) and printed using Fused Deposition Modelling (FDM) printing.

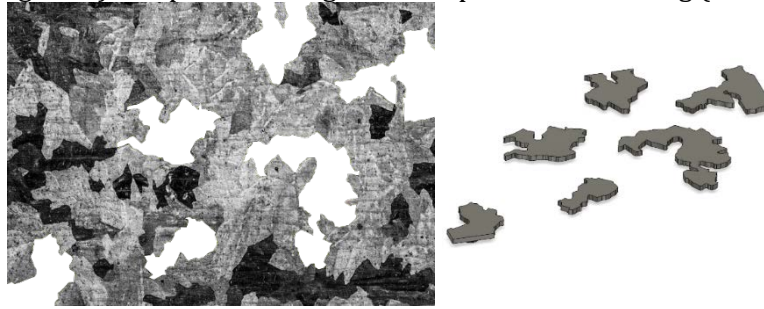


Figure 3. 3D modelling of the “holed” pattern and its counterparts.

The resulting patterns were analysed with a colorimeter to assess colour coordinates and UV-VIS characterization was ensued. Further testing, including stability assessments and visual blending evaluations are planned to determine the effectiveness of the camouflaged prototypes in both urban and forest environments.

4. CONCLUSION

In conclusion, several prototypes were successfully modelled and quickly printed onto selected textile substrates. The success of the printing process was achieved through parametric optimization to achieve both structural cohesiveness and textile surface adhesion.

The camouflage performance evaluation will follow focusing on the visible spectrum. The Defence area can greatly benefit from 3D modelling and AM technologies, which permit fast, reliable and more sustainable product refining and prototyping.

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DESIGN AND PERFORMANCE EVALUATION OF FLAME-RESISTANT PROTECTIVE FABRICS

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Abstract: *This study investigates the design and performance evaluation of high-performance flame-retardant protective fabrics. Yarns composed of mode acrylic, flame-resistant viscose, para-aramid, and antistatic nylon produced twill denim fabrics. The fabrics underwent various finishing treatments, including water repellency, and were evaluated for air permeability, water vapor permeability, water repellency, flame retardancy, abrasion resistance, and crocking fastness. Test results indicated that the fabrics demonstrated excellent flame resistance, with no melting or dripping, and achieved an A1 rating. Additionally, the fabrics exhibited adequate water repellency, air permeability, and durability against abrasion. These findings suggest that the developed fabrics suit protective clothing applications in various industries requiring enhanced safety and performance.*

Keywords: *Protective textiles, flame-resistant fabrics, water repellency, air permeability.*

1. INTRODUCTION

Textile fabrics have been integral to human life for centuries, yet most are highly flammable and can be easily ignited by minor sources of fire (Qi, P et al, 2023). Protective textiles are textile products designed to ensure human safety and survival. These textiles are developed by utilizing fibers or yarn structures with superior performance characteristics, such as chemical resistance, microorganisms, weather conditions, high strength and fireproofing, and various finishing treatments (Basak et al, 2018). The primary objective of protective textile-based clothing is to safeguard human life. These garments protect without requiring an additional barrier between the wearer and potential sources of injury (Watson et al, 2019).

Protective clothing and equipment are designed for various fields of work and activities, including soldiers, security personnel, police officers, firefighters, sailors, submariners, aircraft personnel, astronauts, warehouse workers, seabed oil and gas equipment operators, caving, climbing, skiing, water sports, winter sports, racing drivers, foundry workers, mountaineering, coal mining, commercial fishing, and healthcare (Şardağ et al, 2024). Various finishing treatments have been applied to develop environmentally friendly protective textiles, as discussed in several studies (Chowdhury et al, 2025; Zhang et al, 2021; Liu et al, 2020; Cheng et al, 2020). These methods still have certain drawbacks for large-scale production, including the need for specialized equipment and lengthy processing times. This research presents a practical approach to producing high flame-resistant fabrics while maintaining their appearance and other performances.

2. MATERIALS AND METHODS

2.1 Materials

In this research, yarns composed of dyed staple fibers were utilized. These flame-retardant technical yarns were intended for use as both weft and warp yarns with a composition of 50% mode acrylic, 43% FR (flame-resistant) viscose, 5% para-aramid, and 2% antistatic fibers (nylon). Flame-resistant technical yarn in yellow and navy blue (24/2) was sourced from Kavilteks Company. The characteristics of the sourced yarns are illustrated in Table 1.

Table 1. Characteristics of sourced yarn

Yarn type	Yarn count (Ne)	Breaking strength (CN)	Elongation (%)	Twist (TPM)	CVm (%)	Thick place (+50)/km	Thin place (-50)/km	Neps (+200)/km
Navy color yarn	24/2	496	10.22	628	14.20	36	10	23
Yellow color yarn	24/2	506	9.15	621	11.83	23	0	27.5

2.2 Methods

Two different types of fabric have been developed using two different colored yarn (navy and yellow) in both directions (warp and weft). The 2/1 'Z' twill denim fabric with an EPI (Ends per inch) $\times$ PPI (Picks per inch) of 52×46 was manufactured using a Picanol OptiMax-i model machine (weaving) with a speed of 550 rpm and the fabric width was 180cm. After being woven on Picanol machines, the fabrics underwent finishing operations, including the application of a water-repellent treatment. The characteristics (performances) of each fabric sample were evaluated following standard testing procedures. Each measurement was performed five times, and the mean results were calculated for examination.

3. RESULTS AND DISCUSSION

3.1 Air and water permeability of the fabric

The air permeability of the fabric was examined using an air permeability tester by the related standard (ASTM D737-04) under a pressure difference of 100 kPa. Five specimens from each fabric type were tested. Figure 1 presents the air permeability values of different fabrics, revealing that each fabric shows acceptable results.

The Water vapor permeability index of the fabrics was assessed utilizing the "TESTEX (TF165A)" by the related standard (BS 7209:1990). Figure 2 presents the Water vapor permeability index values of different fabrics, revealing that each fabric shows acceptable results.

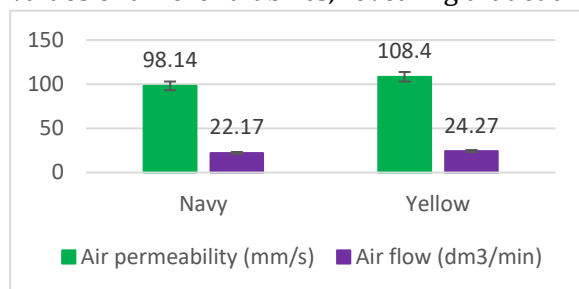


Figure 1. Air permeability of the fabric

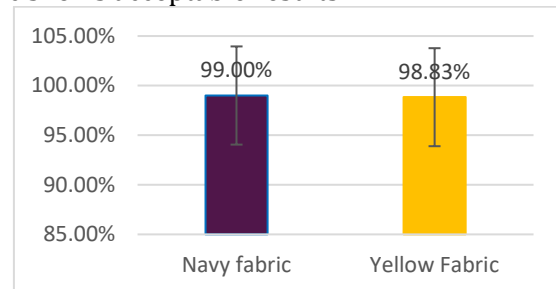


Figure 2. The water vapor permeability index of the

3.2 Water-repellency of fabric

For the water-repellency test, the test specimen is placed flat and stretched on a surface, with a liquid prepared with methylene blue being sprayed onto the taut fabric under controlled conditions maintaining the standard AATCC 22. The resulting wetted pattern varies according to the fabric's water-repellency level, which is assessed by comparing it to a visual rating scale. The results obtained for each fabric was 70 (ISO 2). Figure 3 presents the spray test (Water-repellency) results in images.

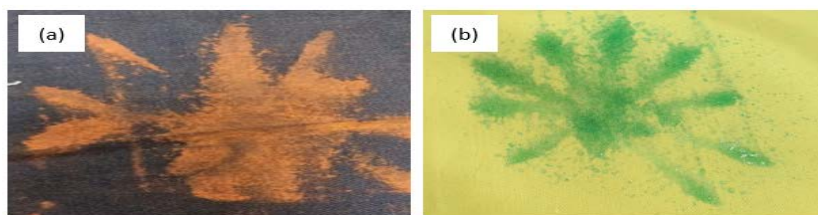


Figure 3. Water-repellency test results of fabric- (a) Navy fabric, (b) Yellow fabric

3.3 Flame retardancy test

According to the ISO 6330 standard, after 5 washes and 5 dryings, the sample was conditioned at 65% RH (relative humidity) and 20°C. The tests were performed using a Devotrans DVT HG DLC model device, with the flame positioned perpendicular to the horizontal fabric. The flame length was adjusted by the standards and applied to the sample fabric for 10 seconds. Following the test, no flame or dripping was observed on the fabric. Carbonization was noted, but hole formation did not exceed 5 mm, and there was no melting or dripping. The flame and ember combustion lasted for no more than 2 seconds, resulting in an A1 rating. Figure 4 presents flame retardancy test results in images.

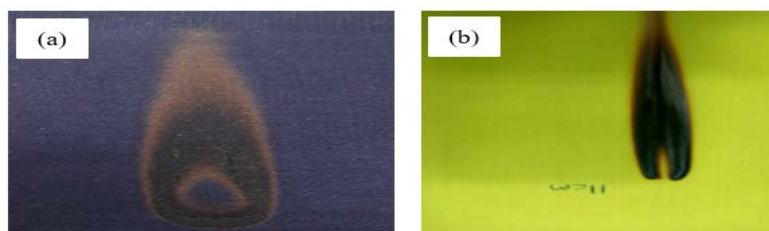


Figure 4. Flame retardancy test results of fabric- (a) Navy fabric, (b) Yellow fabric

3.4 Abrasion resistance and crocking fastness tests

The fabric's abrasion resistance was assessed using the Martindale Abrasion Tester, and no visible signs of abrasion were detected up to 25,000 cycles in all directions (weft and warp). Additionally, a crocking fastness test (wet and dry) was conducted on the fabric in compliance with the AATCC8 Standard. The dry crocking fastness of all samples ranged between '4 and 5', while the wet crocking fastness was consistently '3'. There were no notable variations in crocking (rubbing) fastness, attributed to the fabric's 2/1 twill construction (warp-faced).

4. Conclusion

The study successfully developed protective fabrics with high flame resistance while maintaining durability. The test results confirm their suitability for protective clothing in hazardous environments, offering improved safety and performance. These findings highlight the potential of these fabrics for use in protective clothing across various high-risk industries, such as firefighting, military, and industrial applications. Future research may highlight optimizing the balance between protection and comfort and exploring sustainable alternatives for improved environmental impact.

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A NEW METHODOLOGY TO ASSESS THE SAFETY OF MODIFICATIONS TO FIRE PROTECTIVE CLOTHING

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Abstract: Fire protective clothing (FPC) is vital in protecting firefighters against hazards. However, the protection provided by FPC depends on the fit. As a growing minority in firefighting, women have difficulty finding FPC that is well-fitted, resulting in issues of comfort, safety, and functionality. As a result, many women are altering their FPC to improve the fit and function. However, the impact of these alterations on safety is unknown. This project introduces a new, multimodal methodology to assess the safety of these modifications. Interviews and surveys with female firefighters are first conducted to assess the types of modifications and their perceived efficacy in improving FPC fit and function. Next, the performance of mock-ups of modified garment elements are assessed based on NFPA 1971 to evaluate the safety of the alterations. This methodology presents a way to assess the safety of customized garments, ensuring safety without compromising the comfort of the wearer.

Keywords: Fire Protective Clothing, Female Firefighters, Modification, Customization, Safety

1. INTRODUCTION

Firefighters perform a high-risk job, facing chemical, thermal, physical, and biological hazards in uncontrolled environments (Nayak et al., 2014). Fire protective clothing (FPC) is critical in protecting firefighters against these hazards. However, poorly-fitted FPC may also make work more dangerous due to a restricted range of motion (Huck, 1991), increase risk of heat stress (Boisvert et al., 2024; Liao et al., 2001), and increased risk of carcinogen exposure (McQuerry et al., 2023). Thus, well-fitted FPC is critical in ensuring wearer safety (Castillo, 2015). The current sizing system for FPC is based on male proportions (Flynn et al., 2017). Thus, female firefighters struggle to find appropriately fitted FPC, resulting in increased safety risks (Hulett et al., 2008; Liao et al., 2001; McQuerry, 2020). To overcome the poor fit of FPC for female firefighters, pattern and garment alterations have been reported (Keefe, 2022; Park & Hahn, 2014). However, the impact of these modifications on the safety of the FPC is not well understood. The objectives of this research are to develop a methodology which can assess the types of alterations performed by female firefighters on their FPC, the efficacy of alterations in improving the fit and function of the FPC, and the impact of alterations on the safety of the FPC.

2. METHODS

This research uses a multimodal approach, starting with qualitative data collection through interviews of female firefighters, the development of a larger-scale survey, and finally uses mock-ups of modified garment elements to assess the safety of alterations. Participant data collection has been approved by the University's Research Ethics Board.

2.1 Interviews

Qualitative interviews were conducted with n=5 volunteer and career structural female firefighters in Alberta, Canada. Participants were asked to bring their FPC to the interview, and to share information on the fit of the FPC, their satisfaction with the FPC in terms of comfort and functionality, and the modifications they have made to their FPC. Data collection included interview recordings and photographs of the modified FPC. Data will be analysed by coding for major themes.

2.2 Survey

Based on the data collected during the interviews, a broader-scale survey will be developed to assess the types of modifications that are being performed by female firefighters across Canada

and the United States. The survey asks participants to rate their satisfaction with various elements of their FPC and equipment using Likert scales. In addition, the survey includes open-ended questions focused on modifications. Survey data will be analysed using descriptive statistics and correlations for the quantitative questions, and thematic coding for the qualitative questions. The results of the survey and interviews will be used to determine the types of alterations most commonly performed on FPC by female firefighters, as well as the perceived efficacy of these alterations in improving the fit and function of the FPC.

2.3 Prototype Development

Mock-ups of the altered garment elements will be produced using similar materials and techniques to the modifications described in the interviews and surveys. These mock-ups will be used for safety assessment, allowing for destructive tests to be done.

2.4 Safety Assessment

The safety of the modification mock-ups will be assessed against standard tests in NFPA 1971 (2018). Tests will include flame resistance (ASTM D6413/D6413M, 2022), heat and thermal shrinkage resistance (ISO 17493, 2016), thread melting (NFPA 1971, 2018, sec 8.11), cleaning shrinkage resistance (AATCC 135, 2010), seam breaking strength (ASTM D1683/D1683M-22, 2022), and moisture barrier seam resistance to water penetration (NFPA Method 5512). The measured performance of the modification mock-ups will be evaluated according to the criteria in NFPA 1971.

3. RESULTS AND DISCUSSION

3.1 Interviews

Five participants with varied experience in volunteer and career firefighting were interviewed. Participants discussed their experiences with both custom fitted gear and communal gear, with varying levels of satisfaction for both types. Advocacy and solidarity among female firefighters in the fire departments were identified as themes which positively impacted access to well-fitted FPC. In contrast, communal gear pools and turnout gear sharing were identified as major barriers for female firefighters in accessing well-fitted FPC, especially during training and early career. In terms of modifications made to the FPC, several themes were identified including changes to undergarments, PPE compatibility issues, in-process modifications to movements and gear, manufacturer-approved modifications, and resistance to modifications. The results indicate that access to well-fitted FPC has improved over the years as more women have entered the fire service, but modifications are still often needed in order to cope with wearing FPC that was designed for a male physiology.

3.2 Future work

Moving forward, the use of this methodology will combine qualitative user experience data with quantitative textile test methods to bridge the gap between human factors and material testing. Outcomes of the project will include a list of modification methods that can be used by individuals, certified repair professionals, and FPC manufacturers to improve the fit of FPC for those who do not fit within the standard sizing range, such as female firefighters, without compromising the safety of the FPC.

4. CONCLUSION

This work aims to develop a new methodology that can be used to assess the safety of modified FPC by building on the current standards for FPC in North America. Protective clothing requires a constant balance between comfort and protection. Individual modifications, especially among minorities, highlight the need for specific human factors to be included in protective clothing design. Although focused on modifications made by female firefighters, this methodology could be adapted to other protective clothing users who do not fit within the standard size range.

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BENCH-SCALE ASSESSMENT OF PHYSICAL AND THERMOPHYSIOLOGICAL PROPERTIES OF SPORTSWEAR FABRICS INFLUENCED BY GARMENT FIT AND HUMAN DYNAMIC ANTHROPOMETRY

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Abstract: *This study aims to employ experimental approaches to develop a more ecologically valid assessment of fabrics for the determination of physical and thermophysiological properties of sportswear fabrics influenced by garment fit and human dynamic anthropometry, which cannot be reasonably approximated by the existing test methods and standards. For this purpose, a bi-axial (X-Y axes) fabric extension frame was developed, and fabrics' physical and thermophysiological properties were determined at 0% to 70% extension. In addition, fabrics' tensile properties were determined at elevated temperatures, simulating human skin. Statistical analysis was employed, and the effect of bi-axial stretch on the physical and thermophysiological properties of the sportswear fabrics, as well as the tensile properties of the fabrics at simulated skin temperature, were analyzed and discussed. The findings from this research can assist in optimal fabric selection with desired properties in conditions relevant to exercise activities and occupations where ergogenic properties are crucial.*

Keywords: *Physical and thermophysiological properties, bi-axial fabric extension frame, sportswear, garment fit, dynamic anthropometry.*

1. INTRODUCTION

One of the most important characteristics of performance, outdoor, and sports-inspired wear is freedom of movement while maintaining other aspects of comfort (Ashdown, 2011). Clothing with interspersed contacts and gaps with human skin is required to elongate, slip, and/or provide space for skin strain. When clothing restricts the skin's dimensional change during joint movement, it reduces manoeuvrability and causes body movement discomfort, manifesting in day-to-day activities and exercise. Conversely, garments should provide appropriate compression and deliver ergogenic benefits, such as increased force, muscular power, strength, and movement accuracy, while enhancing post-exercise recovery and improving proprioception. In dynamic anthropometry, sportswear with optimum compression may further contribute to improved blood circulation, alleviate muscle fatigue, reduce post-exercise trauma and perceived muscle soreness, and shorten recovery time (Mason et al., 1999). As such, fabric properties should be determined under realistic dimensional extensions (0%<) to reflect a more ecologically valid assessment of fabrics' properties influenced by garment fit and human dynamic anthropometry, which cannot be reasonably approximated by the existing test methods and standards. This study intends to measure the physical and thermophysiological properties of the fabrics, considering the deformation of the fabrics due to body movement and garment fit, thus better approximating real-world garment performance.

2. MATERIALS AND METHODS

2.1 Fabric Systems

The study was conducted on sportswear fabrics primarily designed for next-to-skin layers in garments, featuring a range of structural characteristics (Table 1).

2.2 Bi-Axial Fabric Extension Frame

An in-house biaxial fabric extension frame was developed to enable fabric extension in both the X (warp/wale) and Y (weft/course) directions. The frame supports a combined extension range of 0% to 70%, per the fabric extension requirements specified in ASTM D4964-96(2020).

2.3 Physical and Thermophysiological Properties

The physical properties of the fabrics were determined using the bi-axial frame extension, ranging from 0% to 70% in both X and Y directions. The physical properties include fabric count (ASTM D3775-17, ASTM D8007-24, and ISO 7211-2:2024), fabric mass (ASTM D3776/D3776M-20), fabric thickness (ASTM D1777 19), and fabric air permeability (ASTM D737-18). Fabric samples were also tested under uniaxial tension (ASTM D4964 96(2020)) using an Instron equipped with a thermal chamber to evaluate the effect of temperature (21°C vs. 35°C) on fabrics' tensile properties. Fabrics thermal and evaporative resistances (ASTM F1868) and their water-wicking and drying behavior were evaluated using an integrated chamber sweating hot plate (Lahiri et al., 2024) using the bi-axial frame extension at 0% to 70% in both X and Y directions.

3. RESULTS AND DISCUSSION

The results show that the stretched fabrics' physical and thermophysiological comfort properties differed from the values observed in a relaxed state. These changes were more pronounced at fabric extensions of 50% and above in both the X and Y directions, specifically when the elastomeric textiles are more dominant in the fabric's fiber content. Fabric structure was also a contributing factor and influenced the measured physical and thermophysiological comfort properties of the stretched fabrics. In addition, the tensile properties of the fabrics measured at an elevated temperature of 35°C were significantly different from those obtained under standard atmospheric conditions (typically 21 ± 2°C and 65 ± 5% relative humidity, as defined by existing textile testing standards) indicating that temperature has a meaningful impact on fabric tensile behavior (Table 1).

Table 1. Fabric systems' modulus at 30%, 50%, and 70% extension, tested at 21°C and 35°C.

Fabric code	Fiber Content	Fabric Structure	Temp (°C)	Fabric Extension at x%		
				30%	50%	70%
S-1	69% Nylon, 31% Elastane	Weft knitted-Purl	21 °C	0.24 (0.03)	0.42 (0.02)	0.53 (0.04)
			35 °C	0.28 (0.01)	0.54 (0.01)	0.59 (0.02)
S-2	78% Nylon, 22% Elastane	Weft knitted-interlock	21 °C	0.41 (0.01)	0.7 (0.06)	0.88 (0.18)
			35 °C	0.47 (0.06)	0.77 (0.05)	1.16 (0.39)
S-3	56% Polyester, 33% Nylon, 11% Elastane	Weft knitted-Rib	21 °C	1.06 (0.18)	6.4 (0.17)	12.55 (0.49)
			35 °C	2.04 (0.14)	11.3 (0.11)	14.35 (0.29)
S-4	77% Nylon, 23% Elastane	Weft knitted-interlock	21 °C	0.22 (0.01)	0.41 (0.02)	0.71 (0.06)
			35 °C	0.24 (0.01)	0.55 (0.04)	0.96 (0.00)
S-5	73% Nylon, 27% Elastane	Warp knitted-Tricot	21 °C	0.41 (0.07)	1.47 (0.18)	6.81 (0.34)
			35 °C	0.54 (0.05)	2.52 (0.69)	14.71 (1.33)

4. CONCLUSION

The findings from this research can assist in optimal fabric selection, including desired properties in conditions relevant to exercise activities. These findings could also be relevant to the development of functional ensembles with enhanced properties for occupations such as the Armed Forces, frontline workers, firefighters, industrial workers, first responders, and other occupations where the garment's ergonomic properties are crucial.

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ERGONOMIC IMPACTS OF BALLISTIC VESTS ON THE MOBILITY OF FIREFIGHTERS

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Abstract: *In this study, we investigate the possible adverse effects on firefighters' mobility when they wear ballistic vests. As the number of gun-related incidences, involving firefighters and medical emergency responders, has increased in the US, the use of ballistic vests in combination with their normal PPE has also increased. However, an additional level of protection may impair their mobility. To evaluate and quantify their impact on mobility, we test the effects of wearing ballistic vests by firefighters in three categories including the range of motion (ROM), balance ability, and time to complete tasks. These experiments will be done for different ensembles and wear scenarios to investigate the ergonomic influences of each on mobility.*

Keywords: *Firefighters' mobility, ballistic vests, range of motion, balance ability, timing tests.*

1. INTRODUCTION

There is an increased need for firefighters in the US to wear ballistic protective vests in combination with their normal PPE. Since ballistic vests are bulky and heavy, they may negatively impact the firefighters' mobility, function, and effectiveness. Ergonomic impacts of wearing turnout suits on firefighters' movements have been addressed in a standard test method and some previous studies (ASTM F-3031-17; Coca *et al.*, 2010; Hur *et al.*, 2013; Ciesielska-Wróbel *et al.*, 2017). However, in this study, we include the ballistic vests in the firefighters' ensembles, which has rarely been addressed in previous studies. It is required to measure alterations in their range of motion (ROM), balance ability, and time to complete tasks to assess mobility (Tochihara *et al.*, 2022). In addition to these traditional ROM-type tests, we will evaluate new methods to quantify the impact of PPE on mobility to obtain further insights into the impact of PPE on ergonomics.

2. METHODS and EXPERIMENTS

Participants and Ensembles

For this study, eight healthy male subjects participated. According to Son *et al.* (2014), we selected our participants among real, active firefighters from regional fire departments to ensure reliable results. They came to our laboratories for the experiments in different sessions, and each visit took less than three hours. The firefighter used ensembles in different wear scenarios, including a) the station uniform as a control, b) the station uniform plus turnout suits, c) wearing a ballistic vest over the turnout jacket, and d) wearing a ballistic vest under the turnout jacket.

Range of Motion (ROM)

Ballistic vests may restrict the wearer's range of motion (ROM). Previous studies have used different methods to measure ROM for firefighters such as goniometry. This study used the motion capture system to evaluate torso movements, such as lateral bending, rotation, flexion, and extension.

Balance Ability

Wearing heavy and bulky garments may cause a displacement of the body's center of mass. Maintaining balance for firefighters who wear ballistic vests could be challenging. Balance ability has to be tested in static and dynamic postures. A foot pressure mapping plate was used to evaluate postural sway in standing and static conditions. Also, we designed a narrow platform with obstacles, and the pace at which participants walk along this platform is associated with their dynamic balance ability.

Time to Complete Tasks

We simulated a set of experiments firefighters perform in their jobs involving their upper extremities. We measured the time it took them to complete the tasks with different ensembles to assess how wearing ballistic vests affected their mobility. The tasks included lifting boxes, dragging a manikin, rolling a hose, crawling, and searching by hand.

3. Results

We are in the middle of data collection and analysis. To address the referees' comments, we announce that we will definitely have the results ready in May and present them at the conference. The results will include comparing the static and dynamic balance data, as well as the range of motion (ROM) and time to complete tasks data.

For the static balance, we collected data from human subjects to measure the excursion of the center of pressure (COP) and the COP ellipse area (mm²) which are associated with the balance ability. We are analyzing the static data to find which wearing combinations are significantly different from others in static balance. Also, the velocity of subjects walking along the narrow platform is collected as a dynamic balance indicator. the final analysis will demonstrate how they are consistent with static balance test results.

4. DISCUSSION

Wearing personal protective equipment (PPE) by firefighters could reduce their job efficiency and functionality. Since wearing ballistic vests may significantly impair firefighters' mobility. In this study, we found some differences in ROM, Balance ability, and time to complete tasks for some wear combinations and ensembles. We are in the process of completing data collection and analyzing data to find out how much these differences are significant.

5. CONCLUSION

Firefighters are required to be protected from firearms. Ballistic protection equipment is inherently bulky and heavy. Consequently, wearing a ballistic vest could negatively affect firefighters' mobility. In this study, by testing ROM, balance ability, and time to complete tasks of human subjects in different firefighter ensembles and wearing conditions, we understand how wearing ballistic vests impacts the mobility of wearers and which wear scenario is better regarding the mobility impairments.

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A NOVEL METHOD FOR MEASURING AIR GAP THICKNESS UNDER THE TURNOUT GEAR DURING WALKING

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Abstract: *In this study, a novel method was developed to calculate the dynamic air gap thickness between the human body and the turnout gear. To simulate the continuous air gap variation, a complete gait cycle was separated into five phases, and each time-point posture was scanned by twelve male males and then replicated in a geometric model. Interpolation technique was employed to predict the air gap thickness curve during walking. The results found that the air gap fluctuated as a sine curve during walking and varied in different body regions. The minimum air gap occurred at the leg during the toe off phase. The findings suggested that the asymmetrical leg position may cause the air layer to be distributed unevenly, which would decrease the thickness of the air gap. The design of turnout pants should be focused on leg flexibility.*

Keywords: *Air gap, firefighters, turnout gear, 3D body scan.*

1. INTRODUCTION

The air gap entrapped in the garment could characterize the multifaceted relationship between the body and the garment (Loker et al., 2005), which is a crucial indicator for assessing how well turnout gear fits firefighters. The three-dimensional (3D) body scanning and 3D reconstruction technology currently provides an effective method to visualize and quantify the air gap (Lu et al., 2014; Mert et al., 2017; Wang et al., 2019). Nevertheless, previous body scanning research generally scanned subjects when they were standing upright and presuming the air gap was fixed or stationary (H. Song et al., 2010). Turnout gear is worn in various firefighting activities, and the air gap maintains dynamic changes due to the joint movement (Wang et al., 2024). Currently, real-time and continuous measurement of point cloud data is still impossible due to technical restrictions. The purpose of this study was to calculate the dynamic air gap between the turnout gear and the real human body during walking.

2. MATERIALS AND METHODS

Figure 1 shows the procedure for determining the dynamic air gap, including the scanning posture selection, 3D body scanning, scan data processing, air gap extraction, and dynamic air gap calculation.

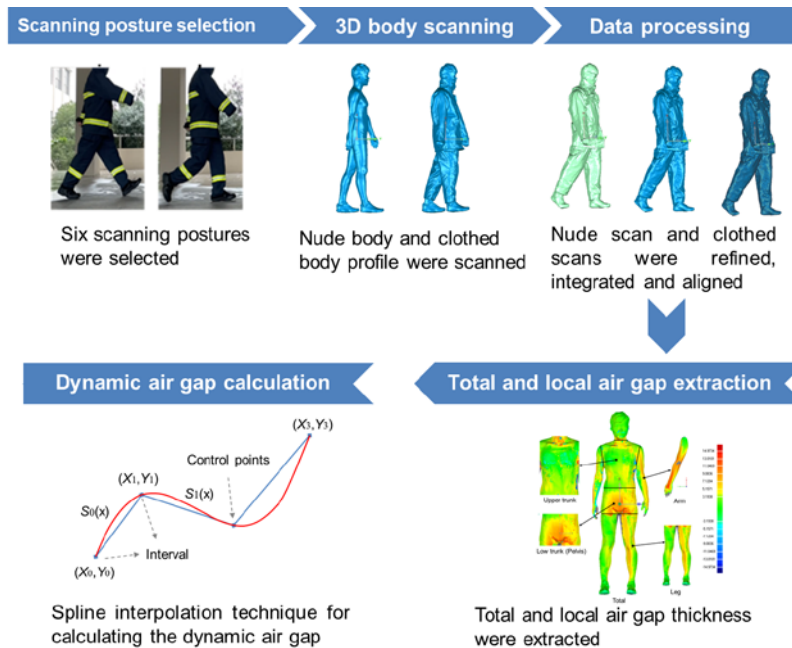


Figure 1 Procedure for determining the dynamic air gap

2.1 SUBJECTS AND INCLUSION CRITERIA

Twelve healthy males were recruited for the experiment and they have similar physical characteristics (age: 24.40 ± 2.00 years, height: 174.60 ± 2.40 cm, mass: 67.00 ± 3.50 kg, BMI = 22.00 ± 1.00 kg/m², body fat percentage = $16.50 \pm 3.40\%$). Similar physical characteristics were selected to reduce variability and ensure consistency and comparability in the results, since air gap parameters are significantly influenced by body shape and size. All subjects were healthy, non-smokers, and with no history of musculoskeletal or cardiopulmonary conditions. The research was approved by the Shanghai Yangzhi Rehabilitation Hospital (Shanghai Sunshine Rehabilitation Center) (SBKT-2022-008).

2.2 3D BODY SCANNING AND PROCESS

A 3D body scanner (Human Solutions GmbH, Kaiserslautern, Germany) was used to acquire the outer shape and dimensions of the subject at a high resolution of 300 pixels/cm², and generate a .stl CAD file of the outer surface of the subject. As illustrated in Figure 1 (a), six phases of a complete gait cycle (heel strike, foot flat, mid stance, heel off, initial swing, and mid swing) were divided and scanned to simulate the walking. These postures were carefully chosen to cover key phases of the gait cycle, ensuring that the results remain relevant and applicable to real-world walking scenarios.

The turnout gear used meets the GA621 (2006) standard was a three-layer construction composed of an outer heat resistant shell, a water-resistant moisture barrier layer, and a thermal liner. Each subject was scanned twice times for each posture (see Figure 1(b)), once wearing the underpants (nude scan), and the other wearing the test ensembles (clothed scan) in sequence. Some posture-fixing devices were created to keep the subjects' feet, arms, and legs in the same position and angle during nude and clothed scans.

2.3 EXTRACTION AND CALCULATION OF AIR GAP THICKNESS

To extract the air gap thickness, both the nude and clothed images were imported into Geomagic (version 12.0, Geomagic Inc., Morrisville, NC) for processing, merging, and aligning. The whole body and the local (arm, upper trunk, pelvis, and leg) air gap thickness at each scanning posture was extracted. The cubic-spline technique was employed in this study to predict the air gap variation curve during walking. The extracted air gap in each posture was fitted to obtain 60 interpolation nodes and interpolating fitting curves. For easy identification, the total, arm, upper

trunk, pelvis, and leg air gap thickness were abbreviated to AG_{Total} , AG_{Arm} , AG_{Trunk} , AG_{Pelvis} , and AG_{Leg} , respectively. The detailed process procedure is shown in Wang and Wang (Wang et al., 2024).

2.4 STATISTICAL ANALYSIS

Statistical tests were performed using the SPSS software (version 22, SPSS Inc., IBM, Armonk, NY, USA) with a significance set at $p < 0.05$. One-way analysis of variance (ANOVA) was performed to assess differences in the air gap thickness between different postures.

3. RESULTS AND DISCUSSION

Figure 2 shows the air gap variation curve and thickness during a complete gait cycle. The curve fluctuated as the sine function and presented two peaks and two valleys, which was consistent with the variation trend of the joint motion in the sagittal plane.

The difference in air gap thickness between the peaks and valleys reached a maximum of 1.20 cm. Statistical analysis showed that air gap thickness was significantly different at six scan postures (CC: $F=18.950$, $p < 0.001$, $\eta^2=0.716$; LS: $F=19.227$, $p < 0.001$, $\eta^2=0.719$; MS: $F=14.528$, $p < 0.001$, $\eta^2=0.660$; TS: $F=7.624$, $p=0.005$, $\eta^2=0.504$). It was found that the maximum air gap occurred near the foot flat (Posture 2, 3.16 ± 0.13 cm), while the smallest value occurred near the toe off (Posture 5, 2.81 ± 0.02 cm). The mid swing belongs to the one foot swing phase, during which one leg is standing and the other leg is most flexed or extended (Park et al., 2015). Asymmetric posture may lead to uneven distribution of the air layer, resulting in a minimum thickness (Kim et al., 2002; Mert et al., 2015; Wang et al., 2019).

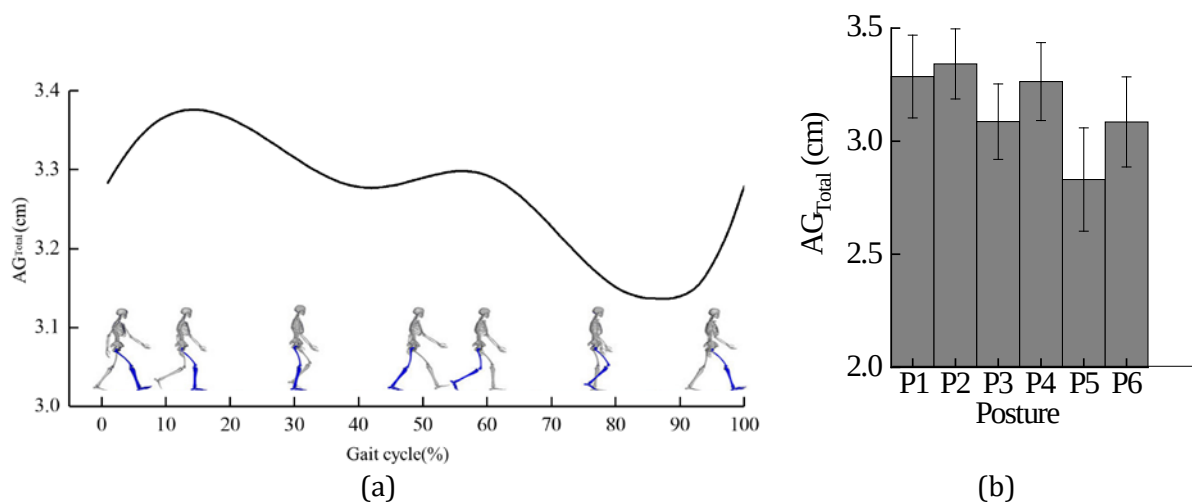


Figure 2 The air gap curve and thickness during a complete gait cycle

Figure 3 shows the air gap distribution and variation at the arm, trunk, pelvis, and leg. It was observed that the air gap was not evenly distributed over the body, which was consistent with previous studies (Frackiewicz-Kaczmarek et al., 2015; Hu et al., 2019; G. Song, 2007). The arm had the largest mean air gap (3.39 ± 0.52 cm), followed by the pelvis (3.29 ± 0.24 cm) and trunk (3.11 ± 0.92 cm), while the thigh (2.82 ± 0.69 cm) was the smallest. This may relate to greater leg abduction that would drive the air gap to move and finally cause the air gap unevenly distributed at the leg. Based on this finding, our study suggested that the design of turnout pants should be focused on leg flexibility, and avoid redundant ease that may cause unnecessary bulkiness.

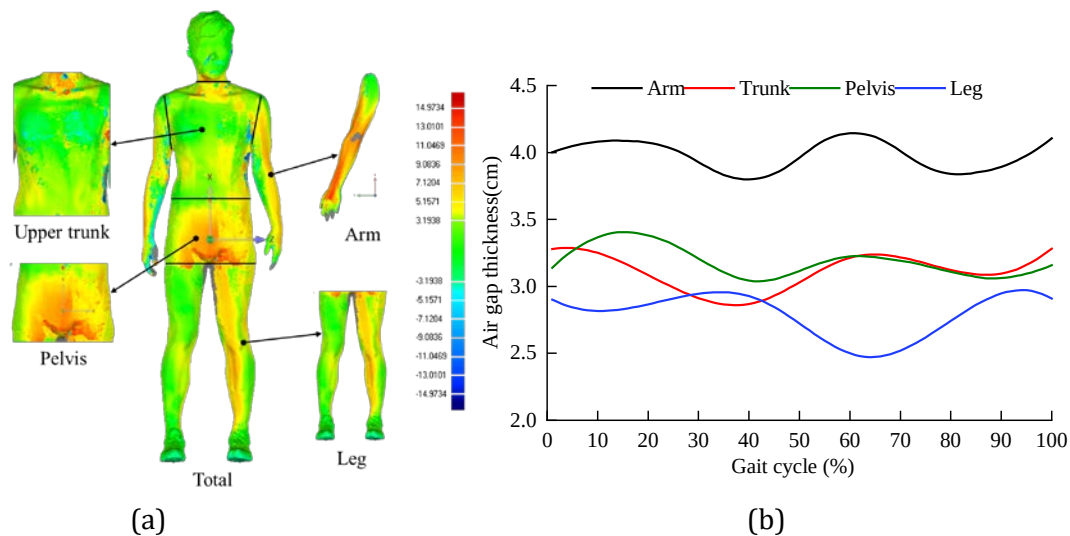


Figure 3 The local air gap distribution and variation

The current study has some limitations that should be mentioned. Considering the effects of different motions on the garment restriction are not the purpose of this paper, we only measured the walking in this study, which may restrict the results' application. Furthermore, the physical characteristics of the 12 subjects were similar. Future research is necessary to test more complex firefighting-simulated tasks, such as climbing, rescuing, and filling hoses. More firefighters with different physical characteristics should be recruited in the future, to propose more specific instructions on ergonomic design and use of firefighters' PPE.

4. CONCLUSION

In this work, a novel method for characterizing the dynamic air gap thickness inside the turnout gear was developed by combining 3D body scanning, 3D image reconstruction, and the cubic-spline technique. The results found that the air gap fluctuated as a sine curve during walking and varied in different body regions. The minimum air gap occurred at the leg during the toe off phase. Asymmetrical posture may cause the air layer to be distributed unevenly, which would reduce the thickness of the air gap. Leg flexibility should be the primary objective of turnout pants design.

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PARA-ARAMID MECHANICAL RECYCLING AND VALORISATION OPPORTUNITIES

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¹Citeve

Abstract: *Considering the European Commission's 2030 objectives for the textiles sector, it is imperative to produce and integrate recycled textiles free of harmful substances, reducing their environmental impact and promoting circularity. To meet this challenge, this study proposes the recycling of high-performance technical fibres, p-aramid, using mechanical recycling methods. The process of recycling pre-consumer waste was evaluated, producing two studies on the valorisation of these products (yarns and nonwovens). This work presents itself as the beginning of the valorisation of these materials, contributing to their re-entry into the production cycle, with promising results of minimal loss of quality.*

Keywords: *P-aramid, sustainability, mechanical recycling, yarns, nonwovens.*

1. INTRODUCTION

Following the main objective of the European Commission strategy for 2030 regarding textile sector, it is imperative that textiles are made with a substantial proportion of recycled fibres, are free from hazardous substances, and produced in accordance with practices that uphold social and environmental right (European Commission, 2022). The study of fibre recycling is therefore of paramount importance, with technically more resistant fibres, such as p-aramid, being among the most challenging. P-aramid is a high performance, heat-resistant synthetic fibre with the chemical formula $(C_8H_4Cl_2O_2.C_6H_8N_2)_x$. It has a tensile strength of approximately 3.7 GPa and retains integrity at temperatures as low as -150 °C, being flame-resistant, and it decomposes at around 500 °C. P-aramid's applications span from personal protection to sports equipment, and construction (Elgohary, 2024). In alignment with European guidelines, this study aims to overcome recycling challenges, targeting the recycling process of p-aramid pre-consumption waste fibres and its valorisation into yarns, contemplating 100% recycled and mixing with virgin fibres; and, 100% recycled nonwovens, promoting sustainability and circularity.

2. MATERIALS AND METHODS

2.1 Materials

Pre-consumer p-aramid rovings and yarns waste materials and p-aramid virgin fibres were used for this study.

2.2 Characterisation

2.2.1. Yarns

The produced yarns were characterised in accordance with EN ISO 2060:1995. The average yarn count was determined by testing three samples. Tensile testing was conducted in accordance with EN ISO 2062:2009, employing Uster Tensorapid 5 equipment.

2.2.2. Nonwovens

The nonwoven samples produced were characterised in terms of thickness, mass per unit area and mechanical properties. The average thickness was calculated by measuring the thickness at three random points on the specimen using the SYLVAC S229 thickness gauge (Karl Schröder, Germany). The mass per unit area was determined by cutting a known area representative of the sample and then weighing it. The procedures for determining tensile strength and elongation, puncture resistance and bursting properties followed EN 29073-3:1992, EN 863:1995 and EN ISO

13938-1:2019, respectively. The air permeability of the nonwovens was determined according to EN ISO 9237:1995.

2.3 Recycling Yarns Production

The mechanical recycling of aramid waste started with the material processing in the Laroche STARCUT cutting machine (France), then the material was opened and cleaned, forming a fibrous lap sample in the Laroche Cadette 1000 fibre extraction equipment (France). The recycled fibres from aramid rovings (AR) and aramid yarns (AY) waste were used with virgin p-aramid fibres to produce 100% recycled yarns and a yarn blend of 85% virgin and 15% recycled fibres. To achieve this goal, the following operations were conducted: a) Batches of staple fibres were manually opened and carded using a Mesdan-lab Felt Carder 337A (Italy) to form a homogeneous web; b) Samples were rolled into a long sliver which was drawn into rovings on a Mesdan-lab Stiro roving lab 3371; c) Rovings were then spun into yarn on a Mesdan-lab Ring lab 3108A ring spinning machine; d) Yarn winding was performed on a Savio Loepfe YarnMaster® Zenit+ (Switzerland).

2.4 Recycled Nonwoven Production

The nonwoven production with recycled fibres resulting from the aramid rovings and yarns recycling processes was studied using a carder to produce a web and a needle punching machine (Technoplants Technologies for nonwoven, Italy). This resulted in the production of eight samples varying in the quantity and type of raw material (AR/AY) and needle parameters (speed, needle penetration/cm², stripper and penetration depth).

3. RESULTS AND DISCUSSION

3.1. Recycling Yarns

This study resulted in the development of four recycled yarns and a mixture (85% virgin and 15% recycled yarn). Table 1 displays the linear density (Ne) and tenacity (Rkm) of the obtained results.

Table 1. Yarn count and tenacity testing results.

Sample	Composition	Yarn Count (Ne)	Tenacity (Rkm)
Y-AR1	100% recycled p-aramid rovings waste	30	35
Y-AR2	100% recycled p-aramid rovings waste	7,8	28
Y-AY1	100% recycled p-aramid yarns waste	26	30
Y-AY2	100% recycled p-aramid yarns waste	6,5	30
Y-85V15R	85% virgin p-aramid/15% recycled p-aramid rovings waste	20,1	52

As demonstrated in Figure 1, the 100% recycled yarn produced with p-aramid rovings waste (Y-AR1) exhibited superior breaking strength in comparison to the other 100% recycled yarns. Concerning elongation, higher values were achieved by sample Y-AR2, which possesses a lower yarn count, thereby explaining these results. The (85/15)% blend demonstrated superior mechanical performance when compared to all the other yarns, which proves the enhancement effect of mixing recycled with virgin fibres. A comparison of the obtained values for the 100% recycled yarn Y-AY1 (26 Ne, 30 cN/tex breaking strength and 3% breaking elongation), with a virgin yarn of a similar yarn count (26,6 Ne, 66,3 cN/tex breaking strength and 3,57% breaking elongation – Şardağ and Erkurt, 2023) clearly demonstrates the considerable potential for enhancing the characteristics and a wide range of potential applications for this recycled material in several sectors. In conclusion, the most promising 100% recycled yarn is Y-AR1.

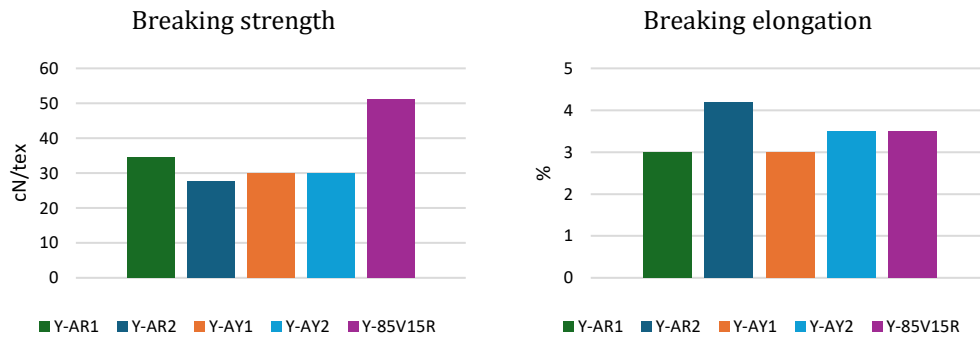


Figure 1. Produced yarns tensile testing results.

3.2 Nonwoven Results

The analysis of the recycled nonwoven samples (Table 2) shows significant differences in their mechanical and physical properties. NW-AY2 stands out as the strongest overall, with the highest tensile strength (CD), burst strength and mass per unit area, indicating its suitability for applications requiring durability and resistance to pressure. NW-AY5 offers the highest air permeability and puncture resistance, making it ideal for breathable yet everlasting applications. NW-AY6 stands out given its high tensile and burst strength which is due to its web orientation. As for elongation, the samples with highest values are NW-AY5 and NW-AR1, suggesting they are the most ductile. The correlation between mass per unit area and mechanical properties is evident, with heavier samples generally having higher strength. However, air permeability does not follow a direct trend as some stronger materials (e.g. NW-AY2) have lower permeability. In terms of mechanical properties, a general analysis shows that nonwovens produced with yarn waste have superior properties compared to samples produced under the same conditions but with different raw materials (roving or yarn waste).

Table 2. Nonwovens characterisation results.

	Thickness (mm)	Mass per unit area (g/m ²)	Tensile strength (CD)	Elongation at maximum strength (CD)	Tensile strength (MD)	Elongation at maximum strength (MD)	Puncture resistance (N)	Burst strength (kPa)	Air permeability (l/m ² s)
NW-AY1	2,1	180	460	22,5	144,2	91,5	96	1890	800
NW-AY2	2,8	290	962,9	24	218	73	151	>5000	448
NW-AY3	2,7	199	426,9	21,5	56,4	132	60	2010	1040
NW-AY4	2,8	186	219,1	26,5	70,3	136	130	1630	1340
NW-AY5	3,9	173	133,3	40	27,5	134,5	157	2010	1410
NW-AY6	2,4	246	436,8	23,5	322,9	44,5	150	3490	620
NW-AR1	2,4	171	209,9	30,5	39,1	163,5	69	1300	1130
NW-AR2	2,8	238	220,9	31,5	179,5	51	86	1740	720

*MD (Machine Direction); CD (Cross Direction)

4. CONCLUSION

The present study demonstrates that even highly resistant technical fibres can be recycled and reused for other applications, thereby reducing waste and promoting sustainability. With promising results, this study signifies an important advancement in the development of higher quality recycled fibres, ensuring their circularity and the sustainability of the textile sector.

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TOWARDS SUSTAINABLE PERSONAL PROTECTIVE EQUIPMENT: EXPLORING MATERIAL SEPARATION AND RECYCLING METHODS

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Abstract: Textiles are among the largest emitters of greenhouse gases, with clothing textiles in particular making a significant contribution. While sustainability aspects are receiving increasing attention, workwear, in particular personal protective equipment (PPE), is often ignored in these discussions. PPE prioritizes protection, often sidelining sustainability considerations. However, because of the high-quality materials used in PPE, these should be integrated into recycling strategies. This paper examines possibilities for the reuse of PPE through the use of material recognition and separation processes. Based on the separated parts, concepts for reuse are developed that take into account the specific functionalizations of the textiles. Recyclable material flows are identified, showing that protective clothing textiles can be reused and hold added value potential. Future work should focus on the development of recycling concepts for the entire range of PPE and highly functional materials. The automation of such processes could be of particular interest for mass application.

Keywords: Recycling PPE, circular economy, laser cutting, Reuse,

1. INTRODUCTION

Personal protective equipment is designed to meet the highest standards in order to protect the lives of those wearing it. High-quality and highly functional materials are used for this purpose (Gao et al., 2010; Hursa Šajatović et al., 2022; Lou et al., 2021; Purandare & Xiang, 2024; Shi et al., 2021). Strict rules apply to the equipment components, which can quickly lead to them being withdrawn from service, whether due to the slightest damage or a product that is considered too old (NFPA). However, these rejection criteria make no statement about the overall integrity of the equipment. Large parts can still be used, not to protect human life, but the highly functional features can continue to be used in a second product life.

Material identification is one of the biggest challenges in textile recycling. Infrared spectroscopy is an established method (Cura et al., 2021). Personal protective equipment represents a particular challenge due to material mixes, functionalizations and coatings.

The objective of this work is to demonstrate the recyclability of PPE using the example of a firefighter jacket. The aim is to show to what extent infrared recycling systems are suitable and what new products can be created that utilize the remaining functionality as efficiently as possible.

2. MATERIALS AND METHODS

Investigated Firefighter Protective Equipment

A used HF Bayern 2000 firefighter overjacket is used for the tests. Care has been taken to ensure that the jacket used is not contaminated with any substances harmful to the recycling process. The jacket has a 3-layer construction, the outer protective layer consists of Nomex III with a mass per unit area of 260g/m². Underneath is a layer laminate made from 100% PES interlock and a compact PU membrane, 140g²/m that acts as a moisture barrier. The third layer is mainly used as insulation and consists of a 2-layer para-meta aramid mix in a quilted structure. A number of reflectors and Velcro fasteners are also applied to the surface. The signs of wear are mainly limited to the seams, the reflectors and the inner lining, as shown in Figure 1. The material is slightly discoloured, which is mainly due to perspiration. The selected jacket is not contaminated with any harmful substances; this must be ensured before it is introduced into recycling cycles.



Figure 1. Used firefighter jacket with various signs of use: **A**-blind reflectors, **B**-extinguishers, **C**-washed out inner lining with sweat stains, **D**-broken seams and frayed edges

SmartAutoSort system

The SmartAutoSort system, shown in Figure 2, is used to characterise and sort the firefighter clothing described above. The core components of the system are a 100 W laser for cutting operations, a Siemens controller, a linear system and an NIR camera. An optical distance sensor for height measurement and a metal detector for recognising conductive materials are also used. Different sensors, like triangulation and microwave, analyses together with the VIS camera the thickness and moisture content of the textiles without contact. Manual input of the textiles initiates an automated analysis that records visual and material-related data. A robot arm with variable grippers ensures precise handling. Based on the sensor results, the textiles are separated using a cutting laser. The handling system controls movements, sorting and transport to programmable collection points

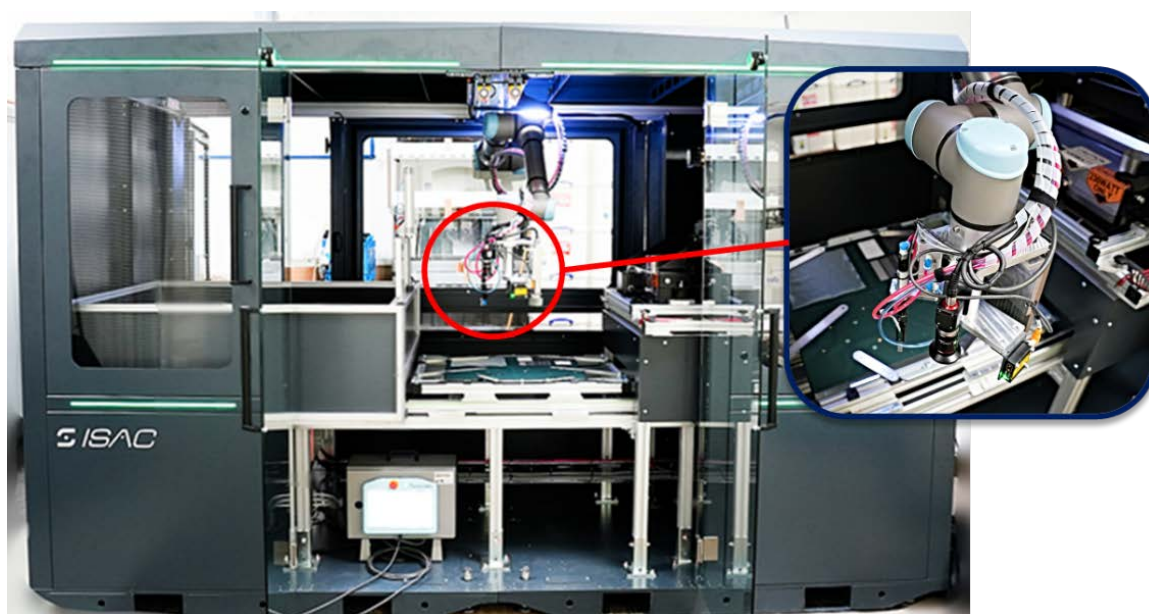


Figure 2. The SmartAutoSort system

3. RESULTS

The analysis of the separated textile areas shows which products can be manufactured, taking into account the specific functionalities of the materials. Some examples are shown in Table 1. To assess the efficiency and sustainability of the process, the proportion of the reused area in relation to the original total area was calculated. This analysis makes it possible to estimate the potential for saving resources and avoiding waste within the scope of the method under consideration.

Table 1 Possible new products

Layer	Functionalities	Products (Examples)
Outer Protective Layer	Heat-resistant, durable, high surface mass	Heat-resistant pot holders or trivets, Sturdy bags or backpacks, Protective mats for workbenches
Moisture Barrier Layer	Water resistant, protects against liquids	Waterproof covers for outdoor furniture, Reusable shopping bags, Bicycle rain covers
Insulation Layer	Thermally insulating, lightweight, breathable	Insulating picnic blankets, Warm seat cushions for outdoor furniture, Thermal padding

4. CONCLUSION

This work presented the initial results of analysing the separation process of firefighter clothing using the SmartAutoSortsort system. The efficiency and robustness of the system with regard to metals and other non-textile components were analysed and evaluated. In addition, the handling of the different layers of the multi-layer structure was analysed. It was possible to show which new products can be manufactured from the residual materials of firefighter jackets by utilising their functional properties. There is a particular need for further research into the automation of the process and the handling of complete jackets without prior disassembly.

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SPECIAL-PURPOSE CLOTHING PUBLIC PROCUREMENTS IN LATVIA: SITUATION AND PERSPECTIVES

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Abstract: *This study analyzes the legislation governing public procurement for special-purpose clothing in Latvia, with a focus on state-level institutions and the mandatory regulations of the European Union. It examines individual stages of the procurement process and incorporates insights from recent studies on the topic. Latvia's internal affairs sector comprises large institutions requiring adequate resources, including special-purpose clothing, uniforms, workwear, and personal protective equipment (PPE), to effectively perform their functions. The public procurement process in Latvia is highly regulated and aligned with EU directives. Additionally, the textile and clothing sectors across the EU face emerging challenges with the transition of Green Public Procurement (GPP) from a voluntary to mandatory framework. This study addresses the growing concerns raised by state institutions, procurement specialists, manufacturers, end-users and industry experts regarding inefficiencies and shortcomings in the procurement process. The research aims to identify and evaluate theoretical solutions for improving public procurement practices for special-purpose clothing, ensuring efficiency, sustainability, and compliance with evolving EU regulations.*

Keywords: *Special-purpose clothing, public procurement, sustainability.*

1. INTRODUCTION

In Latvia, the procurement of special-purpose clothing - including uniforms, workwear and PPE - is managed by several ministries and their subordinate institutions. These entities provide uniforms for state services, local governments and other institutions such as The National Armed Forces, The State Police, The State Border Guard, The State Fire and Rescue Service; Municipal police services, The State Revenue Service, as well as medical and sanitary workers.

Despite strict regulations at the national and European levels governing the procurement of special-purpose clothing, audits, cases of disputes and litigation, practical studies, and end-user feedback indicate problems in the processes. Addressing these challenges requires identifying procurement process shortcomings and fostering collaborative development efforts among all stakeholders to improve the system's efficiency and effectiveness.

2. PUBLIC PROCUREMENT IN LATVIA FOR SPECIAL-PURPOSE CLOTHING OF STATE-LEVEL INSTITUTIONS

The European Union Directives 2014/24/EU (Directive 2014/24/EU, 2014) and 2014/25/EU (Directive 2014/25/EU, 2014) set out the common principles, objectives and rules applicable to all public procurement in the EU Member States, including uniforms and workwear. Latvia has transposed these directives into its national legislation, mainly the Public Procurement Law (Public Procurement Law, 2017) and the Law on Procurement by Public Service Providers (Procurements Public Service, 2017), thus regulating the procurement of uniforms and workwear. The procurement process in Latvia is defined by horizontal cooperation between institutions, each fulfilling a specific functional role. However, a particular hierarchy is based on decision-making levels and influences on procurement regulation and supervision. At **strategic level** institutions such as the Parliament, the Cabinet of Ministers, and the Ministry of Finance define procurement policy directions and establish the legal framework. At the **monitoring and control level**, institutions like the Procurement Monitoring Bureau, the State Audit Office, the Competition Council, and the Central Finance and Contracting Agency ensure compliance with the law, promote transparency and maintain accountability throughout the procurement process. At the **operational level**, institutions including the Ministry of Defence, the Ministry of the Interior, the Ministry of Finance, the Ministry of Health, and local government entities execute procurement

activities in accordance with the regulations and guidelines provided by supervisory institutions. The Electronic Procurement System (EIS) serves as a centralized procurement platform, facilitating data standardization and ensuring transparent access to relevant information. The key stages of the procurement process in Latvia (Fig.1) are defined and procedurally known to all parties involved: procurement announcers, offer submitters and monitoring institutions.

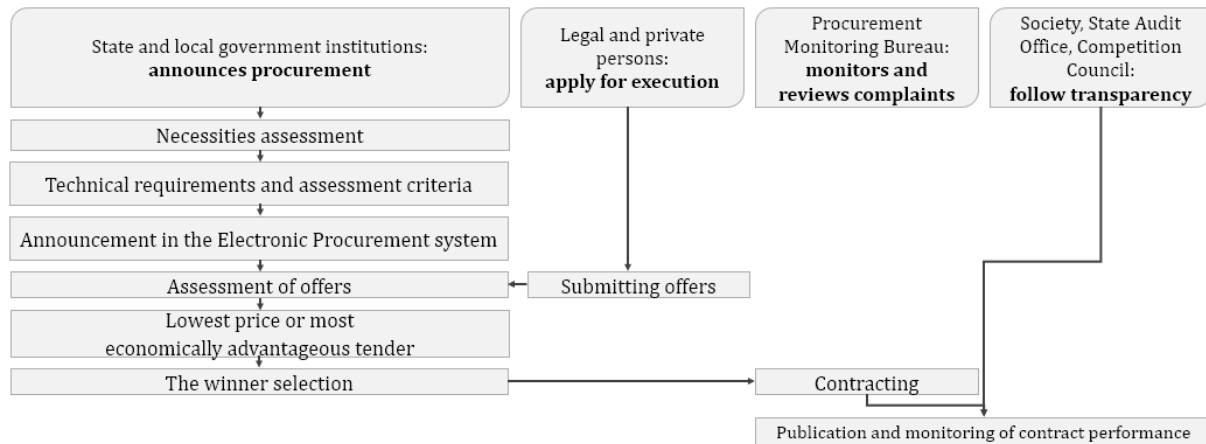


Figure 1. Main stages and stakeholders of the procurement process

To assess the situation and implement improvements, each stage should be evaluated separately and, in the system, considering the specifics of each institution.

3. GREEN PUBLIC PROCUREMENT CHALLENGES

In alignment with the European Green Deal (Green Deal, 2019) and the United Nations Sustainable Development Goals (2030 Agenda, 2015), the European Commission introduced the EU Strategy for Sustainable and Circular Textiles in 2022 (Strategy for Textiles, 2022). This strategy aims to enhance the sustainability and circularity of the textile sector by 2030. It outlines a comprehensive legal framework, with the 2024 Ecodesign Regulation (Ecodesign Regulation, 2024) as a central measure to achieve these objectives. The Regulation aims to establish Green Public Procurement as a mandatory requirement, transitioning it from its previously voluntary status. GPP requires public authorities to prioritize procurement with reduced environmental impacts over their lifecycle compared to conventional alternatives (Public Procurement for a Better Environment, 2008). For textiles, this mandate applies to uniforms, workwear, personal protective equipment (PPE) products, and accessories containing at least 80% textile fibers. As a significant driver of market demand, public procurement positions GPP as a critical mechanism to advance climate neutrality, improve resource efficiency, and foster a circular economy.

Despite its potential, the practical implementation of GPP faces several challenges. These include insufficient supply chain traceability, marked by a lack of reliable data on materials from their origin to end-of-life; material constraints, where recycled and natural fibers may not consistently meet durability or functionality requirements, particularly for special-purpose textiles; and issues with monitoring and compliance, including risks of greenwashing, unfair practices, and a shortage of skilled procurement specialists. Nevertheless, GPP represents a significant step toward aligning environmental and economic goals in the EU textile sector, facilitating the transition to sustainable production and consumption practices.

4. COMPLEXITY OF PUBLIC PROCUREMENT

At the end of 2024, the State Audit Office of Latvia completed a performance audit of the public procurement system and published two audit reports, "Problems and Opportunities for the Development of Public Procurement" (Problems of Public Procurement, 2024) and "Effectiveness of Public Procurement in the Interior" (Effectiveness of public procurement, 2024). These reports include summaries, personnel surveys, and recommendations for addressing systemic challenges.

Key findings from the audits highlighted several obstacles impeding the successful execution of public procurement. These include: a complicated and inflexible legal framework, shortage of professional procurement specialists, and the slow progress in procurement centralization.

A particularly concerning statistic revealed in the audit (Effectiveness of public procurement, 2024) indicates that during 2021-2023, over one-third (34%) of announced procurements (and/or parts) concluded without a result. Further conclusions align with various sector representatives, identifying persistent issues such as: insufficient staff capacity and expertise; limited knowledge among procurement specialists; poor-quality procurement documentation and technical specifications; unclear and non-compliant requirements; insufficient market research (suppliers, products, prices, delivery times, volumes); inadequate competence within procurement committees; lack of joint or centralized procurement efforts; failure to divide procurements into smaller parts (lots). A survey of personnel involved in public procurement indicated specific areas requiring additional training and support: assessment of offers (32%); development of documentation (26%); implementation and monitoring of procurement contracts (19%); procurement planning (10%). Additionally, green procurement was highlighted as an area needing further knowledge in the context of sustainable procurement practices.

5. DISCUSSION AND CONCLUSION

The analysis conducted in this study highlights the complexity of public procurement and identifies the stages and factors that contribute to its failures. Each stage in the public procurement process requires the expertise of qualified professionals; without this expertise, challenges arise not only at individual stages but throughout the entire system. Additionally, the introduction of mandatory Green Public Procurement presents further challenges, requiring careful consideration and adaptation.

A question for future research is: What are the challenges and experiences facing other EU member states. Could the exchange of best practices and a unified approach provide solutions to promoting the efficiency of the public procurement process for special-purpose clothing?

ACKNOWLEDGEMENTS

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DEVELOPMENT OF HIGH-PERFORMANCES MILITARY FABRICS: SILENT, LIGHTWEIGHT AND SUSTAINABLE

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Abstract: *This study describes the development of high-performance fabrics for military applications, aiming to create a material that integrates the traditional requirements (such as water penetration resistance, good breathability and high mechanical performances) with specific requirements in terms of silencing properties, sustainability, lightweight and compactness.*

These new generation textiles were made using 100% recycled nylon yarns; various fabric constructions and weaving techniques were explored to enhance the fabric's inherent quietness. The fabrics were laminated using hot melt technology, optimizing the adhesive type and processing parameters to improve fabric noise reduction. Three different configurations were finally developed: a twill, an elastic ripstop and a firm ripstop were laminated to a polyurethane membrane, 100% PTFE-free and polyester backing. Sound power level test showed a reduction of more than 4 decibels compared to traditional fabrics, while all the other performance tests showed results comparable to those achieved with PTFE membranes.

Keywords: *Noise reduction textiles, recycled polyamide fabrics, PTFE-free membrane technology, military tactical fabrics, sustainable fabrics.*

1. INTRODUCTION

Military operations often require specialized materials with unique performance characteristics to meet the demands of harsh environments (Horrocks & Anand, 2000). Key factors include water penetration resistance, breathability, mechanical strength, and the ability to remain silent under movement—essential traits for soldiers operating in the field. Current military fabrics, while functional, often fail to provide optimal performance in all these areas simultaneously. The primary objectives of this research were to develop a fabric that is lightweight, compact, mechanically durable, resistant to water penetration, and breathable, while also addressing the need for noise reduction in tactical situations.

Furthermore, the preference for using PTFE-free membranes and recycled yarns positions the product towards a future where the reduction of non-biodegradable and potentially hazardous substances will not only be necessary but also imperative.

This paper presents the design and testing of new fabrics with significant advancements in all these areas.

2. MATERIALS AND METHODS

2.1 Fabric Base Materials

The base fabric material used in this study was 100% recycled polyamide, with 50% derived from post-consumer recycled content. Polyamide fibers were chosen for their mechanical strength, durability, and resistance to abrasion, while the choice of use recycled yarns was selected as it contributes to the sustainability of the fabric, reducing the environmental footprint compared to virgin materials. Various fabric constructions were investigated to optimize the performance of the textile, with particular emphasis on noise reduction. Additionally, yarn density, fabric tightness, and surface texture were varied to enhance the quietness of the fabrics (Leclinché et al., 2019) without compromising their mechanical strength or other technical properties.

2.2 Lamination with PTFE-Free Membranes

To enhance the water resistance and breathability of the fabrics, they were laminated with a Polyurethane, 100% PTFE-free membrane and PES backing, in a 3-layers configuration. The membrane was applied using hot melt lamination technology. The adhesive and processing

parameters were optimized to ensure a high-quality bond between the fabric and the membrane, improving the overall performance of the fabric in terms of both water resistance and noise reduction, without compromising the breathability or other mechanical performances.

2.3 Physical Properties

The mass (g/m^2) of the fabrics was determined in accordance to UNI EN 12127:1999

2.4 Mechanical Properties

Tear strength, tensile strength and abrasion resistance were measured according to UNI EN ISO 13937-4:2002, UNI EN ISO 13934-1:2013 and UNI EN ISO 12947-1:2000 respectively.

Abrasion was evaluated with a weight of 12 kPa, on the face side of the 3-layers material, interrupting the measurement either at the breakage of the first wire or once 200.000 cycles have been reached.

2.5 Performance Properties

Specific performances, such as water penetration resistance and breathability were determined according to UNI EN ISO 811:2018 and UNI EN ISO 11092:2014 respectively.

Water penetration resistance analyses were conducted with an increasing water pressure of $100 \pm 0.5 \text{ cm H}_2\text{O/min}$ and stopping the measurement after the penetration of the first drop through the fabric. The resistance of the fabrics to contamination was also evaluated, by assessing the water penetration resistance after 24 hours of contact with oil and fuel as contaminants, as per the standard procedure UNI EN 343. The water penetration resistance was tested both on the fabric immediately after contamination and after five cycles of washing at 60°C with final tumbler drying, according to UNI EN ISO 6330:2022.

2.6 Silence Test

Silence test was conducted by determining the sound power levels in reverberation room in accordance with standard UNI EN ISO 3741:2010/EC 1-2013. Noise was produced by rubbing fabric against fabric.

3. RESULTS AND DISCUSSION

Among the different combinations of different types of base fabrics, membranes and backings, three specific 3-layer fabric combinations emerged as the most promising, considering all the required technical performances. The fabric structures developed are as follows:

NEXGEN® 154/48: Twill with PU membrane and PES backing

NEXGEN® 130/48: Firm ripstop with PU membrane and PES backing

NEXGEN® WHISTLER: Elastic ripstop with PU membrane and fleece

3.1. Weight Reduction and Compactness

The new fabrics developed in this project have demonstrated a weight reduction of up to 10% compared to standard products currently used in military applications. This significant weight reduction enhances the overall compactness of the material, making it easier to transport and handle. Such improvements in material properties contribute to more efficient logistical operations, offering greater flexibility and mobility in field applications.

3.2. Water Resistance and Breathability

The fabrics exhibited excellent water penetration resistance, with values higher than 15.000 mm, both at initial stage and after different washing cycles, surpassing the requirements for military-grade waterproof textiles. Additionally, their breathability was found to be within the optimal range for tactical gear ($< 10 \text{ m}^2 \text{ Pa/W}$), allowing for effective moisture management and ensuring comfort during prolonged wear.

3.3. Mechanical Performances

The mechanical properties of the fabrics demonstrated outstanding durability. Tensile strength, tear strength and abrasion resistance were well above the required threshold for military applications, as shown in Table 1.

Table 1. Mechanical properties

		NEXGEN® 154/48	NEXGEN® 130/48	NEXGEN® WHISTLER
Tear Strenght [N]	Warp	≥ 60	≥ 35	≥ 60
	Weft	≥ 100	≥ 20	≥ 70
Tensile Strenght [N]	Warp	≥ 850	≥ 750	≥ 700
	Weft	≥ 1.200	≥ 400	≥ 700
Abrasion [Nr. cycles]		≥ 150.000	≥ 150.000	≥ 150.000

3.4. Sound Power Level Reduction

The most significant achievement of this study was the sound power level reduction observed in the fabrics. The reduction of up to 4 decibels respect to a fabric normally used for military application (“*standard fabric*” in figure 1) was significant, considering not only the decrease in noise but also the reduced strain on the eardrums of the end user.

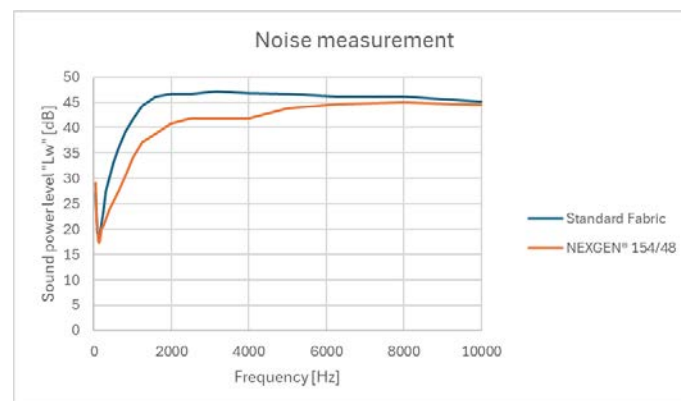


Figure 1. Noise measurement

4. CONCLUSION

The developed fabrics represent a significant step forward in high-performance materials for military applications.

The combination of superior mechanical properties, excellent water penetration resistance and breathability, together with the results obtained in terms of weight and sound power level reduction provides a critical benefit in tactical operations, making these fabrics suitable for a wide range of military applications.

If sustainability is also considered, achieved through the use of recycled fibers and the PTFE-free membranes, the result is a solution that positions this material as a gateway to the future.

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INFLUENCE OF BETA AND GAMMA RADIATION ON THE PROPERTIES OF NBC PROTECTIVE CLOTHING

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Abstract: *The aim of the study was to investigate the effect of beta and gamma radiation on the mechanical and protective properties of a full-rubber suit used as NBC (Nuclear, Biological, and Chemical) protective clothing. Changes in resistance to cutting, puncturing, tearing, and surface microstructure, were examined. It was found that beta radiation leads to material degradation, manifested by a decrease in resistance to cutting and tearing. In contrast, gamma radiation improves puncture resistance and reduces susceptibility to chemical degradation, which may result from polymer crosslinking processes. The microstructure analysis revealed the presence of surface cracks in both irradiated and non-irradiated samples. The results indicate a significant impact of ionizing radiation on the protective properties of the tested materials.*

Keywords: *Clothing NBC, Beta and Gamma Radiation, Properties, Polyvinyl Chloride.*

1. INTRODUCTION

Protective clothing NBC (Nuclear, Biological, and Chemical) used by firefighters during radiation events is the most important form of protection for workers against radioactive contamination. These are typically gas-tight, full-rubber suits combined with footwear and a visor. They consist of several layers, such as fabric that reinforces the suit's structure and a laminate coating that seals and protects the inner layer. The outer layer should have fire-resistant, antistatic, and hydrophobic barrier properties to prevent dangerous substances from penetrating and repel radioactive dust (Dhyani, Bharati, Thakare, Singh, Meher, Boopathi, 2022). One of the materials commercially used as a laminate layer is polyvinyl chloride (PVC). It is a thermoplastic polymer, to which functional additives are added during processing to achieve the appropriate level of plasticization and provide protection against degradation caused by UV radiation and oxygen (Patrick, 2005). When used in firefighting suits, this polymer may also undergo degradation due to ionizing radiation, resulting in the deterioration of certain protective properties. The aim of this study is to determine the changes in the mechanical and structural properties of a full-rubber suit caused by the exposure to beta and gamma ionizing radiation.

2. MATERIALS AND METHODS

2.1 Materials

The subject of the study was a commercially available, gas-tight, full-rubber suit. This suit is made from polyester fabric coated with polyvinyl chloride, with a surface mass of 530 g/m². According to the manufacturer's data, it meets the following standards: EN 943-1:2015-12 + A1:2019; TYPE 1a-B (protection against chemicals); EN 1073-2:2002; EN 14126:2003 (protection against radioactive contamination by solid particles); EN 1149-5:2008 (protection against infectious agents).

2.2 Preparation

The material under study was exposed to accelerated electron beam radiation in a linear accelerator Elektronika ELU-6 (beta radiation - β). The irradiation was carried out using an electron beam with an energy of 6 MeV, a pulse frequency of 20 Hz, and a pulse duration of 4 μ s. The average dose rate, measured using an alanine dosimeter, was 5.8 kGy·min⁻¹ $\pm$ 6%.

To simulate gamma radiation exposure, the materials were subjected to irradiation from the isotope ⁶⁰Co, which has a half-life of 5.272 years and an average photon energy of 1.25 MeV. The radiation source was a metallic sinter enclosed in sealed, double-walled capsules made of acid-

resistant steel, placed in a frame container surrounded by a concrete shield. The average dose rate, measured using an alanine dosimeter, was $2.0 \text{ kGy} \cdot \text{h}^{-1}$.

Before the tests, the samples were acclimatized for 24 hours at a temperature of $23 \pm 2 \text{ }^{\circ}\text{C}$ and a humidity of $50 \pm 5\%$.

2.3 Tear resistance

The tear resistance was measured using an INSTRON testing machine. To conduct the test, samples were cut into samples with dimensions of $(100 \pm 10) \text{ mm} \times (50 \pm 5) \text{ mm}$ and a cut length of $50 \pm 5 \text{ mm}$ at the midpoint of the width. The test was carried out according to EN 388:2016+A1:2018, section 6.4. The acclimatized sample was clamped in the jaws to a depth of 20 mm. The jaw movement speed was set to $100 \pm 10 \text{ mm/min}$, and the jaw spacing was at least 10 mm.

2.4 Chemical degradation resistance and puncture resistance

The testing method considered the impact of chemical substances on material degradation, correlated with the examination of mechanical properties. For this purpose, a testing setup was used, consisting of a static tensile and compression testing machine (STM 566, SATRA Technology, UK) in accordance with EN 388:2016+A1:2018, section 6.5. Tests were conducted on the suit by taking 16 samples with a diameter of 20 mm (8 control samples and 8 subjected to chemical degradation), ensuring uniformity in the tested areas. The tests were performed following EN ISO 374-4:2019 [IDT], using commonly used disinfectants: isopropanol, 30% hydrogen peroxide, and 15% sodium hypochlorite. The tests were carried out under controlled laboratory conditions ($23 \pm 2^{\circ}\text{C}$). In the first stage, the samples were exposed for one hour to liquid substances in tightly sealed vials, eliminating the influence of climatic fluctuations. In the second stage, the puncture force of the polymer material was measured (on the control and exposed samples) at a speed of 100 mm/min, recording the maximum force value and percentage differences between reference and chemically degraded samples.

2.5 Blade resistance test

The acclimatized test samples consisted of a strip with a width of $(60 \pm 6) \text{ mm}$ and a length of $(100 \pm 10) \text{ mm}$, cut at an angle. The material under test was placed in the holder, and a blade arm was lowered, then the number of cycles (blade rotations) at which the sample was cut through (T) was recorded. For each test sample, five tests were conducted in the following sequence for each trial: testing the reference sample, testing the sample under investigation (exposed to radiation), and testing the reference sample again.

2.6 Microstructure

The surface microstructure of the examined visors was analyzed based on images taken using a scanning electron microscope SU-8010 (Hitachi, Hitachi-shi, Japan) with an electron acceleration voltage of 5 kV and a Lower InLens (L) detector. Samples were mounted using carbon tape on an aluminum holder and cleaned with an alcohol wipe to remove dust prior testing. The samples were then coated with a thin layer of gold, approximately 7 nm thick, using a high-vacuum sputter coater from Quorum Technologies LTD, model Q150 T (United Kingdom).

3. RESULTS AND DISCUSSION

The change in resistance to puncture, cutting, and tearing before and after the irradiation process was determined (Table 1). For the samples exposed to beta radiation, an increase in the cutting resistance value was observed. In contrast, for the 100 γ samples, an increase in the force required for tearing and puncturing was recorded. This upward trend may result from the crosslinking of the polymer matrix. A decrease in the force required for tearing and puncturing was observed for the 100 β samples, which is the effect of ongoing degradation processes.

The results regarding chemical degradation are presented in Figure 1. The most significant degradation was observed in the 100 β sample exposed to isopropanol, indicating a deterioration

of the physical-mechanical properties of the rubber material under the influence of ionizing radiation. No unfavorable changes were recorded for the reference sample exposed to sodium hypochlorite. Negative values of puncture force changes, as seen with the 100 γ sample for all reagents, suggest no degradation and possible crosslinking of the polymer after contact with the substance.

Table 1. Properties of irritated and non-irritated samples

Radiation dose, kGy	Tear resistance, (N) $\pm$ SS	Puncture resistance, (N) $\pm$ SS	Indicator, (-) $\pm$ SS
0	188,8 $\pm$ 16,7	130,66 $\pm$ 4,38	1,74 $\pm$ 0,02
100 β	185,7 $\pm$ 12,3	135,23 $\pm$ 2,27	1,98 $\pm$ 0,14
100 γ	201,2 $\pm$ 4,6	146,65 $\pm$ 3,14	1,64 $\pm$ 0,12

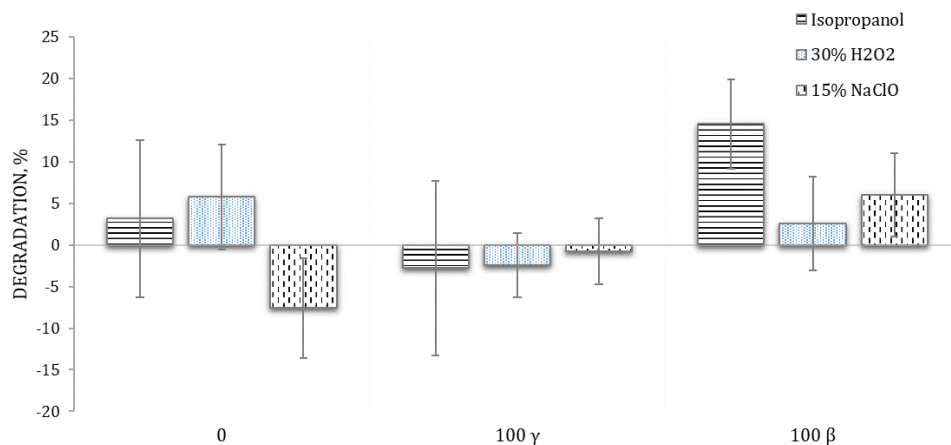


Figure 1. Chemical degradation resistance.

Figure 2 shows micrograms obtained during the surface microstructure analysis of the suit. Surface cracking was observed for both irradiated and non-irradiated samples.

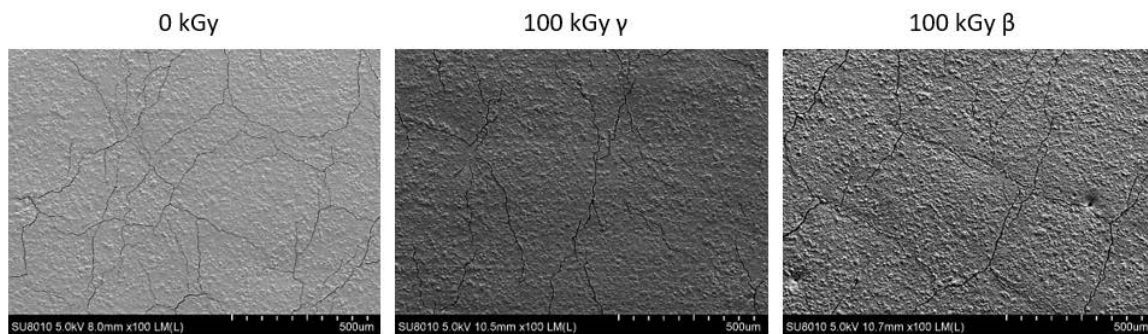


Figure 2. Microstructure before and after irradiation.

4. CONCLUSION

The purpose of this study was to assess the effect of radiation on the key protective properties of a full-rubber NBC (Nuclear, Biological, Chemical) suit. It was found that exposure to beta radiation caused a deterioration in cut and tear resistance, suggesting that degradation processes were occurring in the samples. Gamma radiation, on the other hand, improved chemical degradation resistance and puncture resistance. Meanwhile, the microstructure analysis indicated significant changes in the surface of the tested material. The conducted research showed the influence of radiation on the mechanical and protective properties of the studied suit. The study's findings suggest practical implications for users, including the need for increased inspection or early replacement of NBC suits exposed to radiation due to weakened mechanical integrity, regular testing to address microstructural changes, and enhanced training to identify degradation.

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EVIDENCE OF THE CRITICAL ROLE OF THE FIRST LAYER IN REGULATING MICROCLIMATE AND IMPROVING THERMAL COMFORT

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Abstract: *Climate change and extreme environments pose significant challenges for ensuring thermal comfort in protective clothing systems. This study focuses on the critical role of the first clothing layer in regulating the microclimate and enhancing thermal comfort. Experimental trials showed that the first layer significantly reduces temperature and increases humidity, with greater reductions on the outside of the layer, especially at the front where convective airflow was higher. These findings suggest that effective sweat evaporation in the first layer is key to improving thermal regulation and comfort. The results emphasize the importance of optimizing the first layer in protective clothing systems to better manage sweat and enhance comfort in extreme conditions.*

Keywords: *thermal comfort, microclimate regulation, sweat evaporation, multilayer clothing system, heat and moisture management*

1. INTRODUCTION

Climate change and global warming pose significant challenges for ensuring thermal comfort in extreme environments, particularly in CBRN (Chemical, Biological, Radiological, and Nuclear) scenarios. One of the major challenges is reducing risks while ensuring optimal thermal comfort for individuals wearing protective gear (Havenith et al., 2011). Multilayer clothing systems, especially those used in protective contexts, involve complex dynamics of thermal and moisture regulation. However, the understanding of microclimate evolution within these multilayer systems is limited, particularly regarding the first clothing layer, which plays a crucial role in managing sweat and body heat (Raccuglia et al., 2018). The goal of this study is to explore the impact of the first layer on microclimate regulation and evaluate its influence on overall thermal comfort.

2. MATERIALS AND METHODS

Trials were conducted in a controlled climatic chamber set to a temperature of 30 °C, a relative humidity of 75%, and the airflow of 2 m/s. Participants, consisting of 4 men and 2 women, walked continuously at 4 km/h for 90 minutes on a treadmill, wearing a cotton shirt and a CBRN protective outfit, excluding additional protective gear (e.g. ballistic vests or helmets). This configuration allowed a focus on the thermal and moisture management properties of the clothing system.

Temperature and humidity of the clothes were recorded at various points (chest and middle of the back, inside and outside each clothing layer) with MSR® sensors (MSR147WD, accuracy ± 0.1 °C and $\pm 2\%$ RH). Core body temperature was measured using ingestible temperature sensors (BodyCap®, eCelsius Performance, accuracy ± 0.1 °C), while skin temperature was recorded at eight specific locations using thermistors (TEA CAPTIV®, T-Sens Temperature). These measurements provided insights into the thermal and moisture dynamics within the multilayer system during physical activity.

Data were averaged for all 6 participants, and the Crawshaw temperature (a weighted average of skin temperature) was calculated to assess the overall impact on thermal comfort (Crawshaw et al., 1975).

3. RESULTS AND DISCUSSION

The experimental results showed significant temperature reductions and increases in humidity across the microclimate layers. The temperature decreases were notably greater on the outside of the first clothing layer compared to the inside. Specifically, temperature reductions of -5.45% at the front and -2.67% at the back (outside) were observed, compared to -3.23% at the front and -1.97% at the back (inside). Meanwhile, humidity levels increased more substantially on the outside of the first layer, with values reaching +59.57% at the front and +66.91% at the back, compared to +45.25% and +46.38% on the inside front and back, respectively. The results also indicate that the microclimate at the back of the body is warmer at the front, reflecting a temperature gradient influenced by the positioning and airflow dynamics at the T-shirt scale.

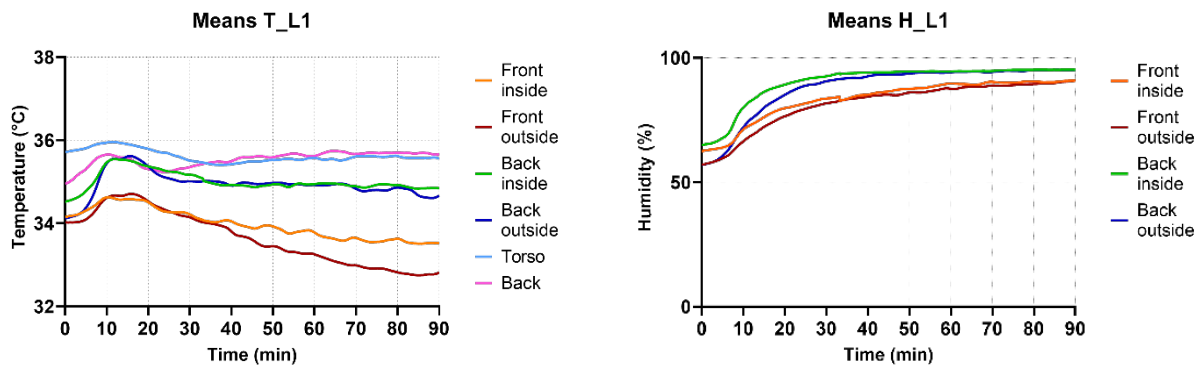


Figure I. Left: Skin and first layer clothing temperature averaged on 6 participants. Right: First layer clothing humidity averaged on 6 participants.

These results confirm the hypothesis that sweat evaporation in the first layer plays a crucial role in thermal regulation. According to the laws of thermodynamics, in this case, heat flows from the body to the environment through the textile, while moisture moves from the T-shirt to the surrounding air. These flows indicate the efficiency of sweat evaporation in the T-shirt. The key question is whether the cooling effect benefits only the T-shirt or also contributes to effective body heat dissipation. While a cooler T-shirt can provide a more comfortable sensation on the skin, this does not necessarily mean improved heat loss from the body. If the fabric retains too much moisture, it may reduce evaporation efficiency and act as a thermal barrier rather than enhancing cooling.

Moreover, by effectively evaporating sweat, the T-shirt can absorb additional perspiration, preventing skin wetness and allowing continued sweating, which is essential for maintaining an adequate core temperature in a hot and humid environment. This effect is particularly relevant for cotton, which has good moisture absorption and release properties. However, depending on the hydrophilic characteristics of the material, the thermoregulatory performance may vary. Hydrophobic materials, for instance, promote faster evaporation, potentially enhancing cooling efficiency.

The difference in temperature and humidity between the front and back highlights the impact of convective airflow (2 m/s), which enhances evaporation efficiency, particularly at the front of the body. This airflow not only improves moisture removal from the textile but may also facilitate direct heat dissipation from the skin, further contributing to overall thermal comfort.

4. CONCLUSION

This study demonstrates that the first clothing layer plays a fundamental role in regulating the microclimate, particularly by enhancing sweat evaporation, which helps reduce temperature and improve thermal comfort. The simultaneous observation of temperature and humidity dynamics during exercise in a protective multilayer outfit represents a significant advancement, providing new insights into how clothing systems manage thermal and moisture exchanges.

The results highlight that effective sweat evaporation in the first layer significantly contributes to thermal regulation. The observed temperature reductions and humidity increases, especially at the front of the body where convective airflow is higher, support the importance of optimizing the first layer for better comfort. These findings are crucial for the design of protective clothing systems, suggesting that improving the management of sweat and moisture within the first layer could significantly enhance thermal comfort in extreme environments.

In conclusion, this research not only confirms the critical role of the first clothing layer in microclimate regulation but also offers valuable insights for optimizing protective garment designs. Future research should further explore temperature and humidity dynamics within multilayer systems, particularly in real-world applications, to improve efficiency and comfort of protective clothing in various environmental conditions.

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CHATBOT AS AN INFORMATION SUPPORT IN THE FIELD OF PROTECTIVE CLOTHING SELECTION, USE, CARE AND MAINTENANCE

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Abstract: *The COVID-19 pandemic caused a sudden and significant increase in demand for personal protective equipment and revealed the limited knowledge regarding their selection, use and the requirements. Therefore, it was decided to create a chatbot containing information about protective clothing against infective agents and chemicals. The study began with the creation of a database of questions based on customer inquiries and surveys conducted with manufacturers and users of this type of protective clothing. The database structure was properly adjusted so that all the information could be easily retrieved. The functionality and look of a new chatbot was designed so that it will be easy to use and more appealing.*

Keywords: *Personal protective equipment, protective clothing, infective agents, chemicals, chatbot.*

1. INTRODUCTION

Although the chatbot market size is constantly growing (Spherical Insights LLP, 2024), there are few reports regarding the use of chatbots in the field of protective clothing. There are few examples of chatbots that relate to this matter indirectly. For example a chatbot developed by Colabianchi et al. (Colabianchi et al., 2022) for use in improving the safety of container transport workers at seaports. The mentioned chatbot had the ability to inform the user what kind of personal protective equipment (PPE) is required for a given operation. Thorough analysis on this matter shows lack of solution for a quick access to knowledge of protective clothing and PPE in overall. A particularly significant moment, revealing the real need for using PPE and the limited knowledge of their selection and use, was the COVID-19 pandemic (Kiss & Elhedhli, 2024). The perceived lack of ability to quickly obtain systematized knowledge on the subject was the reason for CIOP-PIB to take actions aimed at creating a tool that would allow easy access to this kind of information for a wide audience by creating a chatbot. This tool will be designed to provide users with quick answers to frequently asked questions and to help identify the user's real needs.

2. CREATING A DATABASE

Creating a database for a chatbot was an essential step for enhancing the chatbot's functionality and accuracy. A well-structured database serves as the backbone of a chatbot, enabling it to provide relevant and timely information to users. To tailor the database content to the users, the input for chatbot was prepared in consultation with them by analysing their inquiries and conducting surveys.

2.1 Analysis of inquiries regarding protective clothing against infective agents and chemicals

In order to find the most important aspects for the database, more than 230 inquiries about protective clothing against infective agents and chemicals were analysed. The inquiries were received by the CIOP-PIB's Protective Clothing Laboratory between April 2020 and October 2020. The analysis showed that the main part of the inquiries concerned information on standards (46%) and certification (19%) (Figure 1).

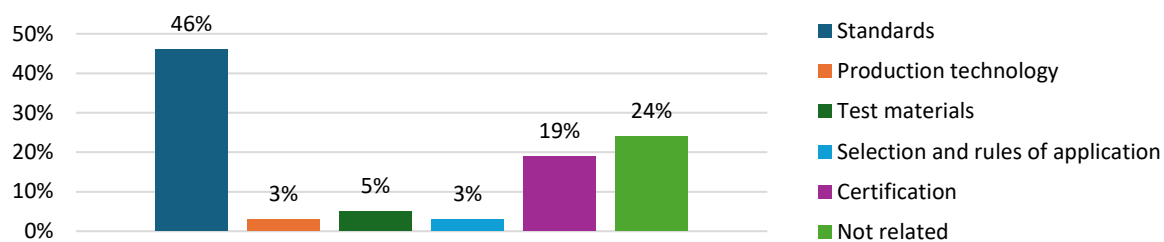


Figure 1. Main areas of inquiries

The results of this research pointed out the most important topics that should be covered by the chatbot.

2.2 Survey on the needs and requirements of manufacturers of protective clothing against infective agents and chemicals

Surveys were also conducted with manufacturers of protective clothing against infective agents and chemicals. As a result, 8 responses were obtained, which identified the type of liquid chemicals for which the greatest demand for protective clothing is observed (concentrated inorganic acids – 75%, aqueous solutions of strong bases – 63%), as well as colloquial and alternative expressions for protective clothing, which will increase the ability to easily access the issues covered by the chatbot.

2.3 Survey on the needs and requirements of users of protective clothing against infective agents and chemicals

The opinions and questions of protective clothing against infective agents and chemicals users were also an important element in creating the database for the chatbot. Employees from units where this kind of protective clothing is used, such as hospitals were invited to participate in the survey. This resulted in six survey responses. The survey shows that one of the biggest problems faced by users of this type of protective clothing is the determination of the duration of use of the clothing exposed to a given infective/chemical agent, which was indicated by as many as 67% of respondents. For 50% of respondents, determining the useful life is also a significant problem.

2.4 Database structure

Based on the questions, concerns and challenges collected during the analysis of the inquiries and surveys, sets of questions and answers were created and divided into 4 categories: protective clothing against infective agents, protective clothing against chemicals, certification and general information. These formed the basis for building the database. An Excel-type file was adopted as the format of the chatbot database file. This solution will improve the management of the database and transfer of this data to the chatbot system. The database was additionally divided into six columns: Topic, Category, Question number, Question, Answer, Keywords. This mapping makes it possible to organise and group the data into thematic blocks, which in turn will translate into easier access to the information that chatbot user is interested in.

3. DESIGN

3.1. Functionality

The main concept of chatbot's functionality is based on two paths: the main one and the script one. The main path is used when the user's prompt significantly correspond to the predefined questions from the database. When the prompt is not like any of the predefined questions or the user chooses something from the list placed on the main chatbot page, the script path will be used. Then, the chatbot will try to lead user to a similar question from the database by giving them suggestions. The aim of both paths is to answer the user's question as good as possible.

3.2. Design

At the beginning of this study, the look of a new chatbot was designed. Few mock-ups were created and the best was chosen based on the additional carried-out survey. The icon of a chatbot was also proposed. The designed icon represent a robot with a safety helmet. The robot was supposed to remind people using chatbot that they are talking to a computer program and not a real person. The safety helmet refers to the application of this particular conversational agent.

4. CONCLUSION

The chatbot for protective clothing against infective agents and chemicals fills a need for organized knowledge in this field. Analysis of inquiries and surveys points out the necessity for information on standards, certification, and usage of this type of clothing. The well-structured database and dual-path response functionality ensure that the users receive accurate answers. This tool might significantly contribute to improved safety by providing quick access to essential information.

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REVIEWING INTEGRATED ERGONOMICS OF PPE TEXTILES

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Abstract: *This study shows that ergonomics, anthropometry, material properties, and thermal properties (regarding textile layering and air permeability) work together to enhance textile items of PPE functionality. To evaluate the environmental compatibility of PPE items, considered data from 142 test subjects in three different research work. There was in one study the military performance-based test was used to evaluate combat clothing compatibility in the real environment. To evaluate protective clothing of firefighters there were used static and dynamic anthropometry which was applied in operational postures. The third study focuses on the importance of selecting the correct size for the wearer of protective clothing. Manual measurement and using the 3D body scanner proved to be the most reliable methods, yielding closely matching results. Material properties also play a crucial role, as they directly influence both durability and flexibility. However, the study also revealed limitations, as these materials can become overwhelmed during prolonged exposure to heat and may lack sufficient insulation in cold environments, highlighting a trade-off between cooling and warmth. The results highlight the interdependence of ergonomics, anthropometry, material properties, and thermal properties in optimizing PPE textile items.*

Keywords: *anthropometrics, 3D body scanner, thermal properties, PPE textiles, integrated ergonomics, material properties.*

1. INTRODUCTION

The design and performance of Personal Protective Equipment (PPE) rely on multiple intertwined factors, including ergonomics (Teyeme et al., 2021), anthropometry, material properties (Lou et al., 2021), and thermal properties in regard to textile layering and air permeability (Basodan et al., 2021; CEN, 2024; Dolez et al., 2022). This abstract synthesizes insights from research on combat clothing, protective clothing, and station uniforms, highlighting how these aspects interact to create functional and protective gear (Traumann et al. 2022, 2023; Traumann, Kivistik, and Peets 2021). Understanding the relationships between these elements is crucial for optimizing PPE across various high-risk professions, where comfort, mobility, and protection are equally vital. It is necessary to undertake this work, as it not only contributes to the ongoing dialogue on the importance of integrating ergonomics into PPE development but also lays the groundwork for future innovations in the field.

2. MATERIALS AND METHODS

This comparative analysis synthesizes findings from three studies (Figure 1):

- 1) combat clothing. Dynamic test battery modelled after military tasks was used to assess ergonomics. Anthropometric measurements were conducted to determine how well combat clothing accommodates movement across a variety of postures.
- 2) protective clothing. Mix of static and dynamic anthropometry was applied, with firefighters undergoing tests in operational postures such as bending and crawling. Material properties like air permeability and stretch were analyzed in conjunction with these movements to ensure thermal properties during high stress tasks.
- 3) station uniforms. Manual, 3D scanning, and app-based anthropometric techniques were compared to optimize uniform sizing for diverse body types. This approach demonstrated the precision of digital methods in achieving accurate fits, crucial for flexibility and thermal regulation in varied work environments.

The data from these methods were evaluated to determine how each PPE type addresses user movement, material durability, and temperature control. By contrasting and merging insights from these studies, we present a unified understanding of the essential factors for PPE across different fields.

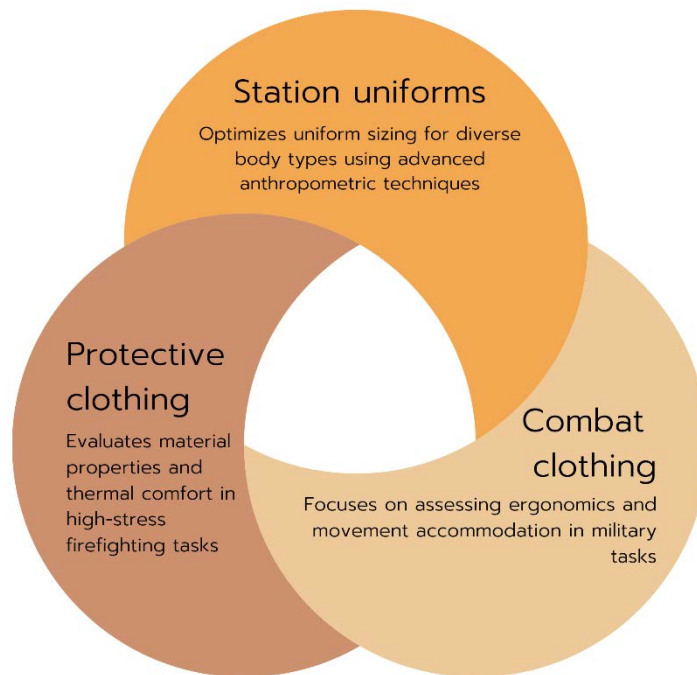


Figure 1. Three studies and their main objective included in this work

3. RESULTS AND DISCUSSION

3.1 Ergonomics and anthropometry

Across all three studies, ergonomic design was strongly influenced by anthropometric data. In combat clothing, the dynamic test battery revealed that precise body measurements were critical to ensuring unrestricted movement during military manoeuvres. Similarly, in firefighter PPE, the dynamic movements required for emergency tasks were best supported by ergonomic designs informed by detailed body measurements.

3.2 Digital anthropometric tools

The rescue uniform study showed that 3D scanning technology provided more accurate body measurements, enabling better fit and comfort across various body types. This precision was found to be beneficial for all PPE types, as well-fitting uniforms directly improved ergonomic performance and material interaction. While precise body measurements allow for tailored designs, some studies still rely on manual methods. Digital anthropometry tools like 3D scanning offer greater precision but face limited adoption due to cost and accessibility (Traumann et al., 2022). Expanding their use across disciplines could ensure a consistent, high-quality fit.

The layers of undergarments and their fit under outer clothes have not been investigated, as dimensions of outer layers include ease of clothing in the pattern design.

3.3 Material properties and flexibility

Both protective and combat clothing demonstrated the need for materials that offered durability and flexibility. For firefighters, fabrics with higher elongation improved mobility in bending and crawling tasks, while combat clothing required materials that could withstand abrasive environments without restricting movement. However, there is often a trade-off between robustness and comfort. Researchers are focusing on developing fabrics that adapt to different environmental conditions and user movements to fill this gap in textile science (Dolez et al., 2022; Teyeme et al., 2021).

3.4 Thermal properties

Thermal properties were particularly emphasized in firefighter PPE, as heat management is vital during fire response. Materials with high air permeability and moisture-wicking capabilities were essential to prevent heat stress. Although not exposed to extreme heat, combat clothing still benefited from materials that managed temperature, enhancing comfort during prolonged outdoor operations. Thermal properties emerged as particularly critical in the firefighter PPE study, where breathable, moisture-wicking fabrics were essential in preventing heat stress during intense physical activity in extreme temperatures. Similarly, in the combat clothing study, temperature regulation was important for soldiers operating outdoors in varying climates. Lightweight, breathable materials improved comfort during long-duration activities but often came at the expense of durability, presenting a similar challenge in balancing robustness with breathability. The limitations in current materials—whether related to insufficient cooling over time or lack of adaptability to different environments—suggest the need for future research into advanced textiles (Lou et al., 2021).

4. CONCLUSION

Integrating ergonomics, anthropometry, material properties, and thermal management into PPE research highlights the importance of a holistic approach. By understanding how these aspects interrelate, PPE can be tailored to the unique requirements of each field, promoting safety, comfort, and effectiveness. In these research works, the properties of the basic materials of the clothes have been discussed separately, but the layering aspect of the clothes has not been studied. Depending on the weather conditions for both combat and protective clothing, it is important to find out what the base layer, intermediate layer and top layer should be in the clothing, ensuring the thermal properties of the PPE textile. Future research is planned to further investigate digital anthropometry, advanced materials, and thermal property strategies, with the potential integration of smart textiles to address the evolving needs of high-risk occupations. Broadening the scope of testing to include a more diverse range of users and exploring the accessibility of these advanced technologies will further enhance the significance of entire research. Gaining deeper insights into these relationships is crucial for enhancing PPE design across various high-risk professions, like military, firefighting, and rescue operations, where achieving a balance between comfort, mobility, and protection is vital.

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STRUCTURAL INTEGRITY OF FIREFIGHTER SUITS AND PROTECTION AGAINST COMBUSTION PRODUCTS

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Abstract: During firefighting and extinguishing interventions, firefighters are exposed to various harmful substances, including gases, vapours, smoke, soot, aerosols, and dust particles, all of which can negatively impact their health. The most concerning risk is exposure to known or potential carcinogens present in combustion products. Firefighter clothing does not fully protect against the penetration of these fumes through construction materials, nor does it act as a barrier at the molecular level. Additionally, harmful substances can enter the body through leaks between clothing components, allowing them to contact the skin, be absorbed, and distributed throughout the body, leading to potential metabolism or accumulation. This study provides clear evidence of these risks, using tests in real indoor fire conditions to confirm the pathways of hazardous substances under protective clothing. It also suggests solutions, such as modifying sealing lines and incorporating advanced adsorbent fabric to better protect firefighters from these dangerous exposures.

Keywords: Integrity, firefighter suit, aerosol, PAH.

1. INTRODUCTION

Firefighter clothing is designed to protect against fires and other hazards during rescue operations. However, when fighting fires, both indoors and outdoors, these garments do not provide adequate protection against combustion products, which include polycyclic aromatic hydrocarbons (PAHs) in aerosol form. Long-term skin contamination with PAHs has been linked to an increased risk of developing skin cancer and cancers of internal organs. These aerosolized fumes can penetrate the skin through gaps in the clothing, including leaks between different parts of the garment and the hood. Chronic exposure may occur in case of insufficient cleaning of the combustion products from clothing and equipment. Currently, there are no standards for firefighting gear that specify the level of protection against the penetration of combustion products through these gaps or the fabric. This study will highlight the critical areas in both 3-layer and 1-layer firefighting clothing with gloves, boots, hood, helmet, and respiratory protection.

2. HEALTH RISKS

Fighting fires, particularly in indoor buildings, and managing the aftermath of fires presents both acute and chronic health risks due to exposure to dust particles, aerosols, vapours, and gases produced during the combustion of various materials. From a health risk management perspective, it is crucial to focus on improving protective equipment to prevent contamination of the body surface by harmful combustion products that penetrate standard firefighter clothing, as well as reducing the absorption of these substances through the skin. During fire extinguishing operations, firefighters are exposed to significant amounts of toxic combustion byproducts, including fumes, soot (which carries adsorbed chemicals), gases such as carbon monoxide, hydrogen cyanide, hydrogen sulfide, sulfur dioxide, nitrogen oxides, and ammonia, along with volatile organic compounds like benzene, acrolein, xylene, furans, persistent organic pollutants, dioxins, flame retardants, and particularly PAHs. These substances present both inhalation and dermatological risks from acute and chronic exposure, with PAHs posing significant health risks due to their carcinogenic, teratogenic, and mutagenic properties.

3. STANDARD REQUIREMENTS

Currently, there are several European standards that outline requirements for the quality of firefighter clothing. However, these standards do not address the risks mentioned above.

EN 469:2021 „Protective clothing for firefighters – Performance requirements for protective clothing for firefighting activities“. This standard establishes requirements for protective clothing against heat and fire, but does not cover other protection demands such as penetration of chemical substances under protective clothing through barrier materials or through interfaces.

EN ISO 15384:2021 „Protective clothing for firefighters. Laboratory test methods and performance requirements for wildland firefighting clothing“. The standard emphasizes the need for loose-fitting protective clothing to reduce heat stress when extinguishing in summer conditions, does not specify any level of protection against the penetration of combustion products to the surface of firefighter bodies.

EN 13034+A1:2009 „Protective clothing against liquid chemicals. Performance requirements for chemical protective clothing offering limited protective performance against liquid chemicals“. The standard does not address neither permeation nor penetration of combustion products.

EN 13911:2018 „Protective clothing for firefighters – Requirements and tests methods for hoods for firefighters“ specifies minimum safety requirements and test methods for fire brigade hood worn during firefighting operations and for heat protection and fire.

Currently, the only available standard concerning the protection against the combustion products is from the National Fire Protection Association (NFPA) in the USA. According to the NFPA 1971:2018 part „Hood Testing Minimum Requirements“, there is only a requirement for protection against the penetration of particles (ranging from 0.1 to 1.0 μm) such as combustion products, with an efficiency of at least 90%.

4. MATERIALS AND METHODS

4.1. Combustion products in real situation

The extensive formation of a wide range of PAHs and other pollutants during fire has been experimentally confirmed. Similarly, contamination of the outer layer of clothing, including the hood, as well as the presence of contaminants beneath the clothing, has also been verified. The procedure of the verification is simply shown in Fig. 1 from a real training fire (a), through sampling in rooms (b) and on and beneath the clothing of the intervening firefighter (c) to samples preparation (d) and GC/MS analysis (e).



Figure 1 (a-e) Confirmation of PAHs formation and their deposition

4.2. Integrity testing in toxicologic chamber

Fig. 2 demonstrates the testing of structural integrity of protective clothing using a dynamic test in toxicologic chamber with model gas (chlorine approx. 5 ppm). The test is based on the colour interaction of the indicator underwear (yellow) (a) dressed under the protective clothing (b, c), with the model gas in toxicologic chamber (d). Subsequently, the pink coloration indicating the penetration points (e) is digitally processed (f).



Figure 2 (a-f) Testing of structural integrity of firefighter protective suit in toxicologic chamber

5. RESULTS AND DISCUSSION

Tests of the 3-layers firefighter clothing revealed minor penetrations of model gas in problematic interface areas, including zippers, sleeve – glove as well as leg – boot interfaces. And massive breakthrough through the firefighter hood for heat and fire protection. However, under the given test setting, the breakthrough of the model gas through the suit material was not observed during the 30-minute test. This may be attributed to the moisture membrane, which regulates moisture removal from the clothing. Besides, it also may accumulate the combustion products inside the membrane, affect the breakthrough time of combustion products through the material and in case of insufficient washing it may be source of secondary contamination later.

Tests of 1-layer firefighter clothing showed penetrations in nearly all areas, including the hood. Breakthrough of the model gas was detected through the structural material of the protective clothing due to the lack of a protective layer against combustion products.

The test method used was primarily developed in the past for testing of chemical protective clothing detecting the weak points related to breakthrough of chemical substances. However, it has also proven to be useful for testing other types of protective clothing and equipment. The method is particularly suitable for the research and development of protective clothing and its combination with other protective elements. As the main advantage, it allows easy immediate visual observation of points of penetration beneath or through clothing followed by a semi-quantitative determination of the penetrated model gas amount using computational imaging methods.

However, it must be kept in mind that the exact breakthrough times of hazardous substances of concern through the protective materials has to be confirmed by permeation tests using appropriate instrumental methods. These tests are now subject of ongoing research.

6. CONCLUSION

The presented findings showed that currently used firefighter clothing do not provide sufficient level of protection against combustion products breakthrough. The results serve as a basis for enhancing the protective properties of firefighting clothing. Improving three-layer protective clothing could involve modification of sealing lines and/or incorporation of advanced adsorbent fabric, while still maintaining thermal insulation and mechanical properties. For single-layer protective clothing, protection could be improved by introducing a removable sorption undergarment made from advanced adsorbent fabric, for example.

Additionally, adjustments to washing frequency or washing technology has to be investigated to clarify the long-term protective performance of the improved designs.

ACKNOWLEDGEMENT

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EFFECTS OF SLEEPLESS AND ALCOHOL ON THERMAL STRAIN WHILE WEARING FIREFIGHTERS' PROTECTIVE CLOTHING IN A HOT ENVIRONMENT

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Abstract: The effects of sleepless and alcohol on heat strain in subjects with full personal protective equipment (PPE) in a hot environment (33°C, 60%RH) were evaluated. Nine male subjects completed three conditions: 1) Control (8-h sleep, no alcohol), 2) Sleepless (no sleep, no alcohol), and 3) Alcohol (8-h sleep with alcohol). Rectal temperature during the exercise were higher in Sleepless ($38.0 \pm 0.4^\circ\text{C}$) and Alcohol ($38.1 \pm 0.3^\circ\text{C}$) compared to Control ($37.7 \pm 0.3^\circ\text{C}$) (all $P_s < 0.05$). The subjects felt hotter and more thermally uncomfortable in Sleepless and Alcohol compared to the Control. IL-6 levels before trial in Alcohol and RPE in Sleepless and Alcohol were higher than in Control (all $P_s < 0.05$). The results demonstrated that sleepless and alcohol consumption increased heat strain in subjects with PPE.

Keywords: Firefighter, personal protective equipment, sleep deprivation, alcohol intake, thermal strain.

1. INTRODUCTION

Firefighters performed their duties while wearing heavy personal protective equipment (PPE), which imposed significant physiological strain under heat stress. This strain led to reduced work performance and shortened work duration (Jung et al., 2019). Firefighters experienced greater thermal stress when engaged in outdoor activities during the summer daytimes (Son et al., 2013). Additionally, due to shift work, their sleep duration was insufficient, and they frequently consumed alcohol on their days off. Sleep is a critical factor influencing body temperature regulation. Insufficient sleep prevented adequate reductions in core temperature, maintaining elevated levels the following day (Fujita et al., 2003). Similarly, alcohol consumption affected thermoregulation. While it initially lowers core body temperature, it maintains higher levels during sleep compared to conditions without alcohol intake (Devaney et al., 2003). This study, therefore, aimed to investigate the additional physiological strain imposed by sleep deprivation or alcohol consumption on subjects wearing personal protective equipment (PPE).

2. METHODS

Nine males (24.2 ± 4.1 y in age, 175.2 ± 4.6 cm in height, 74.6 ± 11.1 kg in body weight, $20.8 \pm 7.8\%$ in total body fat, and body mass index [BMI] of 24.3 ± 3.6 kg/m²) participated in the following three conditions: 1) Control (8-h sleep without alcohol intake), 2) Sleepless (total sleep deprivation without alcohol; watching movies or reading books from 23:00 to 07:00 in an experimental room), and 3) Alcohol (8-h sleep with alcohol intake; 360 ml (16.5% alcohol) – distilled alcohol with 330 ml water). All the three conditions were conducted at an air temperature of 33°C with the relative humidity of 60%. A trial consisted of 90 min (10 min rest, 30 min walking at 5.5 km/h on a treadmill, 10 min break, 30 min walking at 5.0 km/h, and 10 min recovery) with full-PPE (include boots and SCBA; weight: 16.3 kg). Rectal temperature, gastrointestinal temperature, ear canal temperature, skin temperature (8 regions), heart rate, clothing microclimate, thermal sensation, and thermal comfort were continuously measured. RPE was measured include rest, break, recovery phase because of effect of sleepless and alcohol intake. Blood samples were collected before and after every trial to measure inflammatory markers, including IL-1, IL-6, TNF-alpha, CRP, and lactic acid. During rest and recovery, heart rate variability was measured. Physiological responses were analyzed using repeated measures ANOVA via SPSS 26 (SPSS, Inc., Chicago, IL). Representative values were calculated as the mean

values during the following periods: rest (3–7 min), 1st exercise (33–37 min), break (43–47 min), 2nd exercise (53–57 min), and recovery (83–87 min). Psychological responses were analyzed using the Friedman test.

3. RESULTS

The results showed that rectal temperature for Sleepless and Alcohol was significantly higher than that of Control (Table 1). During the break, thermal sensation and thermal comfort for Sleepless and Alcohol were worse than those of Control (all P s < 0.05, Table 1). Ratings of perceived exertion for Sleepless and Alcohol were significantly higher than those of Control (Table 1). AT the starting point, IL-6 level for Alcohol was higher than Control (P < 0.05). Time of completion (stopped) for Alcohol was shorter than Control (P < 0.05), and the number of subjects who expressed to quit while their rectal temperature did not reach 39°C was 2, 4, and 2 for Control, Sleepless, and Alcohol, respectively.

Table 1. Summary of the results in the present study

Variable	Phase	Control	Sleepless	Alcohol	P -value
Rectal temperature (°C)	Rest	36.7 ± 0.2 ^a	37.0 ± 0.4 ^b	37.1 ± 0.3 ^b	0.002
	1 st exercise	37.7 ± 0.3 ^a	38.0 ± 0.4 ^b	38.1 ± 0.3 ^b	0.001
	Break	38.0 ± 0.3 ^a	38.2 ± 0.5 ^{ab}	38.5 ± 0.3 ^b	0.004
	2 nd exercise	38.0 ± 0.4 ^a	38.2 ± 0.4 ^{ab}	38.6 ± 0.4 ^b	0.007
IL-6 (pg/ml)	Before	0.9 ± 0.7 ^a	1.3 ± 0.7 ^{ab}	1.5 ± 0.8 ^b	0.032
Thermal sensation	48 th min	1.4 ± 1.0 ^a	2.5 ± 0.9 ^b	2.7 ± 1.1 ^b	0.004
Thermal comfort	48 th min	-1.0 ± 0.6 ^a	-1.7 ± 0.6 ^b	-1.9 ± 0.8 ^b	0.014
Ratings of Perceived Exertion (RPE)	0 th min	8.8 ± 2.2 ^a	10.3 ± 2.6 ^b	10.6 ± 1.4 ^b	0.016
	8 th min	9.3 ± 2.6 ^a	11.2 ± 3.3 ^b	11.1 ± 1.4 ^b	0.013
	25 th min	12.1 ± 1.4 ^a	14.2 ± 1.5 ^b	13.4 ± 1.4 ^{ab}	0.022
	38 th min	13.3 ± 1.1 ^a	15.8 ± 1.9 ^b	15.3 ± 1.7 ^b	0.002
	48 th min	11.4 ± 1.7 ^a	13.2 ± 2.1 ^b	14.1 ± 3.0 ^b	0.008
Time completed (stopped)(min)		78.4 ± 11.7 ^a	71.2 ± 16.6 ^{ab}	64.9 ± 11.0 ^b	0.009

4. CONCLUSION

We found that sleeplessness or alcohol consumption significantly increased the psychological and physiological heat strain experienced by subjects performing physical tasks in full-PPE in a hot and humid environment. Alcohol intake led to higher rectal temperature during the following day's work than the sleeplessness, while sleeplessness caused slightly more severe fatigue during exercise.

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INTEGRATING A LIQUID SWEAT DIFFUSION MODEL INTO HUMAN THERMAL SIMULATION

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Abstract: *Sweat build-up on the skin and in clothing affects body temperatures and comfort. However, existing human thermal models typically do not quantify the accumulation and diffusion of liquid sweat within clothing layers. We integrate a liquid sweat diffusion model into existing human thermal modeling software and validate the model against experimental data from a human subject study. The simulations show improved accuracy in predicting sweat accumulation and distribution when sweat diffusion is included in the model.*

Keywords: *sweat diffusion, human thermal simulation, moisture transport, clothing model*

1. INTRODUCTION

Accumulation and transport of moisture within multilayer protective clothing can substantially affect its thermal performance and the wearer's thermo-physiological response (Wissler & Havenith, Keiser et al.). Human thermal modeling can be used to predict and understand the impact of sweat accumulation on human thermal physiology. We previously developed and validated a model for simulating heat and moisture transport on the skin and within clothing. However, this model did not consider the diffusion of liquid sweat within the clothing layers. This limitation is particularly significant for protective clothing where high thermal and evaporative resistances often lead to sweat accumulation. Accurate modeling of sweat diffusion is therefore essential to improve predictions of thermal stress and comfort in protective ensembles. In this work, we extend the model to incorporate sweat diffusion. We validate the model by comparison with human subject tests and analyse the impact of sweat diffusion on key physiological results.

2. MATERIALS AND METHODS

2.1 Human Thermal Model

A sweat diffusion model was incorporated into the TAItherm™ software modelling tool. The software includes a comprehensive human thermal model (HTM) based on the Fiala HTM (Fiala et al., 2001), but has been significantly enhanced to model physiology and anthropometry more accurately. The HTM predicts the physiological and psychological responses of humans to their environments. The human is modelled as a 3D shell element mesh with the body tissues considered as layers. Additionally, it includes a moisture transport model that tracks phase change (e.g., evaporation of sweat and condensation of ambient humidity) and its impact on temperature and moisture content within clothing layers, as well as the transport of vapor through the clothing layers. The moisture model also allows considering the transient dependence of clothing thermal resistance on the liquid content accumulating in the clothing.

2.2 Sweat Diffusion Model

While the HTM predicts the transport of vapor between clothing layers, it does not consider the diffusion of liquid. In this work, we address this limitation by implementing an empirical sweat diffusion model that runs at each time-step of the HTM simulation. The sweat diffusion model employs a user-provided maximum liquid absorption capacity for each clothing layer as a diffusion criteria. If the liquid in a given element and layer of the human geometry exceeds the maximum capacity, the excess liquid is distributed to its neighbouring elements until all excess liquid has been distributed. Diffusion of liquid through the thickness of the fabric is assumed to occur immediately such that sweat absorption through the thickness is uniform.

Validation of the sweat diffusion model was completed by simulating human subject experiments that gravimetrically quantified the sweat absorption in 22 distinct t-shirt regions during treadmill running (Raccuglia et al., 2018). Simulations set the whole-body sweat rate equal to the observed average of 22.45 g/min from the experiment and used a sweat map derived from (Smith & Havenith, 2011). The material properties of the cotton shirt were set to the values reported in Raccuglia et al. ($R_{ct} = 0.039 \text{ m}^2\text{K/W}$, $R_{et} = 3.1 \text{ m}^2\text{Pa/W}$, $\rho = 289 \text{ kg/m}^3$, $t = 0.55 \text{ mm}$). The wet thermal resistance of the shirt was estimated as $0.00123 \text{ m}^2\text{K/W}$ (see Appendix I of Wang, 2017). 27.2°C ambient, 49.7% RH, and 1.5 m/s wind boundary conditions were imposed. Thermal convection around the human was modelled using empirical correlations based on estimated effective wind speeds for each body segment that account for body motion during treadmill running (Nishi & Gagge, 1970).

Simulations were run with and without inclusion of the liquid diffusion model to quantify the impact of sweat diffusion on the results. For the sweat diffusion model, the maximum absorption capacity of the shirt was set to 381 g/m^2 as reported by Raccuglia et al. On clothed segments, the maximum capacity of the skin to hold sweat was set to 35 g/m^2 (see Fiala et al., 2001). To account for the additional surface area due to folds and looseness of clothing, an effective clothing area for each garment was defined. The effective surface area of the modelled shirt was set to that measured in the human subject tests (0.873 m^2).

3. RESULTS AND DISCUSSION

Figure 1a compares the measured and predicted total sweat absorption of the shirt with and without consideration of sweat diffusion. The software used in this study allows setting a maximum absorption capacity of clothing after which the liquid is assumed to drip off. The simulation results using the existing software without including our new sweat diffusion model significantly overestimated the absorbed sweat when the maximum absorption capacity was set to the measured 381 g/m^2 . Without the sweat diffusion model, sweat appearing on the skin remained on the skin-facing side of the clothing, never diffusing through the thickness. When sweat diffusion was added to the model, the absorbed sweat was larger than but within the standard deviation of the experimental results. One source of error in the model is that it assumes diffusion only occurs once a user-defined saturation level is reached rather than increasing gradually as a function of fabric saturation.

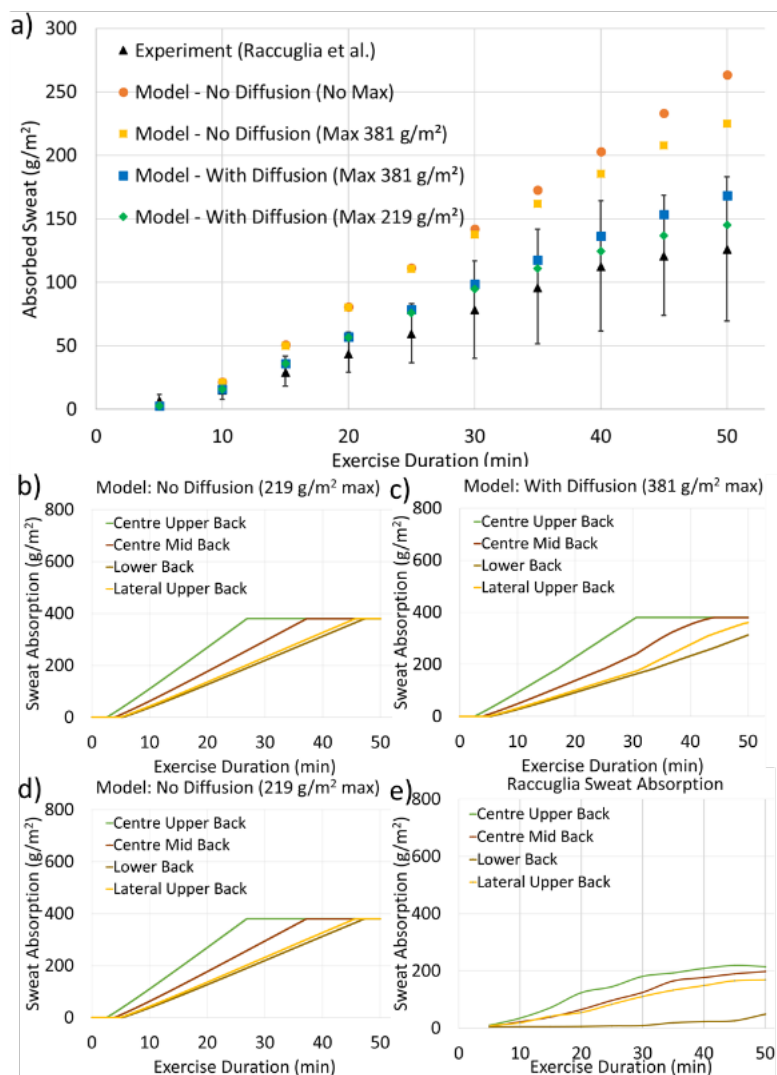


Figure 1. Predicted vs. measured total (a) and segment-level (b) absorbed sweat in the shirt.

Decreasing the threshold at which diffusion starts from 381 g/m² to the observed segment-level maximum liquid content of 219 g/m² effectively modeled an earlier onset of diffusion and yielded predictions closer to the experimental mean values.

Figure 1b-e shows the segment-level sweat accumulation results. Without the liquid diffusion model, the segment-level sweat accumulation (Figure 1b) followed a simple linear trend with a sharp cut-off once the maximum absorption capacity was reached. When sweat diffusion was added, the sweat accumulation trends became non-linear and more similar to the measured results. Especially notable were the similarities between the centre lower back and lateral back regions of the measured and simulated results, where model predictions showed an increase in liquid accumulation slope at the onset of sweat diffusion from the most saturated segment (centre upper back). Decreasing the sweat absorption threshold forced an earlier onset of diffusion and therefore increased the liquid accumulation rate in the neighbouring segments to shorter exercise durations. Another source of error in our model is the assumption of perfect contact between the shirt and skin in all areas of the shirt, while the actual contact with the skin can be intermittent in some areas. This would limit garment sweat absorption, which could, result in low measured sweat absorption in areas like the lower back, despite having a physiologically higher sweat rate (Raccuglia et al. 2018). Despite these errors, our sweat diffusion model provided a good first-order approximation to sweat accumulation in garments.

Figure 2 compares the mean skin temperatures, centre upper back and left lower arm skin temperatures, and total evaporative cooling rate for the different simulations (core temperature impacts were insignificant). With the sweat diffusion model, the evaporative cooling rate increased, resulting in lower skin temperatures. Additionally, the threshold for sweat diffusion impacted the skin temperatures of segments where diffusion occurred due to its impact on fabric saturation levels, which in turn affected liquid-dependent thermal resistance values. Using a lower threshold caused less liquid accumulation, resulting in higher fabric thermal resistance.

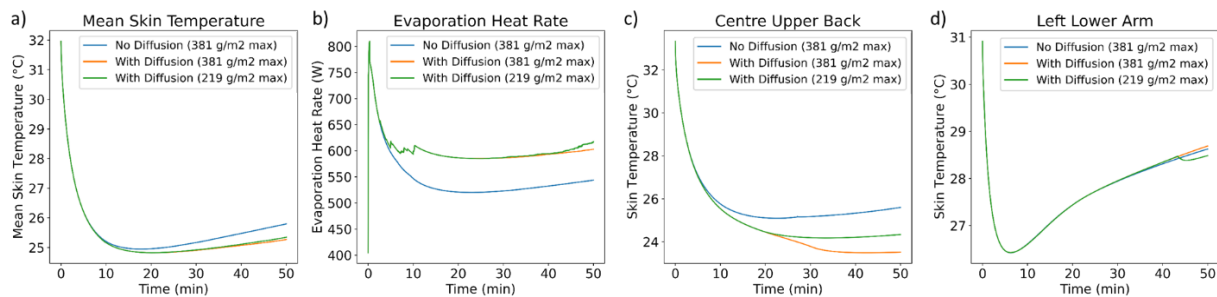


Figure 2. Mean skin temperatures (a), evaporation rate (b), and local skin temperatures (c, d).

4. CONCLUSION

This study integrated a liquid sweat diffusion model into an existing human thermal modelling software and demonstrated an accuracy improvement of liquid sweat accumulation prediction through comparison with human subject test results. Incorporating liquid sweat diffusion into the model significantly increased the predicted total sweat evaporation rate and resulted in lower skin temperatures. Further, the amount of liquid sweat accumulation significantly impacted skin temperatures due to liquid-dependent thermal resistance. Future work may include additional liquid diffusion model validation using stand-alone fabric wicking/diffusion experiments and incorporation of a gradual onset of diffusion based on liquid gradients.

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COOLING CLOTHING BASED ON THERMOELECTRIC PHENOMENON - EVALUATION OF FUNCTIONALITY AND ERGONOMICS

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Abstract: *The problem of thermal load due to the exposure to a hot microclimate still persists for a significant number of workers. In some working environments, such as glass works, ongoing technological processes further negatively affect thermal comfort, and the collective protection measures used are not sufficient. We proposed a cooling clothing that can dissipate heat from the skin through the use of thermoelectric modules, thereby improving the thermal comfort of its wearer. The cooling clothing was tested with 6 users in laboratory conditions in terms of its functionality and ergonomics of use. The study showed that the most significant cooling effect was achieved at the beginning of the test, with a maximum difference in local skin temperature decrease of up to 3 °C. The research made it possible to formulate conclusions for the modification of the cooling clothing's design in order to achieve a more perceptible cooling effect.*

Keywords: *cooling clothing, thermoelectric effect, Peltier modules.*

1. INTRODUCTION

The problem of thermal load due to the exposure to a hot microclimate still persists for a significant number of workers (Kjellstrom et al., 2019). Prolonged exposure to a hot microclimate can adversely affect human's health, and also cause a decrease in concentration and an increase in errors and accidents (Traczyk & Trzebski, 2001; Bogdan et al., 2012; Gwóźdź B., 2001). In addition, in some working environments, such as glass works, ongoing technological processes further negatively affect thermal comfort. The working environments of glassworks involve close contact with the glass mass, with temperatures reaching around 1,000°C, causing exposure to heat radiation. These additional hazards place additional requirements for the clothing used in glass factories, such as flame retardancy and resistance to heat. Sometimes, collective protection measures, eg. air conditioning, are not sufficient enough. Therefore, there is a need for other means that could ensure comfort and safety in arduous and demanding working conditions. A promising direction in this topic is the application of Peltier modules, which due to the temperature difference between their two sides can be used for either cooling or heating (Tian et al., 2014). We proposed a cooling clothing for use in glassworks that can dissipate heat from the skin through the use of thermoelectric modules, thereby improving the thermal comfort of its wearer.

2. MATERIALS AND METHODS

2.1 Tested object

A cooling garment was developed, which was equipped with 7 thermoelectric modules that realize the cooling function. Six thermoelectric modules were placed around the body: on the chest (2 modules), mid-back (2 modules) and sides (2 modules). One thermoelectric module was placed on the back, between the shoulder blades. A heat sink made of superabsorbent fiber was used to dissipate heat from the hot side of the modules. Due to the intended use of cooling garments in the glassworks, the garment was made of flame-retardant materials and accessories.

2.2 Research conditions

The developed cooling clothing was subjected to laboratory tests under simulated conditions of use with the participation of 6 glassworks workers volunteers, with the focus on evaluating the functionality and ergonomics of use. The tests were conducted in an environment with a

temperature of about 30°C and a relative humidity of 65%. During the tests, the participants were dressed in flame-retardant trouser and blouse typically used in the workplace, and in the developed cooling clothing.

2.3 Measured parameters

The research included measurement of selected objective physiological parameters of the participants and their subjective opinions. In terms of physiological parameters, local skin temperature was measured at two locations: under the thermoelectric module on the back and under the module on the abdomen. In terms of subjective parameters, users' thermal comfort regarding thermal sensations (ASHRAE scale) was evaluated. Thermal comfort assessments were made every 5 min during the conduct of the study.

2.4 Research Procedure

As part of the research procedure in the laboratory tests, physical activity was planned to be performed in 15-minute sequences with 5-minute breaks between each activity sequence. Three activity sequences were performed. During the breaks, the participant remained at rest, in a standing position. The selected activity was walking on a treadmill at a speed of 5 km/h. Walking on a treadmill corresponds to a high level of physical activity, which made it possible to test the developed model of cooling clothing at high exercise. The research was performed in two variants: with and without cooling clothing. After the tests, participants completed a survey questionnaire on the ergonomics of using the tested clothing.

3. RESULTS AND DISCUSSION

The study showed that the maximum difference in local skin temperature between the variant with and without cooling was 3 °C. The most significant cooling effect was achieved at the beginning of the test and a decrease in the cooling effect was observed as the test progressed. It should be noted that in the test with cooling clothing, the increase in local skin temperature was smaller at the end of the test than in the variant without cooling. In addition, the research confirmed a slight subjective improvement of thermal sensations (Figure 1). The research conducted enabled the identification of directions for improving clothing design. The fit of the cooling clothing to the body was rated with an average score of 3.83. This demonstrates the need to refine the clothing's design to ensure that the garment adheres better to the body, which will translate into a better cooling effect. The average rating for freedom of movement reached 4, and the average rating for ease of putting on, fitting and taking off clothing was 3.67.

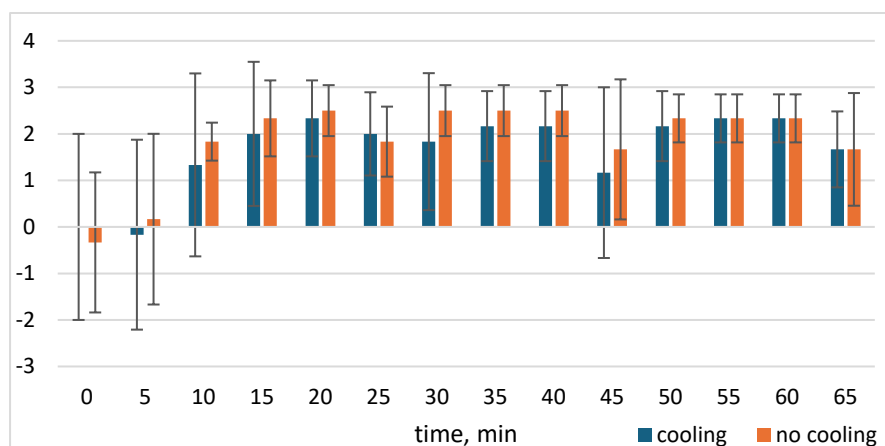


Figure 1. Average rating of thermal sensations during the tests

4. CONCLUSION

The direct effect of the applied cooling can be seen in the results of local skin temperature tests on the back and abdomen. The greatest cooling effect was observed during the initial phase of the experiment, when the difference in local skin temperature reached as much as 3 °C. Particularly noteworthy is the fact that representatives of the end users – workers at the glass works – were involved in laboratory tests under simulated conditions of use. It is important to emphasize the fact that these were people who work in hot microclimate conditions and are acclimatized to work in such conditions, which means that their physiological reactions, as well as subjective feelings, may be different from those of non-acclimatized people, and this adds to the scientific and applied value of the research conducted. In addition, a key aspect of the completed usability study was to gather the opinions of those familiar with the work performed at the glass works in terms of adapting the developed solution to the working conditions there. Improvement efforts in the design of cooling garments should be aimed at increasing the feasible cooling intensity. It is necessary to adjust the construction of clothing to ensure that the thermoelectric modules adhere well to the body, which will enhance the effect of perceived cooling. A special research challenge in this area is to simultaneously ensure the safety of the use of this type of cooling clothing in hot conditions.

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The Central Institute for Labour Protection – National Research Institute is the Programme’s main co-ordinator.

IMPROVEMENT OF FLAME RETARDANCY PROPERTIES OF TEXTILE SURFACES COATED WITH CELLULOSE SOLUTION BY COAGULATION WITH SILANE AND PHOSPHATE-BASED NANO-SOL-GEL

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Abstract: *In this study, nitrogen- and phosphate-based compounds were used to impart flame retardant (FR) properties to cotton fabric. To increase the number of free hydroxyl end groups on the cotton fabric, dissolved cotton fiber obtained through two different methods was transferred onto the fabric via a mechanical scraping method. The regenerated cellulose was then coagulated using a formulation containing silanol and FR compounds. Since the wash durability of the obtained samples was observed to be insufficient, they were treated with a crosslinking formulation, and their wash durability were re-examined. The FR formulation successfully imparted high LOI (Limiting Oxygen Index) flame retardancy to all samples. However, a dramatic decrease in LOI values was observed in samples washed with phosphate-containing detergent. In this study, carboxyl-functionalized crosslinking agents and the hydrophobic functional groups of silanes will be used to enhance washing durability. Additionally, flame retardant (FR) treatment parameters and the FR receipt will be experimentally restructured.*

Keywords: *Guanidine phosphate, Silane based sol-gel, Cellulose dissolution, regenerated cellulose, Fire retardancy*

1. INTRODUCTION

Cellulose fiber, which is widely used in the textile industry, is highly flammable, burns rapidly, and can sustain combustion on its own. With a Limiting Oxygen Index (LOI) value of 19 and a pyrolysis temperature range of 360–420°C, researchers have focused on enhancing the flame resistance of this natural fiber by incorporating flame-retardant (FR) compounds. These flame retardants primarily include halogens and their derivatives, nitrogen-based, and phosphorus-based compounds. The main mechanism of these compounds involves reducing levoglucosan formation, minimizing the release of flammable volatile gases, and promoting char formation, thereby improving flame retardancy (Aksit et al., 2016).

In recent years, the negative environmental and human health impacts of halogen-containing compounds have led to an increased preference for phosphorus-based flame retardants. Despite their relatively low thermal stability, phosphorus-based compounds exhibit high flame resistance and release fewer toxic gases during combustion. Their effectiveness can be further enhanced by the presence of nitrogen and silicon (Liu & Chou, 2005; Zhao, 2010).

Another significant group of flame-retardant compounds is nitrogen-based flame retardants. Among them, guanidine phosphate is particularly noteworthy due to its low toxicity, environmental compatibility, and lack of halogenated acids, as well as the fact that it does not produce toxic fumes during combustion (Wang et al., 2021; Aksoy, 2023).

Over the past two decades, one of the most promising methods for designing efficient flame-retardant coatings has been the Sol-Gel technique. In this approach, silanes serve as precursors, which undergo hydrolysis and condensation reactions catalysed by acid, leading to the formation

of porous Si–O–Si networks. Since these coatings can form covalent bonds with textile surfaces, they have the potential to provide durable and wash-resistant flame-retardant textiles (Wang et al., 2021).

In this study, a sol-gel method was employed to enhance the flame resistance of cotton fabric by forming silanol networks and functionalizing their terminal groups with guanidine. To increase the number of hydroxyl end groups on the cotton fabric surface and improve bonding, an additional cellulose coating was applied using a cellulose solution. The coagulation of the cellulose solution, which was transferred onto the cotton fabric via a scraping method, was carried out using a nano sol-gel solution containing guanidine phosphate, APTES, GPTMS, and urea. As a result, the effects of this method and the increased number of cellulose end groups on the textile properties, particularly flame retardancy, were evaluated. However, the durability of silane networks is highly dependent on the presence of crosslinking agents and post-curing conditions, which will be further optimized in this study. To improve wash durability, carboxyl-functionalized crosslinking agents such as phytic acid, citric acid, tannic acid, and boric acid will be incorporated into the formulation, as they have been reported in the literature to enhance crosslinking with silane compounds. Furthermore, hydrophobic functional groups such as 3-(2-aminoethylamino)-propyltrimethoxysilane (AAPTMS) and 3-Mercaptopropyl-trimethoxysilane will be introduced to increase durability to washing (Wang et al., 2020; Safdar et al., 2024).

2. MATERIALS AND METHODS

2.1 Preparation of cotton dissolutions

2.1.1. DMAc/LiCl dissolution method

The hydrophilic cotton, without undergoing any pretreatment, was dried at 105°C for 24 hours to remove moisture. The DMAc solution (Figure 1) was heated to 80°C, and cotton, pre-dried to its absolute dry weight, was added at a concentration of 2% by weight. This solution was stirred for 30 minutes. Subsequently, 8%wt LiCl salt was added and stirred at 80°C for 3 hours. The temperature was then lowered to 50°C, and the solution was continuously stirred for one day. On the following day, the solution was subjected to thermal treatment at 105°C in an oven for 12 hours. After cooling to room temperature, the solution was filtered through a fine metal sieve to remove any remaining fibers.

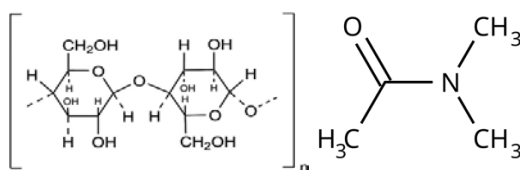


Figure I. Chemical Structure of Cellulose and DMAc Solution

2.1.2. NaOH/Urea dissolution method

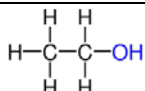
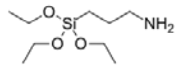
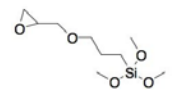
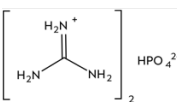
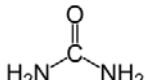
A solution containing NaOH/Urea/Water (7:12:81 by weight) was prepared and cooled to -12°C. Cotton fiber (2g), pre-dried to its absolute dry weight, was also cooled to -12°C. The cotton fiber was then immersed in the prepared solution and kept at this temperature for 12 hours. Subsequently, as the solution was brought back to room temperature, it was stirred for 2 hours.

Afterward, the solution was subjected to high-speed mixing at 15,000 rpm using a high-shear mixer. The resulting solution was used without filtration.

2.2 Perpetration of Silan based FR sol-gel dissolution

To impart flame retardant (FR) properties to cotton fabric, a silan-based (APTES-GPTMS) sol-gel solution, previously formulated in earlier studies, was modified by incorporating guanidine phosphate and urea, both of which contain amine and phosphate functional groups. The solution was prepared by sequentially adding the materials listed in Table 1 in the specified amounts. After preparation, the solution was stirred at 400 rpm using a magnetic stirrer at 25°C for 1.5 hours to ensure homogeneity.

Table 1. Composition of the FR Sol-Gel Solution and Materials (Adapted from Akşit et al., 2016)

Material	Brands	Structural formulae	FR Sol-gel Receipt
Ethanol	Sigma Aldrich		%25 v/v
Distilled water			%35.9 v/v
APTES(3-Aminopropil) trietoksisilan)	Sigma Aldrich		%8.3 v/v
GPTMS(3-Glisidiloksipropil) trimetoksisilan)	Sigma Aldrich		%4.4 v/v
Acetic Acid(CH ₃ COOH)	Merck		%3.5v/v
Phosphoric acid(H ₃ PO ₄)	Sigma Aldrich		%5.1v/v (PH 3-4)
Guanidine Phosphate	Setaş		%5.4w/v
Distilled water			%18 v/v
Urea	Merck		%1w/v

2.3. Coating of cotton fabric surface with cellulose solutions

Due to the challenges associated with cellulose dissolution, experiments were conducted on small-scale samples. To simulate the coating process using a rotating rakel, a glass rod was utilized. A cotton fabric sample (approximately 25 × 25 cm) was placed on a flat surface, and 20 mL of the dissolved cellulose solution was evenly dispensed onto one edge of the fabric using a syringe. The glass rod was then rolled from both ends, ensuring the uniform distribution of the cellulose solution over the cotton fabric. The coated cellulose exceeded 100% of the original fabric weight. Immediately after coating, the cellulose-coated fabric was immersed in a pre-prepared FR sol-gel solution, where deep coating and simultaneous coagulation were achieved. To remove excess solution, the samples were passed between glass rods, after which they were suspended in an oven preheated to 70°C and left to dry until completely cured. At this stage, the obtained fabrics were labeled as TK-001, TK-002, and TK-003.

2.3 Preparation crosslinking dissolution and treatment

Preliminary trials conducted for this study revealed that the silanol network structure formed on the cotton surface was not resistant to washing. Initially, an experiment was performed to examine the binding of the silanol network and cellulose groups using the deep coating method with GPTMS. For this purpose, 20 mL of GPTMS was dissolved in 25 mL of ethanol. Since an acidic environment is required for effective crosslinking and to further enhance flame retardancy, phosphoric acid was added until the pH reached 3.5 (approximately 5 mL, Recipe-2). The FR sol-gel-coated and dried samples were then subjected to crosslinking using the deep coating method. The resulting crosslinked fabrics were labeled as TK-011, TK-012, and TK-013.

2.4 Washing procedure

To evaluate the wash durability of the cellulose layer coated on the cotton fabric surface and the flame-retardant silane network formed via the sol-gel process, a short washing procedure was applied. The washing solution was prepared using 0.5 wt% ECE Phosphate Standard Detergent B. The solution was stirred at 400 rpm until it reached 40°C. The coated and GPTMS-crosslinked fabric samples (20 × 20 cm) were subjected to a washing process at 40°C for 15 minutes. Following the washing step, the samples were suspended in an oven preheated to 70°C and left to dry until completely cured. At this stage, the resulting washed fabric samples were labeled as TK-111, TK-112, and TK-113.

2.5 LOI Test Procedure

The LOI (Limiting Oxygen Index) test was conducted in accordance with the ASTM D2863-77 standard. Prior to testing, the samples were conditioned for 24 hours under standard atmospheric conditions. The test specimens were cut to dimensions of 54 × 140 mm, and the test was performed by setting the %N₂ concentration to 68 for non-burning samples in air and 74 for samples that burned in air. The Limiting Oxygen Index (LOI) was calculated using the following formula:

$$\%LOI = (100 \times O_2) / (O_2 + N_2)$$

where:

O₂ = Measured oxygen concentration (cm³/s)

N₂ = Nitrogen concentration used (cm³/s)

3. RESULTS AND DISCUSSION

Silane-based precursors undergo hydrolysis in water when catalyzed by acids or bases, followed by a polycondensation reaction, leading to the formation of a Si–O–Si network and a porous structure. Figure 2 illustrates the network structure and chemical bonds of APTES, as described by Zhu et al. (2012). The diagram represents: (a) Hydrogen bonding, (b) Electrostatic attraction forces, (c) Covalent bonding with the substrate, (d, e) Horizontal and vertical silane polymerization, (f) Oligomeric silane groups. In particular, the terminal amino groups of vertically aligned silane molecules interact with other amino-terminated molecules via hydrogen bonding. In the FR formulation, guanidine phosphate, urea, and phosphoric acid, which contribute to flame retardancy, can easily bind to APTES via hydrogen bonding due to its amino functional groups. In this study, a cellulose solution was used to enhance the flame-retardant properties of cotton fabric. The primary reason for incorporating cellulose was to increase the number of free hydroxyl groups, thereby enhancing the binding capacity of silicon-based compounds.

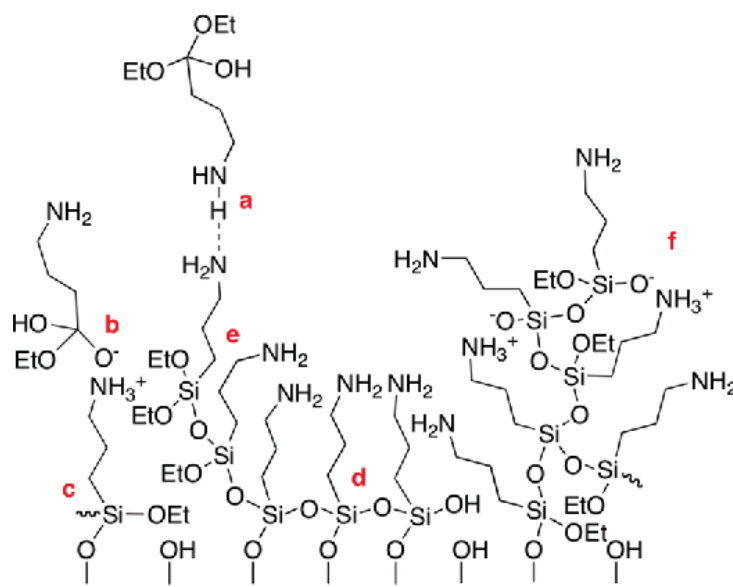
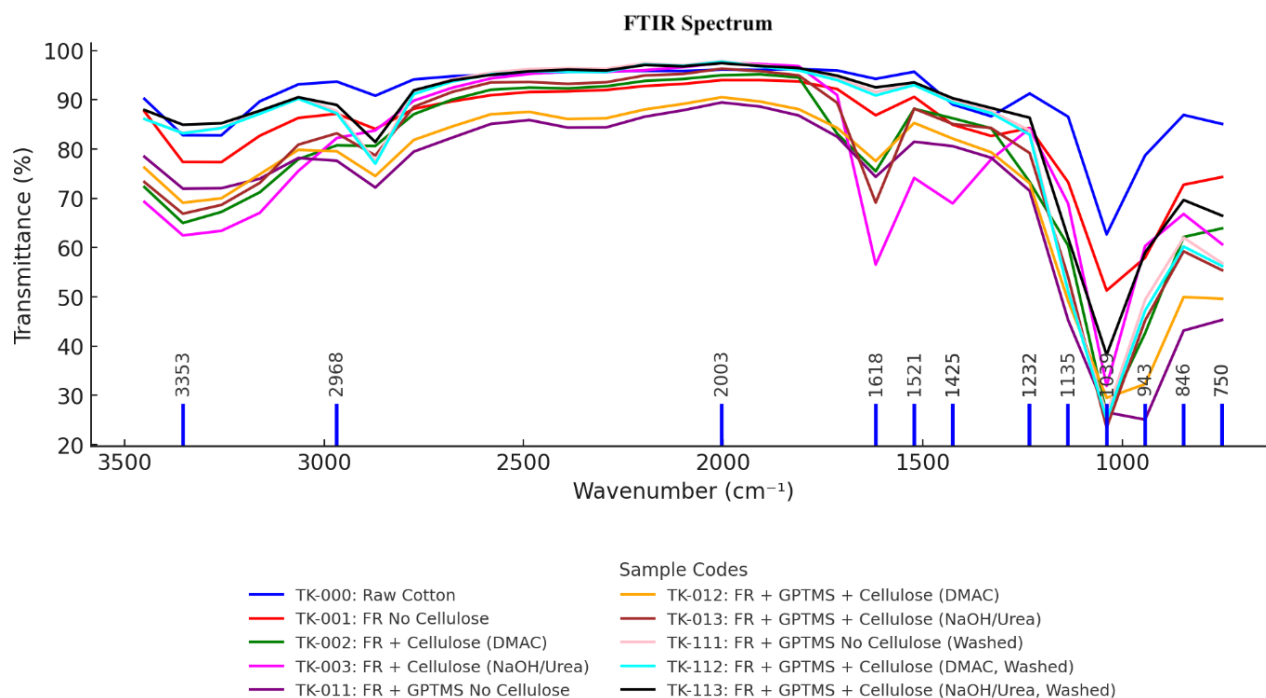


Figure 2. APTES An APTES-derived layer with structural linkages (Zhu et al. 2012)

FTIR analysis was performed to understand the binding mechanisms of silane-based APTES and GPTMS, amino groups, and flame-retardant compounds such as guanidine phosphate and urea on cotton fabric. Based on this analysis, FTIR spectra of the samples, whose codes are detailed below, are presented in Figure 3.

Figure 3. FTIR spectra of samples

TK-000 exhibits typical characteristic peaks of cellulose. The hydroxyl group stretching vibrations of cellulose, located at approximately 3330 cm^{-1} and 3269 cm^{-1} , correspond to intramolecular hydrogen bonding (Zhou and Wang, 2021; Acharya et al., 2017). The C-H stretching vibrations appear at $2923\text{--}2854\text{ cm}^{-1}$ (Meng et al., 2012). Peaks at 1314 , 1108 , 1054 , and 985 cm^{-1} correspond to C-H bending, asymmetric ring stretching, glycosidic bond stretching (C-O-C), and ring stretching mode of cellulose, respectively (Rumi et al., 2021). TK-001 was obtained via deep



coating with the FR formulation without a cellulose coating layer. The FTIR spectrum of this sample exhibits similar peaks to TK-000.

TK-002 (DMAC/LiCl method) and TK-003 (NaOH/Urea method) represent the FTIR spectra of cellulose dissolved in DMAC/LiCl and NaOH/Urea/Water solutions, respectively, followed by coagulation with the FR solution on the fabric.

Based on the spectra, broadening and slight shifts are observed in the OH stretching region (3330–3269 cm⁻¹). The shifts at approximately 2984 cm⁻¹, 1105 cm⁻¹, and 1022 cm⁻¹ are attributed to the rearrangement of hydrogen bonds (Jeoh et al., 2024). Specifically, shifts in the 3260–3220 cm⁻¹ region indicate that amine-containing compounds such as guanidine and urea formed hydrogen bonds with cellulose (Vasiljević et al., 2015; Wang et al., 2006; Zuo et al., 2010).

The TK-001, TK-002, and TK-003 samples were treated with the FR formulation. Based on the FTIR spectra, the peak observed at 1254 cm⁻¹ is attributed to P=O stretching, while the peak at 1694 cm⁻¹ corresponds to P–O stretching vibrations, confirming the presence of phosphate-based flame-retardant compounds in the fabric. The peaks at 1022 and 1015 cm⁻¹ correspond to P–O–C vibrations, indicating that phosphate groups are chemically bound to the organic matrix (Chen et al., 2022; Alongi et al., 2012a; 2012b; Zuo et al., 2010).

A strong peak at approximately 1040 cm⁻¹ is observed in all fabric samples, which is associated with C–C, C–O, and Si–O–Si vibrations (Alongi et al., 2012a; 2012b; Bechi et al., 2013). In the treated fabrics, the peak observed in the 787–752 cm⁻¹ range corresponds to the formation of Si–C bonds (Al-Oweini and El-Rassy, 2009; Alongi et al., 2012b; Liu et al., 2016) and asymmetric Si–O–Si stretching vibrations (Al-Oweini and El-Rassy, 2009; Colleoni et al., 2013). The Si–O–Si vibrations at approximately 900 cm⁻¹ indicate the formation of a silane network by GPTMS. Peaks at 1638 and 1539 cm⁻¹ correspond to N–H stretching vibrations, confirming the presence of guanidine and urea-based compounds (Liu et al., 2016).

After treatment with the flame-retardant (FR) solution, the TK-011, TK-012, and TK-013 samples were subjected to a crosslinking process, in order to crosslink the silane network with cotton fabric. The FTIR spectra of these samples exhibited increased Si-O-Si bond vibrations at $\sim 1105\text{ cm}^{-1}$ and $\sim 1022\text{ cm}^{-1}$, compared to non-crosslinked samples, confirming the formation of a silane network by GPTMS. The shift in P-O stretching vibrations at 1255 cm^{-1} and $\sim 1022\text{ cm}^{-1}$ suggests an interaction between phosphoric acid and GPTMS, further supporting the formation of a crosslinked structure. Theoretically, this confirms that GPTMS has successfully formed a crosslinked network within the treated samples.

The TK-111, TK-112, and TK-113 samples were washed in a phosphate-containing detergent. A decrease in P-O peak intensities at $\sim 1255\text{ cm}^{-1}$ and $\sim 1022\text{ cm}^{-1}$ was observed, indicating that some phosphate compounds were removed from the fabric. Additionally, the reduction in Si-O-Si peak intensities at 1105 cm^{-1} and $\sim 1022\text{ cm}^{-1}$ suggests that GPTMS crosslinks underwent partial hydrolysis. Furthermore, the increase in the O-H region implies that the fabric regained a higher number of free hydroxyl groups.

These spectral changes indicate that a significant portion of the flame-retardant phosphate compounds was washed away, and the silane network structure was largely degraded.

To evaluate the flame-retardant properties of the treated fabrics and to determine whether the silane network remained effective after washing, an LOI (Limiting Oxygen Index) test was conducted. The LOI values of the treated fabrics are presented in Figure 4.

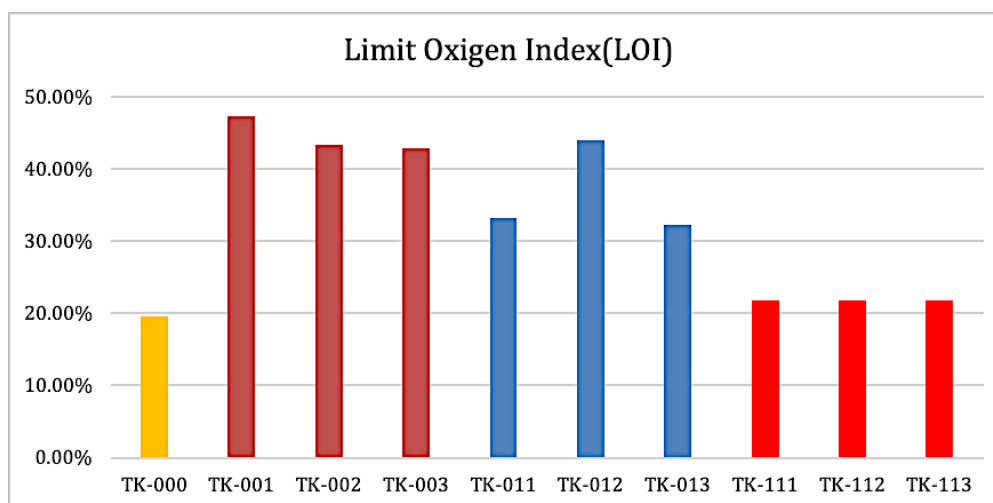


Figure 4. Limit Oxygen Index (LOI) of test samples

According to the results, the FR formulation increased the LOI value of cotton fabrics above 40%. Additionally, the crosslinking formulation caused a slight decrease in LOI values for both samples, except for the one where cellulose was dissolved using the DMAc method. The dramatic decrease in LOI values after washing confirms that the silanol network and guanidine phosphate were bound via hydrogen bonds rather than covalent bonds. After washing, the LOI value remained

slightly above that of the untreated fabric. However, it should be noted that the washing process was performed using an ECE phosphate-based detergent. These findings highlight the necessity of introducing stronger covalent crosslinking through carboxyl-functionalized agents and silanol-functional modifications. In the continuation of this study, further investigations will focus on:

1. Incorporation of carboxyl-functionalised crosslinking agents to increase the stability of the silanol network and flame-retardant compounds to improve the washing durability. For this purpose, phytic acid, citric acid, tannic acid and boric acid have been used in the literature for crosslinking different silane compounds and it is predicted that the washing resistance of crosslinked structures will increase in this way (Safdar et al., 2024; Song et al., 2023; Li et al., 2024).

2. Furthermore, it is aimed to reduce water absorption by giving the structure a hydrophobic character. Thus, it is estimated to increase the washing durability.

4. CONCLUSION

The flame-retardant (FR) compounds bound to both cotton fabric and cellulose-coated cotton fabric via silanol networks significantly enhanced their flame-retardant properties. FTIR analysis confirmed that guanidine phosphate and urea were hydrogen-bonded to the amino groups located at the terminal ends of the silanol networks. This finding is further supported by the LOI results, as the LOI values of washed samples remained slightly higher than those of untreated cotton. The dramatic decrease in LOI values after washing suggests that this reduction may have been caused by the phosphate-based detergent. In the continuation of this study, different crosslinking agents will be evaluated to investigate their effects on LOI values and other textile properties.

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HIGH PERFORMANCE FABRICS, NANOMEMBRANES AND LAMINATION PROCESS IMPROVEMENTS FOR FIREFIGHTERS HOODS SUSTAINABILITY

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¹ Alpex Protection

Abstract: *This study addresses the challenges faced by firefighters during operations, including exposure to heat, fine particles, infectious agents, and mechanical risks. Existing hoods, while compliant with NFPA 1971 or NFPA 1970 standards, have certain limitations. To improve protection and comfort, a multi-layer composite material was developed, combining thermostable mesh textiles with advanced membranes. The membranes studied include CAB (Cellulose Acetate Butyrate), PTFE (Polytetrafluoroethylene), and Polyimide, each evaluated for their thermal resistance, particles filtration, and durability under high temperatures and repeated washes. The research also focused on optimizing the lamination process and adhesive application to enhance the sustainability and performance of the composite material. Tests were conducted on air permeability, filtration efficiency, high temperature behaviour and noise reduction, with additional assessments performed on hood seams.*

Keywords : *firefighters hoods, membranes, particules filtration, comfort, sustainability*

1. INTRODUCTION

Firefighters encounter numerous risks during their daily operations, including fire, heat, fine combustion particles, viruses, bacteria, chemicals, mechanical injuries, and thermal stress. Although their hoods are certified and compliant with NFPA 1971 or NFPA 1970 standards, they still have certain shortcomings. They are composed of aramid bases knits with membrane in between if filtration efficiency needs to be achieved. It is difficult to combine at the same time the particules filtration efficiency especially on seams, the elongation properties, the comfort and situational awareness. This study aims to address these issues by developing a composite material made of two layers of thermostable mesh textiles laminated on both sides of a membrane. The goal is to achieve a high level of particles filtration, reduce perceived noise levels, and ensure wearing comfort. The second phase of the study focuses on optimizing the development and industrial lamination process to enhance washing resistance, improve the durability, sustainability of the multi-layer structure.

2. MATERIALS AND METHODS

2.1. Knits and membranes components used for the multilayers assembly

At the origin of the project we selected aramid based knits to obtain reliable and high performance textiles. We opted for knits with different compositions, similar to current hoods:

- an aramid/viscose FR to prioritize comfort.
- a blend of various fibers, including aramid, modacrylic, and lyocell, to prevent water absorption and facilitate its evaporation.

The primary function of the membrane, although its thickness contributes to thermal performance, is to ensure optimal filtration of fine particles across the entirety of the hood, including the seams. Furthermore, it provides effective protection against the penetration of

infectious agents. The membranes evaluated in this study include CAB (cellulose acetate butyrate), ptfe (which is the most common membrane used) and Polyimide.

2.2. The lamination process and adhesives

To ensure both optimal flexibility and durability under repeated cleaning cycles, we employ a reactive polyurethane hot-melt adhesive. Within this class of polymers, the intrinsic properties of each adhesive, specifically their viscosity and rheological behaviour across different temperature ranges, significantly influence the overall performance of the composite material. Moreover, particular attention has been paid to evaluate the impact of adhesive deposition on the quality and aesthetic properties of the resulting laminate.

2.3. The performances and standards evaluated

2.3.1. Aspect evaluation after washes, NFPA1970 washes procedure and ISO 6330 6N, F

Evaluation of the aspect after a defined number of washes to evaluate the presence of delamination.

2.3.2. Heat and Thermal Shrinkage resistance according to ASTM F2894

In accordance with NFPA 1971 and NFPA 1970 standards, the evaluation is conducted on the hood itself. Tests were carried out on material assemblies at 260°C for 5 minutes, as specified in the standards, to assess the behavior of membranes under high-temperature conditions. Aspect was also reported.

2.3.3. Particles filtrations ASTM F2299

When filtration efficiency is claimed, the 0,1 to 1µm particles filtration efficiency has to be more than 90%. ALPEX Protection tested a specific range of laminated textiles using a nano membrane based on polyimide.

3. RESULTS AND DISCUSSIONS

3.1. Resistance to temperature according to ASTM F2894/F2894M

Tests were conducted to evaluate the shrinkage and aspect of the membranes after 5 minutes at 260°C, requirement of NFPA 1970 standard. We did not notice significant aspect modification with CAB, Ptfе and Polyimide membranes.

3.2. Air permeability and filtration efficiency

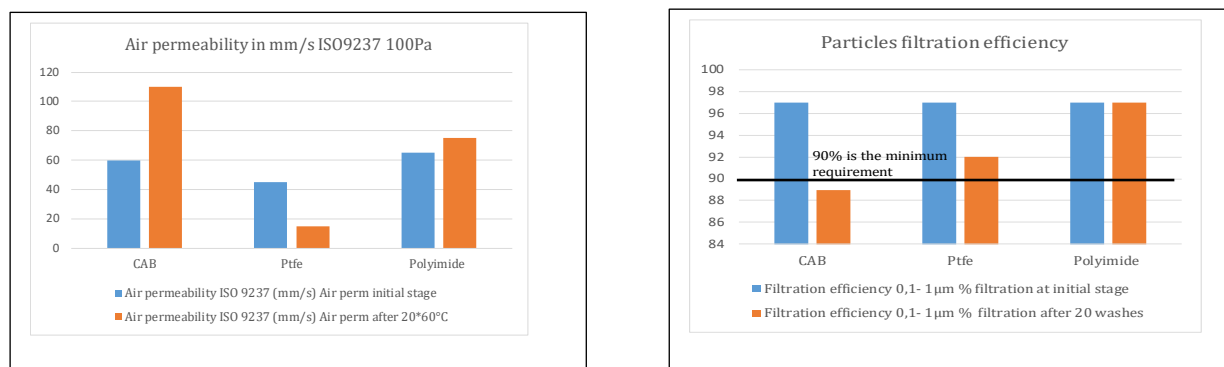


Figure 1. Air permeability and particle filtration efficiency at initial stage and after washes

With CAB membranes, air permeability increases after washing, while filtration efficiency significantly decreases due to membrane degradation during the washing process. These findings were confirmed through additional trials and testing. The PTFE membrane demonstrated lower air permeability results compared to the polyimide nanomembrane, as well as less consistent filtration efficiency after 20 cleaning cycles. Particle filtration tests were also conducted on hood seams. At the initial stage, only the Polyimide membrane achieved the required 90% filtration threshold.

3.3. Noise Measurement

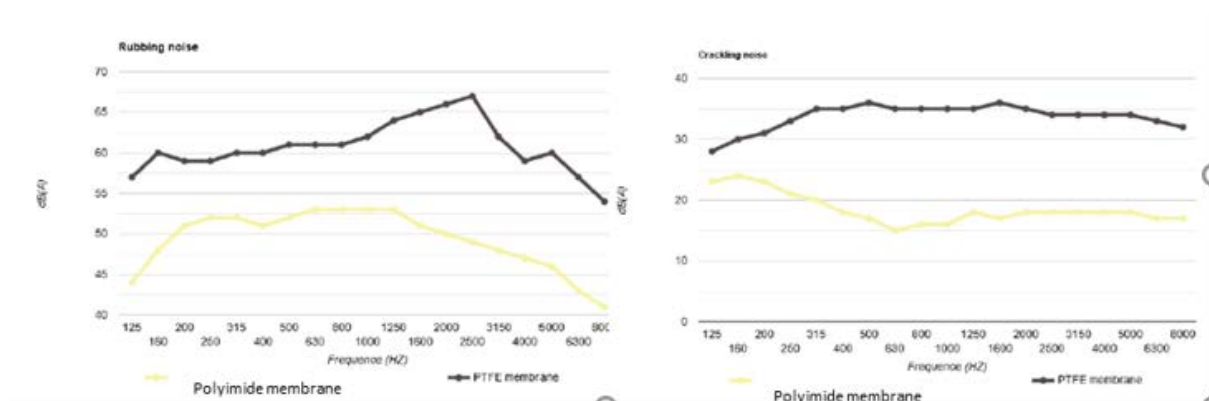


Figure 2. Audible frequency tests of firefighter hoods made with polyimide & PTFE membranes

Hoods manufactured with polyimide membrane are quieter for firefighters compared to those tested and based on PTFE membrane, which leads to a noticeably improved wearing comfort compared to existing solutions.

3.4. Products improvements

The earlier phases of the study demonstrated that the best performance was achieved with the Polyimide membrane. An optimization of the nanomembrane's weight and thickness was conducted. No significant loss in performance was observed with a weight and thickness reduction of between 15% and 30%. Subsequent optimizations focused on the process (adhesive application) and the choice of adhesive to enhance the durability of the multi-layer assembly. The best results were obtained using adhesive formulation C, mesh cylinder X, and a coverage ranging between 7% and 10%.

Table 1. Improvement results summary of adhesive recipe and deposit

	PUR glue recipe with 14% area deposit and mesh X			
	A	B	C	
Resistance to 260°C	✗	✓	✓	=> high amount of adhesive
aspect after 100 washes 60°C	✓	✗	✓	
Hand of the multilayers	✗	✓	✗	
=> Optimization of glue Recipe C				
	4%	8%	10%	
Resistance to 260°C	✓	✓	✓	
Aspect 100 washes 60°C	✓	✓	✓	
Hand of the multilayers	✓	✓	✓	
Aspect after 200 washes 60°C	✗	✓	✓	

4. CONCLUSION

The performance of the multi-layer assembly based on the Polyimide membrane is significantly superior to other tested membranes, such as CAB and PTFE. Another advantage is the Pfas safe solution of this polyimide membrane. Additional tests demonstrated that filtration efficiency remained virtually unchanged even after 250 washing cycles, while maintaining an excellent appearance. These results were achieved not only due to the quality of the materials used but also through the careful selection of the adhesive and the optimization of its application. This represents a major advancement in the composites used for firefighter hoods.

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Engineering Textiles, 2019, Elmogahzy // Different tests reports from laboratories //

AN EFFECTIVE STRATEGY FOR UV PROTECTION OF ARAMID FIBERS: LAYER-BY-LAYER NANOCOATING

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Abstract: *This study investigates the layer-by-layer deposition of hexagonal boron nitride, cerium dioxide and hydroxyapatite nanoparticles in combination with strong adhesion polymer (polyethyleneimine) to enhance the UV resistance of aramid yarns. The effects of different sequential layer arrangements and the incorporation of a radical scavenger (catechol) to mitigate photocatalytic degradation were evaluated. Results indicate that both single and paired sequential orders in LbL coatings contribute similarly to the tensile properties of aramid yarns after UV aging, offering flexibility in process design and scalability. Furthermore, a radical scavenger was easily integrated into the LbL system, protecting against reactive oxygen species. Our findings highlight the significant potential of LbL technology in enhancing the UV resistance of aramid-based materials, offering a simple, efficient, and scalable approach for advanced fiber protection.*

Keywords: *Aramid fibers, UV resistance, Layer-by-Layer, nanoparticle deposition, tensile properties*

1. INTRODUCTION

With its ultra-high strength, high modulus, and excellent thermal and chemical resistance, aramid fiber remains a key material for demanding applications, particularly in defense and aerospace (Zhu et al. 2015; Zhou et al. 2017; Zhu et al. 2017). However, its poor UV resistance compromises mechanical and thermal properties, making UV-induced strength losses unacceptable for high-performance fibers (Zhang et al. 2006). Thus, UV protection is essential. The inert nature of aramid fibers makes coating challenging, often requiring acid or alkali pretreatment, which can cause fiber damage (Zhang et al. 2014; Zhu et al. 2017). Similarly, UV-absorbing semiconductors risk damaging fibers due to their photocatalytic nature (Yasukawa & Tamura, 2021). Therefore, the challenge is twofold: (i) developing a robust UV-protective coating and (ii) integrating it without compromising fiber integrity. Most effective UV protection methods are complex, require special machinery, or are difficult to implement (Cai et al. 2018; Chen et al. 2021). In contrast, the Layer-by-Layer (LbL) self-assembly approach emerges as a simple, versatile, and effective alternative to overcome existing UV protection limitations (Zhou et al. 2017; Ünvar et al. 2023).

2. MATERIALS AND METHODS

2.1 Materials

Para-aramid multifilament yarns (Kevlar, 670 dtex) were purchased from Kipaş Textiles (Türkiye). Catechol and linear polyethyleneimine (PEI) were purchased from Sigma Aldrich, sodium hydroxide (NaOH) and hydrochloric acid (HCl) were purchased from Merck. Hydroxyapatite (HAP, 50 nm), cerium dioxide (CeO₂, 8-28 nm) and hexagonal boron nitride (hBN, 67 nm) nanoparticles were purchased from Nanografi Nano Technology (Türkiye).

2.2 Method

2.2.1 Layer-By-Layer Nanocoating

Aqueous dispersions of all nanoparticles (0.5 g/L) were prepared by 30-minute ultrasonication and adjusted to pH 9 for anionic CeO₂, hBN, and HAP, and pH 4 for cationic CeO₂ using 0.1 M NaOH and 0.1 M HCl, respectively. Similarly, an aqueous PEI solution (3 g/L) was prepared by ultrasonication. Catechol solution (60 mM) was prepared by simply dissolving it in distilled water. First, aramid yarns were immersed in a PEI solution to impart cationic surface charges on the fiber surface. Subsequently, they were alternately immersed following the sequence given in Table 1 to complete one LbL nanocoating cycle, with washing between depositions except after PEI or

catechol immersion. A total of 36 nanocoating layers were deposited on aramid yarns by repeating the cycle six times at room temperature, followed by drying at 80 °C for 10 minutes. Recipes A and B were applied in a single sequential order. To investigate the effect of layer ordering in the LbL process, A_OP was designed using ordered pairs: PEI/HAP for the first 12 layers, CeO₂/CeO₂ for the next 12 layers, and PEI/hBN for the final 12 layers, resulting in a total of 36 layers.

Table 1. UV protective LbL nanocoatings

Recipe	Order of Layers					
	1	2	3	4	5	6
A	PEI (+)	HAP (-)	CeO ₂ (+)	CeO ₂ (-)	PEI (+)	hBN (-)
A_OP	PEI (+)	HAP (-)	CeO ₂ (+)	CeO ₂ (-)	PEI (+)	hBN (-)
B	PEI (+)	HAP (-)	CeO ₂ (+)	Catechol (-)	CeO ₂ (+)	hBN (-)

2.2.2 Characterizations and Tests

The morphologies of the LbL nanocoatings on aramid yarns were observed using a Scanning Electron Microscope (SEM). The chemical structures of untreated and nano-coated aramid yarns were evaluated using Fourier Transform Infrared Spectroscopy in attenuated total reflectance mode (FTIR-ATR). Accelerated UV aging was conducted for 168 hours on ATLAS C1005 machine based on the TS EN ISO 4891-3 standard (cycle 1, UVA 340 nm). Tensile tests were performed on an Instron testing machine with maximum capacity of 50 kN load cell, at a gauge length of 250 mm and at the rate of 250 mm/min. The tenacity and elongation at break were measured before and after UV aging to evaluate the UV protection performance of the LbL nanocoatings.

3. RESULTS AND DISCUSSION

The tenacity (cN/dtex) and elongation (%) at break values of the aramid yarns are presented in Fig. 1a and 1b, respectively. While Recipe A increased yarn tenacity, Recipe A_OP led to a decrease. Unlike Recipe A, which has a more balanced structure and compatible material combinations, the presence of HAP in the first 12 layers of A_OP might have initially made the coating stiffer. Additionally, the CeO₂ blocks in the middle may have increased internal stresses within the coating. These factors together could have limited the fiber's flexibility and made it more brittle under tension. The decreased elongation value for A_OP further supports these considerations. On the other hand, Recipe B caused a considerable reduction in initial tenacity while not affecting elongation. This may have originated from the acidic sequential arrangement of Recipe B and/or the possibility that CeO₂ oxidized catechol in that arrangement (Pota et al., 2023).

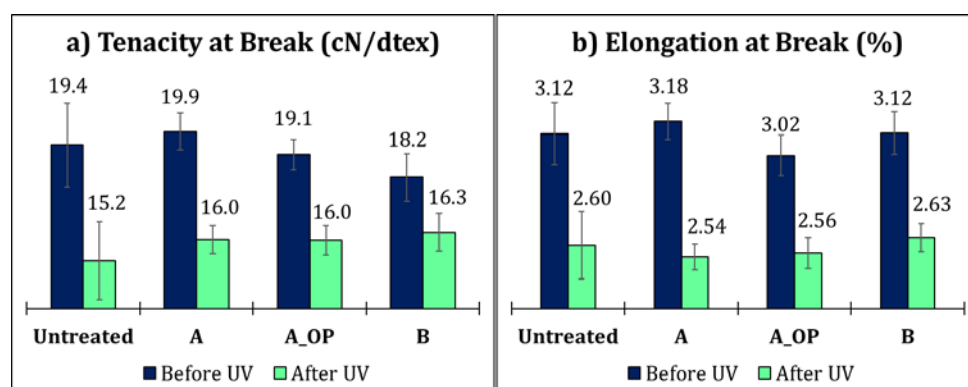


Figure 1 a) Tenacity at break and b) Elongation at break, before and after UV aging

After UV exposure, the tenacity retention for the untreated, A, A_OP, and B treated samples was 78%, 80%, 84%, and 89%, respectively. Despite their initial differences, Recipes A and A_OP both resulted in the same improved tenacity (16 cN/dtex) compared to untreated yarns (15.2 cN/dtex) after UV exposure. In Recipe A_OP, the top PEI/hBN ordered pairs seem to compensate for the

initial mechanical loss by reflecting and absorbing more UV light than a single sequential order. As a result, the UV resistance of aramid yarns was enhanced by both single sequential orders (A) and ordered pairs (A_OP). Nevertheless, the best result was obtained with Recipe B (16.3 cN/dtex), which might be proof of catechol's ability to scavenge radicals generated by redox reactions of CeO₂. The improved tenacity retention of recipe B indirectly proves that even if CeO₂ oxidized catechol, it likely did not significantly increase the Ce³⁺/Ce⁴⁺ ratio, thereby hindering photocatalytic activity to some extent. Overall, the LbL arrangements in this study, particularly Recipe B, effectively enhanced the UV resistance of aramid yarns and provided promising options for maintaining durability under prolonged exposure.

4. CONCLUSION

This paper demonstrates that (i) the first cationic layer of PEI aids in the subsequent deposition of nanoparticles, (ii) the sequential arrangement might be customized based on process requirements while ensuring UV protection, and (iii) UV protection can be further enhanced by integrating a radical scavenger into the LbL process. However, further optimization is required to achieve robust UV protection and statistically significant improvements. In addition, evaluating the wash resistance of these coatings will offer crucial insights into their durability. The findings highlight the potential of LbL as an effective strategy for UV protective modification of aramid-based materials. We look forward to sharing advanced findings along with comprehensive assessments of higher UV protection rates by LbL nanocoating soon.

ACKNOWLEDGMENT

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INCORPORATION OF PHASE CHANGE MATERIALS ONTO A TEXTILE FABRIC: A COMPARISON STUDY

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¹CITEVE

Abstract: *In this study, phase change materials were prepared and incorporated onto laminated fabric using two different approaches, direct filling, and coating method. These materials are usually applied onto fabric due to their high latent heat storage capacity improving textiles thermal protection. It is intended to understand which method provide the highest thermal protection with particular focus on firefighters' personal protective equipment. For that, PCMs modified fabrics were exposed to an external heat source, and a thermographic imaging camera was used to evaluate their thermal performance. The PCMs modified fabrics were exposed to different temperatures and their behaviour was assessed after 30 and 60 minutes of heating and cooling. Physical (weight, thickness, add-on, SEM), chemical (FT-IR) and thermal properties (DSC) were analysed using diverse techniques.*

Keywords: *phase change materials, laminated fabric, coating, thermal protective clothing, firefighters.*

1. INTRODUCTION

Thermal protective clothing is produced through the selection of specific textile fibres to confer the desired thermal protection (Song et al., 2017). Currently, the need for high performance textiles lead to their combination with other materials, especially, in demanding personal protective equipment (Sajovic et al., 2023). In case of firefighters, thermal protective clothing can not only provide fire resistance but also deliver body heat homeostasis to achieve thermal comfort during operations (Santos et al., 2023).

Phase change materials (PCMs) have been employed in thermal energy storage due to their ability to store and release thermal energy during isothermal phase transition (Pielichowska et al., 2014). PCMs are frequently used due to their high latent heat storage capacity, consistently melting/freezing, chemical and thermal stability (He et al., 2004). These materials provide thermal protection in clothing, and can be applied onto textiles through different methods, usually, coating, lamination or yet incorporated in the structure of fibre or yarn (Hossain et al., 2023).

2. MATERIALS AND METHODS

2.1 PCMs physical and thermal properties

PCMs are white dry powders with an inorganic carrier matrix to avoid leakage, acquired from Rubitherm. PX82 and PX52 shown a melting area of 77 - 85°C and 49 - 53°C, congealing area of 85 - 77°C and 52 - 48°C, and heat storage capacity of 105 J/g and 100 J/g, respectively.

2.2 Characterization of fabric

A laminated fabric composed by a polytetrafluoroethylene membrane with aramid non-woven were used to avoid PCMs release and thermal barrier, respectively. This fabric was found to have $150,57 \pm 0,58$ g/m² and $0,634 \pm 0,022$ mm. The thickness was determined using a Mitutoyo 547-500S. The laminated fabric was used to produce three pouches (7.5 × 8 cm).

2.3 Preparation of PCMs

PCMs were incorporated onto laminated fabric through two different methods: direct filling onto fabric and using coating technique. Before, PX82 and PX52 were reduced into a fine powder through ball milling (Retsch S100) and sieved using a sieve shaker (Retsch AS200). The obtained PCMs powders had an average diameter size equal or inferior to 125 µm.

2.4 Direct application of PCMs onto fabric

A membrane pouch was used to keep 7.5g of each PX82 and PX52 powder. Then, the membrane was closed using double side PET tape (Tesa 4965).

2.5 Coating of PCMs onto fabric

The coating was performed onto the non-woven side of the laminated fabric, for the formulation containing the PCMs adhere to the surface of the fabric. A polyacrylic formulation of 50g containing 7.5g of each PX82 and PX52 was coated onto a square of 6.5 × 6.5 cm that was drawn onto the non-woven fabric. After coating, the membrane pouch was built by gluing the coated fabric with another piece of membrane fabric using the double side tape.

2.6 Thermal performance analysis of PCMs modified fabric

The PCMs modified fabric were placed at a lab hot plate (Raypa Ag-2) under different temperatures and their thermal performance was assessed using a thermographic camera (FLIR E75).

3. RESULTS AND DISCUSSION

Three membrane pouches, without PCMs (F0), with PCMs in powder (Fp), and with PCMs in coating (Fc) were prepared (Figure 1) and analysed using a thermographic camera.

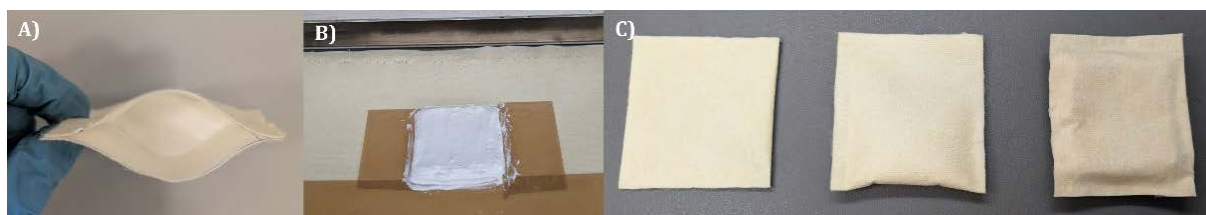


Figure 1. Photographs of the preparation of PCMs modified fabric through A) direct filling of PCMs (Fp), B) coating of a formulation containing PCMs (Fc). C) Photograph of the final pouches.

85+

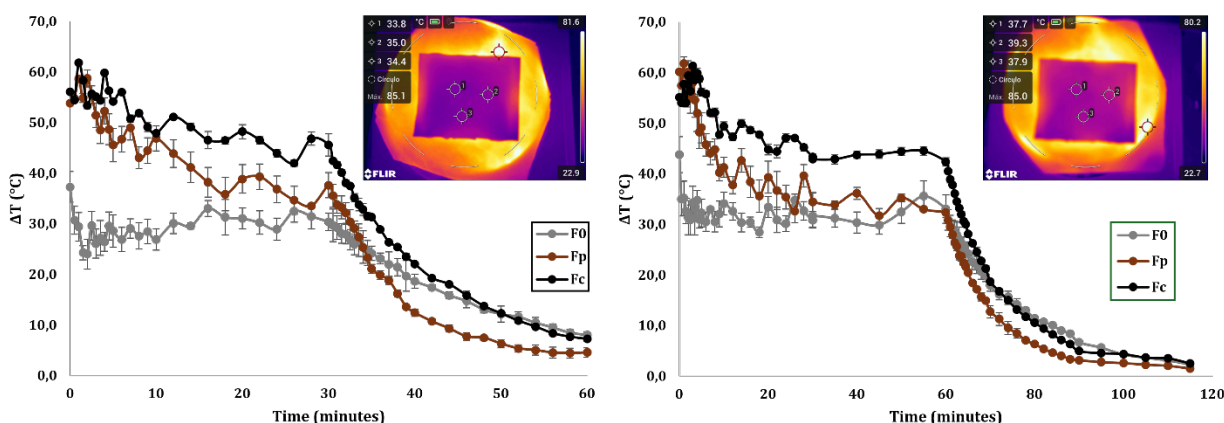


Figure 2. ΔT of F0, Fp and Fc after 30 minutes (left) and 60 minutes (right) of heating and cooling. Inset: Thermal image of Fc exposed to a $T_p \sim 85^\circ\text{C}$.

During the heating process, F0, Fp and Fc shown an average ΔT of $29.3 \pm 0.7^\circ\text{C}$, $45.9 \pm 0.9^\circ\text{C}$ and $51.6 \pm 0.5^\circ\text{C}$, and $32.5 \pm 0.8^\circ\text{C}$, $43.6 \pm 0.9^\circ\text{C}$ and $50.3 \pm 0.2^\circ\text{C}$ after 30 and 60 minutes, respectively. Along the heating process, it was verified a significative decrease of ΔT values for Fp when

compared to Fc. This could be possible related to supercooling PCMs, that was not observed at the same extension for Fc due to PCMs coating. Polyacrylic pastes present lower thermal conductivity (Nejman et al., 2020), decreasing the heat transference and possibly the supercooling effect. Consequently, the thermal protection of Fc was superior if compared with Fp in about 6°C, even after 60 minutes of exposure to heat. In the absence of PCMs, F0, the ΔT value was lower ($\sim 30^\circ\text{C}$) but this difference was practically constant while the heating process. In the cooling process, the difference of ΔT values of F0, Fp and Fc was lower than in the heating process. Yet, it could be noticed that Fp release energy as heat faster than Fc, and F0. Again, the lower thermal conductivity of the formulation contributed to the gradual release of heat by PCMs for Fc.

4. CONCLUSION

In this study, the thermal performance of PCMs applied to a laminar fabric using direct filling of PCMs and PCMs coating was assessed. It was observed that only the laminated fabric was able to decrease the temperature in about 30°C , but the addition of PCMs due to their high latent heat storage capacity led to higher values ($\Delta T = 43^\circ\text{C} - 51^\circ\text{C}$). Besides, the coating technique provided a higher thermal protection along time if compared to Fp.

Coating is a well-established technique in textile modification allowing easier scale-up and great diversity of designs for breathable and flexible approaches. Real-case studies based on body mapping designs, where materials are used based on physiological needs such as thermal regulation in high-heat or cool zones can be applied. Bio-based formulations are also planned to be accomplished, concerning thermal performance, comfort and sustainability.

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DESIGNING AND EVALUATING SMART THERMAL INSULATION CHANNEL LAYOUT USING MPCM IN THERMAL PROTECTIVE CLOTHING

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Abstract: This paper mainly investigated the influence of microencapsulated phase change materials (MPCM) and their channel distribution methods on the thermal protective performance (TPP) of firefighter clothing fabrics. The MPCM was encapsulated in a high-temperature resistant thermoplastic polyurethane (TPU) film to form smart thermal insulation channels (STIC), which reversibly responded to the change of ambient temperature and adjusted the temperature of the fabric system to improve the TPP of the firefighter clothing. To study the effect of different phase change temperature and channel layout intervals of STIC on thermal protection performance, two kinds of phase change temperature (28°C and 37°C) MPCM and three different channel distribution intervals (0.5 cm, 1 cm, 1.5 cm) were used in the experimental design. The second-degree burn time under low-level radiant heat exposure was tested to evaluate the TPP of the fabric system.

Keywords: Phase change materials, thermal protective performance, firefighters, smart thermal insulation channels.

1. INTRODUCTION

Firefighters operate mostly in routine and hazardous conditions (low heat radiation environment, 1.67-12.56 kW/m²), where most skin burns occur (Barker, R. L., 2005). The thermal protective performance (TPP) of firefighter clothing plays a vital role in safeguarding the lives of firefighters. Phase change materials (PCM) have attracted more attention due to their unique endothermic and exothermic properties. The latent heat absorbed during their phase change process reduces the temperature that firefighters may experience on the surface of their skin, thus improving TPP of the firefighting suits (McCarthy & Di Marzo, 2012). Firefighter clothing fabrics with PCM had been developed by coating and dripping (Geng et al., 2018; Gu et al., 2024), and microencapsulated phase change materials (MPCM) were also put into small knitted bags to make a protective vest for firefighters (Sue et al., 2020). High-temperature resistant thermoplastic polyurethane (TPU) film with good tensile and waterproof moisture permeability was used to encapsulate MPCM to form smart thermal insulation channels (STIC) embedded between fabric layers in this study. By designing different layout intervals, the effects of materials' phase change temperature and channel distribution on TPP of the fabrics were explored.

2. MATERIALS AND METHODS

2.1 Fabric System Construction

The firefighter clothing fabric system consists of an outer shell (Nomex IIIA, 204.8 g/m²), a moisture barrier (Nomex, 105.5 g/m²), and a thermal liner (Nomex, 90 g/m²). High-temperature resistant TPU was used to encapsulate the same amount of MPCM emulsion with phase change temperature of 28°C and 37°C, respectively, to prepare STIC (size 1.5*10 cm). The STIC with equal intervals (0.5 cm, 1.0 cm, 1.5 cm, respectively) were fixed between the moisture barrier and the thermal liner with flame-retardant threads. To compare the improvement effect of STIC on TPP, a fabric system without STIC was set as the control group.

2.2 Measurement of Thermal Protective Performance

A SET (stored energy tester), suitable for low heat radiation environment, was used to evaluate the TPP of the fabric systems with a heat flux of 8.5±0.5 kW/m², according to ASTM F2731. The heat flux of the sensor with time and second-degree burn time were obtained. The longer the second-degree burn time, the better TPP of the fabric system.

3. RESULTS AND DISCUSSION

As shown in Figure 1 a), the sensor heat flux initially had a slower rising rate of fabric system equipped with STIC than the control group. The fabric system with the channel interval of 0.5 cm showed the slowest growth trend. As the channel interval increased, the heat flux increased faster. The heat flux of the control group stabilized after about 60 s, while the heat flux of the fabric system containing STIC continued to rise, surpassing the control group in the middle and late stages of thermal exposure, with obvious fluctuations and peaks. This may be due to the change of the thermal conductivity of PCM after the phase state changes (Ling et al., 2015). For MPCM with different phase change temperatures, the sensor heat flux of the fabric system containing MPCM-37°C rose more slowly and reached the peak later than the fabric system with MPCM-28°C, which was due to the better heat storage properties of the MPCM-37°C.

In Figure 1 b), the second-degree burn time of the fabric system with STIC is prolonged to varying degrees, indicating that adding phase change materials can improve the TPP of the fabric. With the decrease of channel interval, the second-degree burn time increased significantly. The fabric system with the channel interval of 0.5 cm increased the proportion of second-degree burn time the most compared with the control group (MPCM-37°C: 56 s, 50.45%). The fabric system containing MPCM-37°C exhibited better TPP than the one with MPCM-28°C.

The duration required to achieve a first-degree burn was determined through calculation. In Figure 1 c), the time interval between the onset of first-degree burn and the transition to second-degree burn in the control group was 39 s, which exceeded that of the fabric system incorporating MPCM. As the channel distribution interval increased from 0.5 cm to 1.5 cm, the duration from first to second degree burn decreased, and the performance of MPCM-37°C was still better than MPCM-28°C.

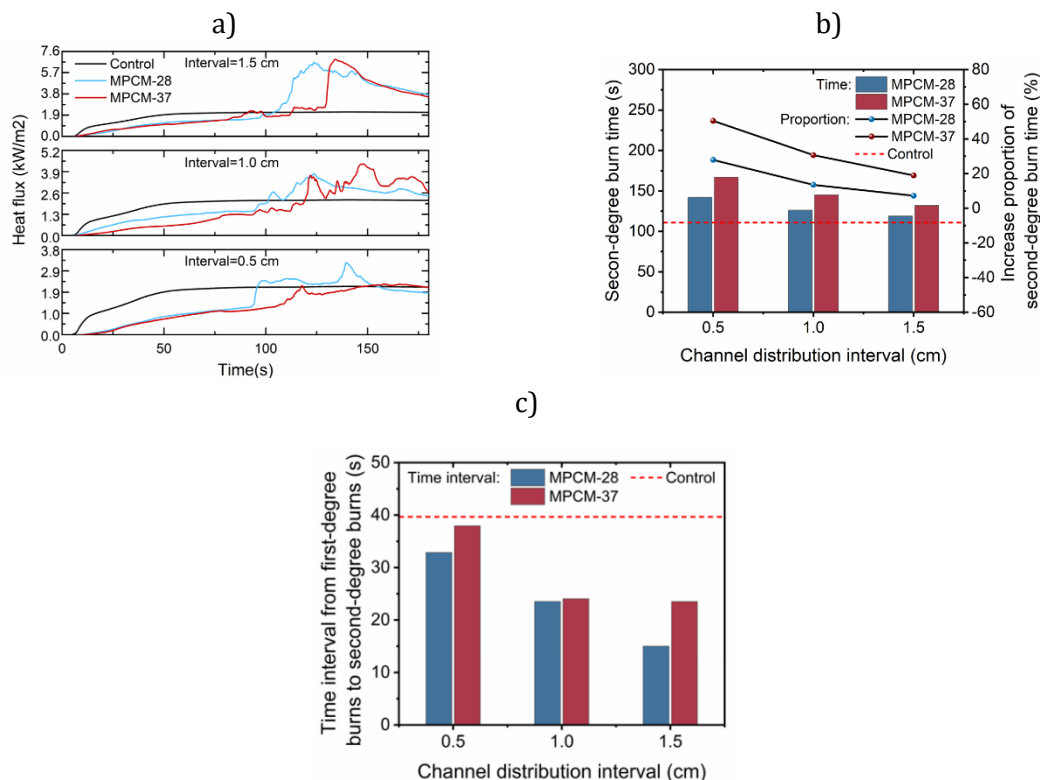


Figure 1. Evaluation of the thermal protection performance of fabric systems: a) Sensor heat flux; b) second-degree burn time and increase proportion of fabric systems; c) Time interval from first-degree burns to second-degree burns

4. CONCLUSION

This study aimed to discuss the impacts of factors such as phase change temperature and channel distribution intervals of MPCM on the TPP of fabric systems. The results showed that the integration of MPCM helped absorb latent heat in high temperature environments. While it shortened the time interval between first-degree and second-degree burns to a certain extent, it generally delayed the skin from reaching second-degree burn and improved thermal protection for firefighters. The smaller the STIC distribution intervals and the higher the phase change temperature, the better the TPP. Further research is needed to coordinate the relationship between the comfort and TPP of firefighting clothing through reasonable channel distribution, and selecting MPCM with appropriate phase change temperature not exceeding the human skin burn threshold of 44°C.

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FLEXIBLE COMPOSITES CONTAINING WO₃/BN PARTICLES FOR IONISING RADIATION PROTECTION

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Abstract: The aim of study is to develop flexible composite materials using PU containing WO₃, BN particles and UHMWPE nonwoven reinforcement, which can be used for personal protection against ionizing radiation. Flexible forms of composites consisting of WO₃, which is effective against X-rays and gamma rays, and UHMWPE and BN components, known to be effective against neutron radiation, have potential to be used in wearable radiation shielding applications. In this study, the effectiveness of the developed materials against X-rays was evaluated, and it was observed that the density of the materials decreased with the increase in the BN ratio, while the radiation attenuation rates decreased due to the decrease in the WO₃ ratio.

Keywords: Tungsten oxide, boron nitride, UHMWPE, nonwoven, radiation protection.

1. INTRODUCTION

Ionizing radiation such as, X-rays, gamma rays, and neutron rays, possesses sufficient energy to remove electrons from atoms or molecules and is encountered in various fields such as medical diagnostics, nuclear power plants, and aerospace applications. Without adequate protection, exposure to ionizing radiation can lead to severe health risks. Consequently, specialized protective materials have been developed to serve as effective shields against harmful radiation (AbuAlRoos N.J. et al., 2019). Compared to heavy metal-based shielding materials, radiopaque polymer composites offer significant advantages, including lower density and enhanced flexibility (Hamisu A. et al., 2023).

Among such materials, tungsten oxide (WO₃) stands out due to its high density and exceptional radiation absorption capability, particularly for shielding against X-rays and gamma rays (Almurayshid et al 2021). Similarly, materials such as ultra-high-molecular-weight polyethylene (UHMWPE) and boron nitride (BN), are highly effective in neutron shielding (Cummings et al. 2011; Cataldo, F., and Prata, M., 2019).

In this study, flexible composite materials comprising varying ratios of WO₃ and BN, reinforced with UHMWPE nonwovens, were developed, and their X-ray attenuation properties were systematically evaluated and compared.

2. MATERIALS AND METHODS

2.1 Preparation of Polymer Composites

In this study, WO₃ and BN particles were added to polyurethane (PU) resin and UHMWPE nonwovens (100 gsm, Mogul, Dynatex) were used as reinforcement to obtain polymer composites by hand lay-up method. The ratios of WO₃ and BN powders added to PU differs in three samples. The ratios were 60% WO₃, 48% WO₃-12% BN and 36% WO₃-24% BN, and 40% PU ratio was kept constant in the mixture. The thicknesses (mm) were measured and densities of the composites were determined by the WSA-224 digital density meter.

2.2 Radiation Protection

The samples, produced in a 10x10 cm square shape tested by the Turkish Energy, Nuclear and Research Agency (TENMAK) for their X-ray radiation shielding capacities. The measurement method used was the "Narrow Beam" geometry (NB) as defined in the TS EN 61331-1:2014 standard. The radiation attenuation ratios of the samples were calculated at 70 kV, 90 kV, and 110 kV energies.

3. RESULTS AND DISCUSSION

In Table 1, the densities of the composite samples which contains the components such as UHMWPE (0.97 g/cm³), PU (1.02 g/cm³), WO₃ (7.16 g/cm³), and BN (2.1 g/cm³). As can be seen in Table 1, the composite densities are between 1.49-1.28 g/cm³ and as the BN ratio in the samples increases, the material density decreases as expected.

Table 1. The properties of the polymer composites.

Sample name	PU (%)	WO ₃ (%)	BN (%)	Thickness (cm)	Density (g/cm ³)
W60	40	60	-	0.40	1.49
W48B12	40	48	12	0.40	1.39
W36B24	40	36	24	0.40	1.28

In Table 2, when the attenuation values of the samples at different energies are examined, all three samples provide over 80% protection at 70 kV, on the other hand, as expected, the protection rates decrease as the energy value increases. In addition, it is seen that the X-ray protection values of the materials decrease with the increase in the BN ratio and the decrease in the WO₃ ratio.

Table 2. Radiation attenuation capacities of polymer composites under different X-ray energies.

Sample name	Radiation Energy (kV)	Radiation Attenuation (%)
W60	70	88.1
W60	90	83.4
W60	110	79.6
W48B12	70	87.9
W48B12	90	83.2
W48B12	110	79.3
W36B24	70	81.1
W36B24	90	75.4
W36B24	110	71.0

4. CONCLUSION

In conclusion, it is possible to achieve high radiation protection rates by incorporating WO₃ powders into flexible composites developed with UHMWPE nonwoven reinforcement. Since BN has low effectiveness against X-ray, the attenuation values of composites have decreased at higher BN ratio. The findings emphasize the importance of carefully considering both material composition and the energy levels encountered in specific applications to ensure optimal radiation attenuation efficiency. These composites, possessing advanced properties, have the potential to be manufactured using various composite fabrication techniques, including hand lay-up, vacuum infusion, and compression moulding, among others.

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AN OPTIMIZED INHERENTLY FLAME RETARDANT FIBER PART I: UNDERWEAR

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Abstract: *In this study, a novel inherently flame-retardant (new-FR) fiber, developed through the surface modification of acrylic fiber, is proposed for use in heat and flame protective undergarments. This fiber offers a unique combination of high moisture absorption, exceptional flame resistance, ease of processing, cost efficiency, and antimicrobial properties. Preliminary investigations indicate that fabrics composed of new-FR fiber are compatible with commonly used fibers in flame retardant textiles. The flame resistance, comfort, and physical properties of various fiber blends were examined to assess their suitability for undergarment applications. Results demonstrate that yarns composed of modacrylic and new-FR fiber exhibit comparable tensile strength to traditional modacrylic/cotton blends. Furthermore, fabric tests conducted in accordance with ISO 11612 revealed that modacrylic/new-FR fiber blends not only meet the standard requirements but also provide enhanced thermal insulation compared to conventional alternatives.*

Keywords: *Underwear, protective clothing, flame retardant, comfort*

1. INTRODUCTION

Firefighters, race car drivers, oil refinery workers and other professionals exposed to fire hazards require protective clothing made from flame resistant textiles. However, despite the availability of such garments, studies indicate that firefighters often wear ordinary underwear composed of cotton or polyester rather than flame-resistant alternatives. Polyester underwear is particularly popular due to its softness, ease of washing, durability, and appealing designs. However, the thermoplastic nature of polyester poses significant risks in extreme heat, as it melts and forms a molten residue that can penetrate cotton fibers, exacerbating burn injuries. Cotton and lyocell, while preferable for moisture management and comfort, burn quickly and leave an ash residue, offering little protection against thermal hazards (Rijavec et al., 2023). Another approach involves treating cotton with flame-retardant chemicals but this method loses effectiveness after repeated washing (Yoo & Barker, 2005).

The market demands affordable flame-resistant underwear. Conventional modacrylic/cotton blends provide a cost-effective solution, as modacrylic fibers are significantly cheaper than meta-aramid fibers, which are considered the gold standard for flame-resistant underwear (Onuktav et al., 2024). Although antimony oxides have long been used to improve the flame retardancy of modacrylic fibers, alternative flame retardant additives are being explored due to environmental concerns (Tanaka et al., 2017). Additionally, FR viscose can be blended with both meta- and para-aramid fibers, creating a more affordable alternative to full-aramid solutions, though still more expensive than modacrylic-cotton blends (Stygiéné et al., 2022; Eryuruk et al., 2022).

Polyacrylate fiber was first produced about four decades ago but its low tenacity limited its use to nonwovens. However, advancements in PAC technology have improved its performance, particularly in terms of non-toxicity and reduced smoke production during combustion. Despite these advancements, no study has extensively examined the mechanical properties of fabrics made purely from polyacrylate fibers (Rijavec et al., 2023).

Given these challenges, the development of a flame-resistant, moisture-managing underwear fabric is crucial to enhancing both protection and comfort for professionals working in high-risk environments. This study investigates a novel modified acrylic fiber with halogen-free flame retardancy, antimicrobial properties, and up to 10% moisture absorption capacity. The fiber, containing amine, hydroxyl, and carboxyl groups similar to polyacrylate, is reinforced with

chemically bound zinc ions to achieve flame retardancy. When blended with other FR fibers, this fiber enhances protective performance while maintaining thermophysiological comfort. The findings aim to contribute to the development of protective undergarments that ensure both safety and wearability for professionals exposed to extreme temperatures.

2. MATERIALS AND METHODS

2.1 Flame Retardant Fibers

Modacrylic fibers blended with cotton contain antimony pentoxide as a synergist to enhance flame retardancy. In contrast, modacrylic fibers blended with new-FR fiber do not incorporate any synergist. Additionally, meta-aramid, para-aramid, and FR viscose used in the study were sourced from top-tier suppliers in their respective fiber categories.

2.2 Test Methods

The flame resistance behaviour of the fabrics was evaluated in accordance with ISO 15025, while heat transmission tests (convective, contact, and radiant) were conducted as specified in ISO 11612. Yarn tenacity was measured following ISO 2062 and moisture absorption was determined according to ISO 3344.

3. RESULTS AND DISCUSSION

The moisture absorption capacity of new-FR fiber was measured at 10%, while fabrics composed of the same fiber exhibited 99.999% antimicrobial activity. The fiber exhibited excellent processability across all machinery associated with ring-spinning. The yarn tenacity was comparable to that of conventional modacrylic/cotton and modacrylic/FR viscose blended yarns, while being significantly higher than that of 100% polyacrylate yarns.

All fabrics complied with the requirements of ISO 15025 in terms of burning behaviour. Additionally, fabrics made entirely of new-FR fiber exhibited superior heat transmission properties compared to modacrylic/cotton fabrics.

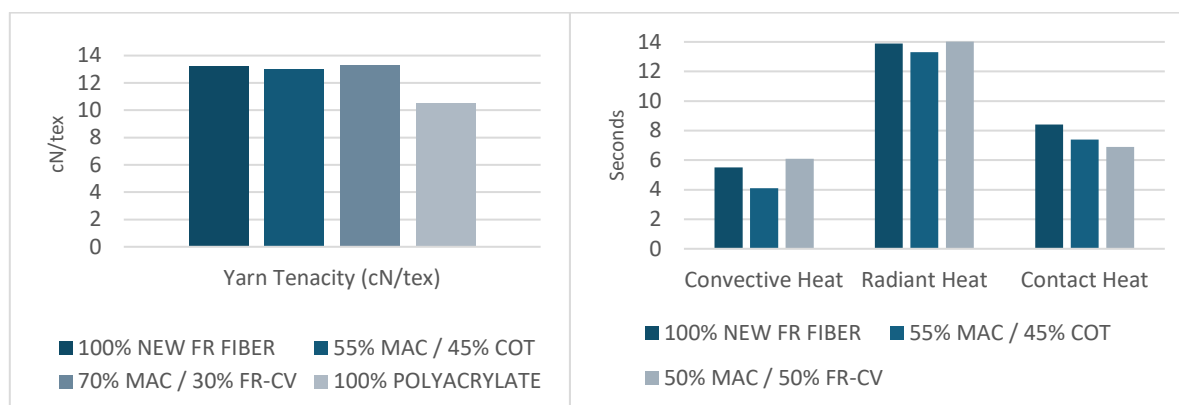


Figure 1. Yarn tenacity and heat transmission properties

4. CONCLUSION

The new-FR fiber offers a unique combination of flame resistance, moisture absorption and antimicrobial properties, making it highly suitable for protective textiles. With 10% moisture absorption, it provides improved comfort, making it a promising candidate for undergarment applications where both breathability and flame resistance are essential. The fiber is easily processable across ring-spinning machines and exhibits acceptable tenacity. All fabric samples met ISO 15025 standards, while 100% new-FR fabrics showed enhanced heat transmission. These properties position new-FR fiber as a versatile option for next-generation flame retardant textiles.

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3D-PRINTED STRUCTURES ON FABRICS FOR SOFT KNEE ORTHOSES: DESIGN AND PRESSURE EVALUATION

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Abstract: 3D printing technologies have transformed manufacturing in various fields, including textiles, by offering flexible, cost-effective, and customizable solutions. Fused Deposition Modeling (FDM), a widely used 3D printing technique, has been pivotal in wearable product development due to its compatibility with diverse materials and production parameters. Direct 3D printing onto fabrics has enabled the creation of hybrid structures for innovative applications. This study aims to develop a knee orthosis capable of applying controlled pressure to specific muscle groups around the knee by integrating 3D-printed structures onto fabric. Thermoplastic polyurethane (TPU) filament was used due to its high elasticity, with structures fabricated under varying production parameters such as infill patterns, densities, and print angles. Pressure measurements, obtained via force-sensitive sensors connected to a computer using Arduino, allowed analysis of pressure distribution during movement. The results aim to enable the production of low-cost, customizable orthoses, advancing 3D printing in medical textiles and supporting the development of functional, personalized orthoses.

Keywords: 3D printing, medical textiles, FDM, TPU

1. INTRODUCTION

Since their emergence in the 1980s, 3D printing technologies have witnessed rapid technological advancements, transforming manufacturing processes across numerous industries. The advantages of flexible production, cost efficiency, and reduced material waste have made these technologies indispensable in modern production systems. Fused Deposition Modeling (FDM) is a widely used technique, offering affordability and material versatility (Liu & Jiang, 2023; Mazzanti et al., 2019). Thermoplastic polyurethane (TPU) due to its inherent flexibility, is particularly suited for producing elastic materials (Cheung et al., 2023).

In addition to its widespread use in other industries, FDM technology has gained traction in the textile sector. Applications include producing multilayer textile-like structures, developing smart textiles, and fabricating medical textile products. Ahrendt et al. (2020) developed orthopaedic textile products through direct 3D printing onto fabric, while Korgner et al. (2020) produced functional garments by printing elastic filaments onto textiles. Soft orthoses provide joint support and apply pressure to muscles, which can influence muscle activation. Studies have shown that varying pressure levels affect muscle response (Yamamoto et al., 2022).

This study aims to develop a knee orthosis with integrated 3D-printed structures on fabric and investigate the effect of varying 3D printing parameters on the force applied to muscle groups surrounding the knee. By utilizing calibrated FSRs, the study seeks to analyze force distribution during movement, contributing to the advancement of hybrid textile-3D printed products and their application in medical and protective textiles.

2. MATERIALS AND METHODS

2.1 Design of 3D Structures and Production via 3D printer

The design of the 3D structures has been developed to encircle the knee joint, stabilizing the patella while providing lateral support forces. The orthosis, tailored based on a personalized

scanned image of the leg, is intended to conform around the knee. The specific area where the orthosis will be applied is illustrated in Figure 1a.

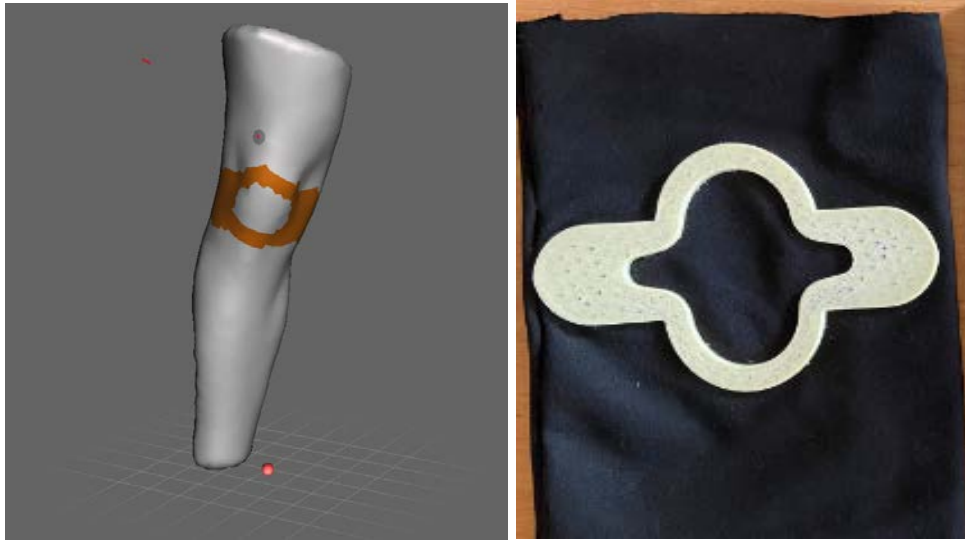


Figure 1. a) 3D Scan of the leg and schematic representation of the orthosis placement around the knee joint **b)** The prototype structure for knee orthosis

The 3D structures were designed with the CAD software (SolidWorks) and then sliced with CURA software. Obtained G-code used for 3D printing. Ender 3 V2 3D printer and TPU filament were used for the production (Figure 1b).

2.2 Development of Force Measurement System Using Force Sensitive Sensor (FSR)

The applied force by the orthosis on the muscle groups around the knee will be measured using Force Sensitive Resistors (FSRs). Several muscle groups are located around the knee, each performing different functions during movement. In this study, the force exerted by the developed orthosis around the knee, including the patella, will be measured. For this purpose, sensors will be placed on the top, right, and left of the patella, and the force impact of the produced orthosis on different areas will be compared.

3. RESULTS AND DISCUSSION

The designed 3D-printed components were integrated into a knitted fabric and sewn together to create a functional knee orthosis. To measure the force applied during sitting and standing movements, Force Sensitive Resistors (FSRs) were placed between the knee and the orthosis. These sensors converted the applied forces into electrical signals, which were recorded and analyzed for comparison. Additionally, a separate orthosis made entirely of sewn knitted fabric was tested under the same conditions. Measurements were taken from the patella and the left side of the knee to assess the improvement in force application.

$$\text{Rate of Force increased} : \frac{F_{\text{hybrid}} - F_{\text{fabric}}}{F_{\text{fabric}}} \times 100$$

The measured force on the left sides of the patella with the fabric and the developed hybrid orthosis during sitting and standing positions is illustrated in Figure 8. It is evident from the figure that the measured value for the plain fabric is approximately 80, whereas it reaches around 450

with the developed hybrid orthosis, which is approximately 5.5 times higher, showing a rate of increase by 543% with the hybrid orthosis.

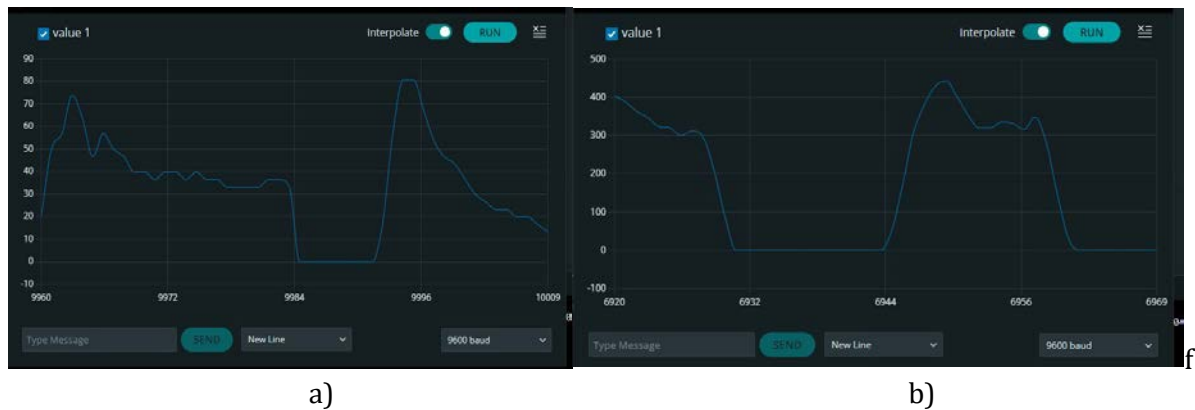


Figure 2. The measured values on the left side of patella at a) Fabric and b) Hybrid Orthosis

4. CONCLUSION

Hybrid structures developed by printing onto textile products using 3D printers have enabled the creation of low-cost, functional, and personalized products. Although soft orthoses developed for medical applications have been the subject of many studies, the functional effects of these structures have not yet been fully established. In this study, the forces applied by a developed soft orthosis on the patella and surrounding muscle groups were measured proportionally using FSR sensors.

The results indicate that the developed orthosis applies greater force on the side of the knee and the patella compared to the fabric-based orthosis. However, the applied force is influenced by the design of the 3D structure, the type of material used, and the 3D printer settings. Since the pressure exerted by garments on the body is related to the material's elastic modulus, future studies should focus on determining the elastic modulus of hybrid structures and examining how the applied pressure alters muscle activation. Such findings will be crucial for the development of personal protective equipment and functional knee braces.

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POSTER PRESENTATIONS

PROTECTING RESCUERS IN THE NORTH: CHALLENGES FROM THE GREEN TRANSITION CHEMICALS AND CLIMATE CHANGE

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Abstract: *The green transition is driving an increase in chemical-intensive industries and mining activities in the North. At the same time, the frequency of extreme weather conditions due to climate change is rising. This means that rescuers may encounter more frequent, extensive, or new kind of chemical incidents. In this study, we gathered information on investment plans and ongoing industrial projects related to green transition in the Northern Finland. We also interviewed representatives from northern rescue services to identify the challenges of chemical protection in the cold environments. A notable safety concern is that personal protective equipment (PPE) designed for chemical incidents does not typically account for use in cold climates. There is a need for better understanding of the limits within which rescuers can safely operate during chemical incidents in the North.*

Keywords: *Chemical protective equipment, cold, rescuers, green transition, climate change effects.*

1. INTRODUCTION

The demands of the green transition are expected to increase the prevalence of chemical-intensive industries in Northern regions, including sectors such as mining, steel production, and chemical manufacturing (Arctic Economy Council, 2024). Additionally, the expansion of industries like the bioproduct sector and the hydrogen economy may introduce new or enhanced chemical risks (Finnish Government, 2021).

Simultaneously, the increasing frequency of extreme weather events due to climate change may influence the operational environment of chemical accidents and impact the occupational safety of rescuers. Persistent cloudiness and increasing precipitation, and more frequent freezing rain and rain-on-snow events that cover the landscape with ice crust, cause challenges to travel and transport (Moon, 2024). Furthermore, the repeated freeze-thaw cycles and freezing are disruptive for many kinds of structures: roads, pipelines and containers (Harikumar, 2024). In addition, the Northern areas typically have challenging weather conditions, long periods of darkness and long distances.

The harsh weather conditions increase physical workload, but also the use of chemical protective equipment is challenging and strenuous for a rescuer. According to studies by Rissanen and Rintamäki (1997 and 2007), it is common that extremities are cooling, and torso area is warming while working in the cold (-10°C) with chemical protective clothing (CPC). However, the effects of cold and windy conditions in chemical rescue operations with modern CPC are not adequately studied.

In this study, our objective was to identify the emerging chemical risks associated with industrial changes driven by the green transition in northern Finland consisting of Lapland, Northern Ostrobothnia and Kalix regions. We also aimed to determine the usage conditions and the associated challenges for chemical protective clothing and equipment necessary for rescuers operating in the challenging northern environment. Furthermore, the materials used in CPC have developed within the past 20 years, and the studies related to their functionality in the cold may need to be updated.

2. MATERIALS AND METHODS

2.1 Survey on green transition projects

Investment plans and ongoing industrial projects related to green transition in the Northern Finland were collected from the Green investments dashboard of the Confederation of the Finnish

Industries in June 2024. Information on related chemicals, their annual volumes and way of use were collected from the companies' environmental permits. In the case of missing information, the companies were contacted directly. Information on the hazard classification and properties of the chemicals were collected from several public databases.

2.2 Interviews

In total five group interviews among rescue services of northern Finland (Lapland, Northern Ostrobothnia and Kalix) were performed during spring 2024 to examine their current preparedness and practises related to serious chemical accidents. The interview themes included information sources, practises of risk assessment and exercise activities related to preparedness, and protocols, personal protective equipment (PPE) and clothing used in rescue operations in wintertime weather conditions.

3. RESULTS AND DISCUSSION

The survey of green transition projects in the North of Finland revealed the chemical intensive industry sectors that are growing in the area (Table 1). High volume chemicals involved in several sectors included e.g. ammonia, sodium hydroxide, sulphuric acid and hydrogen peroxide, all known for their hazard properties and ability to cause chemical accidents. Also, hazardous chemicals specific for the green transition industry were identified, including highly flammable hydrogen, biogas and biocarbon.

Table 1. Green transition projects in planning or starting phase in northern Finland (Lapland, Northern Ostrobothnia and Kalix) in June 2024.

Field of industry	Projects in Northern Finland	Examples of chemicals used or produced in large quantities
Biogas	11	Biogas (methane, carbon monoxide)
Bioproducts (other)	8	Black/white/green liquor; biocarbon; chlorine dioxide; hydrogen peroxide; pine oil; sodium hydroxide; sulphuric acid
Hydrogen economy	7	Ammonia; hydrogen; methanol
Mineral sector	5	Calcium hydroxide; sulfuric acid; xanthates
Circular economy/recycled products	4	Ammonia; hydrogen peroxide; sodium hydroxide; sulphuric acid
Green steel	3	Biocarbon; hydrogen
Battery technologies	1	Ammonia; sodium hydroxide; sulphuric acid

According to the interviews, the most challenging rescue conditions may arise from a combination of extreme cold, release of hazardous chemicals, and the application of water sprays to control spreading of gaseous or easily evaporating chemicals (e.g. liquefied ammonia). Moreover, interview responses indicate that experience with using chemical PPE in sub-zero temperatures is quite limited, and training exercises are generally conducted in good weather conditions or even indoors. Literature suggests that training in cold conditions is needed to demonstrate the restrictions due to protective clothing (Rissanen & Rintamäki, 2008).

In addition, according to the interviews, clothing beneath the CPC is not unified nor instructed. An optimum selection of undergarments maintains thermal comfort and safety in cold environments (Angelova, 2017). Sweat generated from various workloads accumulate inside CPC, potentially affecting thermal comfort and safety in the cold (Rissanen & Rintamäki, 1997). The responses pointed out that the use of the most protective CPC types and thick chemical protective gloves increase user's clumsiness, which may be further exacerbated by cold weather affecting manual dexterity (Orysiak et al., 2022).

Various accident scenarios can be identified based on the high-volume chemicals of the growing industries (Table 1), combined with the extreme weather conditions, such as cold, iciness and low

visibility, in the Northern areas. The selection of PPE for the chemical incidents varies based on the properties of the released chemical, the specific characteristics of the accident, operational requirements, and ambient conditions (e.g. temperature, wind). Although the Finnish TOKEVA guidelines for rescuers outline the organization of rescue operations, delineation of danger zones, protection levels, and necessary preventive measures, the assessment of risks on PPE users aggravated by temperature conditions is largely the responsibility of the operative rescuers.

4. CONCLUSION

The survey revealed that the hazardous chemicals of the green transition cannot be regarded as novel. However, their quantity is likely to increase both within the industry and mining, and along the long roads and railways of the North. Simultaneously, the low-visibility and icy conditions are worsening in traffic. To increase preparedness for protecting rescuers in case of a serious chemical incident in wintertime in the northern environment, it is important to recognize the effects of harsh and changing weather conditions on use and selection of chemical protective equipment. A notable safety concern is that PPE designed for chemical incidents does not typically account for use in cold climates, especially under extreme conditions. There is a need for better understanding of the limits within which rescuers can safely operate during chemical incidents in the North.

ACKNOWLEDGEMENT

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INVESTIGATION OF MECHANICAL PERFORMANCE OF FLUOROCARBONS TREATED ARAMID FABRICS

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Abstract: *The demand for aramid-based textiles has been steadily increasing in industries such as defense, aerospace, and automotive. In an era where sustainability is of paramount importance, the preference for durable and long-lasting materials over disposable products has become increasingly evident. This study investigates the effects of water and oil repellent finishing on the performance and comfort properties of fabrics containing varying proportions of aramid fibers. To achieve this, fluorocarbon-based repellents were applied to fabrics with different aramid contents using the pad-dry-cure method under varying concentrations, wet pick-up levels, curing times, and temperatures. From an environmental perspective, six-carbon fluorocarbon compounds were employed as the water/oil repellent agents. The treated fabrics were evaluated in terms of weight, structural characteristics, tensile and tear strength, water and oil repellency performance, comfort properties, flexural rigidity, colorimetric properties, and the durability of water-oil repellency after laundering.*

Keywords: *Aramid, water and oil repellency, fluorocarbon, strength.*

1. INTRODUCTION

The continuous development of textile production technologies and the increasing demand for high-performance materials have increased the interest in industrial fabrics manufactured with aramid fibres (AFs). These fibres are characterised by their exceptional structural integrity and mechanical properties, making them particularly well-suited for applications that demand superior performance. Aramid fibers are classified into two primary types: meta-aramid and para-aramid, each with distinct attributes that determine their specific applications. Meta-aramid fibers exhibit excellent resistance to heat and flames, making them highly suitable for fire-resistant clothing, heat-stable filtration systems, and other applications requiring thermal durability, lightweight properties, and flexibility. Moreover, in addition to this, para-aramid fibers are renowned for their exceptional tensile strength, making them ideal for reinforcing plastics, rubber components, and fiber optic cables, as well as for manufacturing protective equipment (Khammatova et al., 2021). The introduction of aramid fibers in 1964 represented a major breakthrough in chemical fiber technology, sparking increasing interest in their applications across various industries. With continuous scientific and technological advancements, the aramid fiber family has expanded significantly, leading to numerous variations. Among these, poly(p-phenylene terephthalamide) (PPTA), commonly referred to as Aramid 1414 or para-aramid (p-AF), and poly(m-phenylene isophthalamide) (PMIA), known as Aramid 1313 or meta-aramid (m-AF), are widely recognized. Additionally, heterocyclic aramid fibers such as poly(p-phenylene benzobisthiazole) (PBO) and hyperbranched aramid fibers have been developed, further extending the range of applications for these high-performance materials (He et al., 2024).

With advancements in modern technology, protective textiles have significantly expanded, becoming an essential and integral part of technical textiles (Ibrahim ve Abdel-motaleb, 2013). Water and oil repellency are among the most commonly utilized functional properties in protective clothing materials (Kasturiya ve Bhargava, 2003).

This study examines the impact of a water and oil repellent finishing treatment on the mechanical performance and comfort properties of blended fabrics containing different proportions of meta-aramid fibers. In order to achieve this objective, fluorocarbon compounds were applied to fabrics

with varying aramid content using the padding method, with adjustments in concentration, liquor pickup levels, curing time, and temperature. From an environmental perspective, C6-based fluorocarbon compounds were chosen as the water and oil repellent agents. The results were analyzed in terms of fabric weight, structural properties, thickness, tensile and tear strength, water and oil repellency, comfort characteristics, bending rigidity, color values, and post-wash performance.

2. MATERIALS AND METHODS

2.1 Materials

In the experimental study, two types of aramid fabrics were utilised: the first fabric composition consisted of 93% meta-aramid, 5% para-aramid, and 2% antistatic fibres (F1), while the second fabric comprised 75% meta-aramid, 23% para-aramid, and 2% antistatic fibres (F2). Two types of six-carbon fluorocarbon polymers from two different manufacturers were used as water and oil repellent agents, and an aliphatic booster was applied to improve the durability of the fluorocarbon-based finishing. The experimental applications were conducted within the Sun Tekstil R&D Centre, in the application and prototype development facility.

Table 1. General properties of fluorocarbon and auxiliary chemicals

Properties Chemical Structure	Chemical 1 Fluorocarbon Emulsion	Chemical 2 Fluorocarbon Polymer, Emulsion	Aliphatic Booster Aqueous Polyurethane Dispersion
Ionic Nature	Nonionic	Cationic	Nonionic
Density	1.1 g/cm ³	1.06 g/cm ³	1.0-1.1 g/cm ³
pH Value	3.0-5.0	2,0-5,0	6,4

2.2 Methods

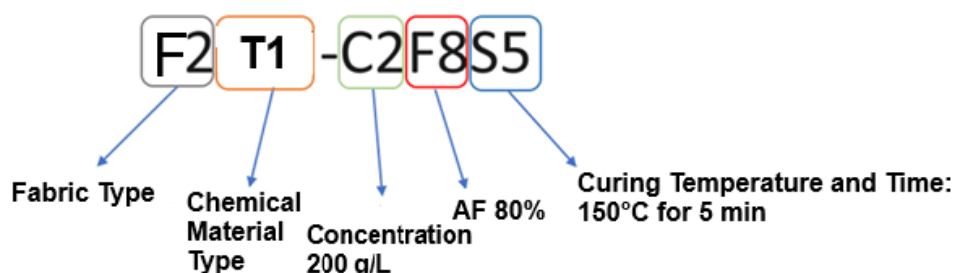
In this study, the fluorocarbon finish was applied to fabrics using the impregnation method in a laboratory-type padding machine. The parameters investigated during the process were determined as follows:

- Fabric type (F1: 93% meta-aramid, 5% para-aramid, 2% antistatic fibers and F2: 75% meta-aramid, 23% para-aramid, 2% antistatic fibers)
- Concentration (100 g/L and 200 g/L)
- Pickup ratio (%) (60% and 80%)
- Curing time (2 min and 5 min)
- Curing temperature (180°C and 150°C)

During the process, for a 60% pickup ratio, the padding machine operated at 3 bar pressure and a speed of 3 m/min. For an 80% pickup ratio, the fabrics were passed through the squeezing rollers at 1 bar pressure and a speed of 3 m/min. Subsequently, pre-drying and curing were performed using a laboratory-type stenter machine. The processing conditions for the treatment recipe are presented in Table 2. Figure 1 presents a sample code breakdown for the specimens.

Table 2. Processing conditions for the treatment recipe

1. Processing Recipe	2. Processing Recipe
100 g/L or 200 g/L Water Repellent Chemical 1	100 g/L or 200 g/L Water Repellent Chemical 2
10 gr/L Aliphatic Booster	2 g/L Wetting Agent
Acetic Acid (pH:4-5)	Acetic Acid (pH:4-5)
Pre-drying temperature and time : 100 °C 2 min	Pre-drying temperature and time : 100 °C 2 min
Curing Temperature and Time: 150°C for 5 min - 180°C for 2 min	Curing Temperature and Time: 150°C for 5 min - 180°C for 2 min

**Figure 1.** Example of Code Breakdown

2.3. Testing and Analysis Methods

After the experiments, the fabrics were analyzed for color values (CIELab), mass per unit area (TS EN 251), bending rigidity (ASTM D 4032), tensile strength (ISO 13934-1), tear strength (ISO 13937-2), water vapor resistance (ISO 11092), air permeability (ISO 9237), water repellency (ISO 4920), oil repellency (ISO 14419), contact angle, and thermal resistance (ISO 11092). Additionally, certain performance properties were evaluated after laundering.

The washing procedures were conducted in accordance with ISO 6330. The fabrics were submitted to a 4G washing programme, utilising 20 g of ECE-B reference detergent, followed by tumble drying. A non-standard additional ironing process was applied at 160–200°C without steam for 15 seconds on both fabric surfaces.

3. RESULTS AND DISCUSSION

The results obtained from the tests and analyses are presented in Table 3, where selected findings are provided.

Table 3. Test and analysis results

Fabric Code	Mass Per Unit Area (g/m ²)	Tear Strength		Tensile Strength		Bending Rigidity (N)	Air Permeability (mm/sn)	Water Vapor Resistance (m ² .Pa/W)
		Warp	Weft	Warp	Weft			
		(N)	(N)	(N)	(N)			
F1	180	70,57	57,45	1327,45	1152,84	2,7	133,6	2,8
F2	173	55,69	53,65	1198,39	1227,4	2,2	142,1	2,4
F1T1-C1F6S8	182	52,78	55,41	1208,52	1077,21	6,8	124,2	3,3
F1T1-C1F6S5	182	68,59	49,89	1075,68	981,85	7,1	138,5	3,1
F1T1-C1F8S8	183	56,58	54,64	1130,47	1060,85	7,9	121,9	3
F1T1-C1F8S5	181	72,68	49,04	1072,85	956,48	10,5	127,1	3,7
F1T1-C2F6S8	183	59,68	50,33	1104,18	995,32	15,1	120,0	3,6
F1T1-C2F6S5	184	57,92	51,38	1157,2	1036,7	15,5	128,9	3,4
F1T1-C2F8S8	181	55,89	50,8	1199,89	1185,41	13,9	134,9	3,6
F1T1-C2F8S5	186	54,35	48,68	1188,84	1144,72	12,8	127,6	4
F1T2-C1F6S8	180	62,92	55,8	1134,74	1039,24	10,7	131,6	3,5
F1T2-C1F6S5	180	62,15	53,07	1140,73	1098,39	8	126,7	3,2
F1T2-C1F8S8	181	50,81	51,69	1208,45	1096,61	12,7	132,9	3,5
F1T2-C1F8S5	180	58,48	55,47	1203,85	1065,26	13	126,5	3
F1T2-C2F6S8	185	52,69	46,03	1204,86	1067,37	22,2	124,7	3,5
F1T2-C2F6S5	180	52,54	51,63	1240,06	1112,74	20,3	127,3	4,1
F1T2-C2F8S8	186	48,55	44,71	1188,83	1129,35	14,7	132,7	4,2
F1T2-C2F8S5	185	54,45	50,38	1225,68	1130,12	31,7	129,0	4
F2T1-C1F6S8	181	50,79	58,41	831,67	855,15	8,4	133,2	3,3
F2T1-C1F6S5	182	59,18	53,52	1173,08	1122,32	9	133,3	3,4
F2T1-C1F8S8	184	53,21	49,82	1232,44	1121,83	10,5	129,3	3,9
F2T1-C1F8S5	182	56,68	51,4	1250,04	1060,62	8	139,1	3,6
F2T1-C2F6S8	181	59,68	51,5	1228,14	1107,29	19,4	133,4	4,1
F2T1-C2F6S5	187	58,18	50,04	1136,46	1079,58	12,7	123,7	4,2
F2T1-C2F8S8	187	53,03	49,26	1086	1070,3	23,8	130,2	4,3
F2T1-C2F8S5	187	54,29	47,04	1159,64	1125,71	11,5	127,4	3,6
F2T2-C1F6S8	180	63,78	64,61	1188,55	1216,67	13	123,8	3,3
F2T2-C1F6S5	181	62,54	53,58	1097,29	1172,98	13,3	128,9	3,1
F2T2-C1F8S8	177	61,28	63,9	1315,12	1126,16	11,3	127,0	3,4
F2T2-C1F8S5	179	63,28	58,63	1243,72	1181,12	11	121,3	3,5
F2T2-C2F6S8	179	52,04	50,32	1248,78	1155,26	14,4	119,2	3,9
F2T2-C2F6S5	180	55,42	49,13	1208,1	1048,73	17,3	122,3	4,1
F2T2-C2F8S8	182	46,99	46,97	1185,97	1141,72	23,5	123,6	4,2
F2T2-C2F8S5	185	54,61	48,17	1221,82	1125,43	15,7	126,7	4,3

According to the water repellency test results, the water repellency performance of untreated fabrics (F1 and F2) improved after the application of the finishing process. The initial water repellency performance before washing was determined as ISO 5. In daily life, textile products are typically ironed before reuse after each wash. Therefore, in addition to investigating the water repellency performance of fabrics before washing, their performance was also examined by applying an ironing process after each wash. It was observed that the fabrics maintained their water repellency performance even after 5 and 10 washing cycles, with the performance level remaining at ISO 5. The preservation of water repellency performance after washing is attributed to the ironing process applied after each wash. The literature suggests that a simple ironing process can facilitate the alignment of fluorocarbon chains by reaching their melting temperature, thereby restoring their original water repellency performance (Bariş, 2012). The obtained results are consistent with the findings reported in the literature.

The oil repellency test results indicate that the initial oil repellency rating of untreated fabrics was 0, which increased to 6 after the application of the finishing process. After five washing cycles, this value increased to 6.5 for all samples, and after ten washing cycles, it further increased to 7. This enhancement in oil repellency performance is similarly attributed to the ironing process applied after washing.

The results indicate that, in general, the mass per unit area of fabrics subjected to water-repellent finishing treatments increased compared to raw fabrics. It has been determined that the increase in concentration level and the amount of liquor uptake leads to an increase in mass per unit area. Water-repellent chemicals are generally applied to the surface of the fabric, and this process may reduce the fabric's natural flexibility. The stiffness and lack of elasticity induced by the chemical treatment can make the fibers more brittle, which in turn may reduce the tear strength of the fabric. The tear strength results indicate that fabrics subjected to water-repellent finishing treatments exhibit lower tear strength compared to raw fabrics. It has been determined that as the concentration amount, liquor ratio, and temperature increase, the tear strength decreases. The tensile strength results indicate that there was no significant change in the warp tensile strength of fabrics treated with a water-repellent finishing process compared to untreated fabrics. However, a decrease in the weft tensile strength was observed for both fabric types after the application of the water-repellent finishing process, which can be attributed to the chemical bonding to the fabric structure. Overall, it was noted that in conditions where "Chemical 2," identified as a fluorocarbon-based chemical, was used at a high concentration and with a high liquor pick-up ratio, the weft tensile strength was relatively higher.

The circular bending rigidity results indicate that fabrics treated with a water-repellent finishing process exhibited increased bending rigidity, meaning higher stiffness, compared to untreated fabrics. It was determined that as the concentration level increased, the fabric stiffness also increased.

The air permeability measurement results indicate that untreated fabrics exhibited higher air permeability compared to fabrics treated with a water-repellent finishing process. It was observed that fabrics treated with "Chemical 1," identified as a fluorocarbon-based chemical, had higher air permeability than those treated with "Chemical 2," another fluorocarbon-based chemical. Additionally, it was concluded that maintaining a lower temperature during the curing process positively influenced air permeability.

The water vapor measurement results indicate that treated fabrics exhibited higher water vapor resistance compared to untreated fabrics (F1 and F2). It was determined that as the concentration amount, liquor pick-up ratio, and applied temperature increased, the water vapor resistance also increased.

According to the color measurement results, it was determined that as the concentration level, liquor pick-up ratio, and applied temperature increased, the color difference compared to the untreated fabrics (F1 and F2) became more pronounced, resulting in a darker shade.

According to the contact angle measurement results, meta-aramid fabrics inherently exhibit hydrophobic properties even in their untreated state (F1 and F2) due to their intrinsic fiber composition. After the application of a fluorocarbon-based finishing treatment, an enhancement in this hydrophobicity was observed. It was determined that the measured contact angle values for the F2 fabric type (75% meta-aramid, 23% para-aramid, and 2% antistatic fibers) were higher compared to those of the F1 fabric type (93% meta-aramid, 5% para-aramid, and 2% antistatic fibers).

4. CONCLUSION

This study aimed to investigate the effects of fluorocarbon-based water repellent finishing treatments on the performance and comfort properties of fabrics containing different ratios of

meta-aramid and para-aramid fibers. The finishing process was applied using the padding method under varying concentrations, liquor pick-up levels, curing times, and temperatures. The treated fabrics were analyzed in terms of thickness, weight, bending rigidity, tensile and tear strength, water and oil repellency, and post-wash performance characteristics.

The results demonstrated that water repellent treatments increased the mass per unit area and stiffness of the fabrics, while reducing their air permeability and tear strength. The application of fluorocarbon compounds enhanced the hydrophobicity of the fabrics, with meta-aramid-rich samples exhibiting higher initial water repellency. Notably, the ironing process after laundering played a significant role in maintaining and even improving the water and oil repellency performance over multiple wash cycles.

Overall, this study provides valuable insights into the impact of fluorocarbon-based treatments on aramid-containing fabrics, contributing to the development of durable and functional textiles for protective applications. Future research could focus on alternative eco-friendly water repellent finishes to address environmental concerns while maintaining high performance standards.

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DEVELOPMENT OF UV-STABILIZED, FLAME RETARDANT, RECYCLED PET YARNS FOR OUTDOOR APPLICATIONS

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Abstract: Textile fabrics used in outdoor environments are exposed to various environmental and physical challenges due to weather conditions and sunlight. Depending on the quality of the fabric, these effects can lead to color fading and fabric deterioration over both long and short periods. During our production process, the UV stabilizers, flame-retardant additives, and pigments used can degrade the yarn structure, negatively impacting color stability and material durability. This study aims to develop an innovative, flame-retardant, and recycled polyester yarn by incorporating high-colorfastness pigments to create a broad color range resistant to sunlight. Additionally, special additives were used to reinforce the polymer structure, preventing deterioration and degradation. Experimental trials were conducted with four different colors, UV additives from three different suppliers, and three different flame-retardant (FR) materials. The physical properties, performance, and durability of the yarns were evaluated under outdoor conditions. After determining optimum parameters and formulations, samples were produced in 19 different colors. The results demonstrated that FR polyester yarns exhibited varying levels of strength retention, with non-FR yarns maintaining 50% of their initial strength after 1,500 hours, while FR-treated yarns lost more than 50% of their strength by 1,000 hours. Further research is ongoing to enhance the longevity and stability of the material.

Keywords: Polyester, recycled yarns, flame retardancy, UV stabilization, outdoor textiles, sustainability.

1. INTRODUCTION

Textile materials used in outdoor applications are constantly exposed to UV radiation, moisture, and temperature variations, which lead to degradation, reduced mechanical strength, and color fading.

Acrylic fibers have traditionally been used for outdoor applications such as upholstery fabrics, garden furniture fabrics, sun umbrellas, and awning textiles due to their weather-resistant nature. However, challenges in raw material supply and high costs have made polyester fibers a viable alternative.

Polyester yarns offer cost-effectiveness, recyclability, and improved durability, making them an excellent choice for sustainable textile applications. Also, flame retardancy is an essential requirement for outdoor textiles, particularly in residential and commercial settings. The goal of this study is to develop high-performance, flame-retardant, and UV-stabilized polyester yarns using recycled materials while maintaining mechanical and aesthetic properties.

2. MATERIALS AND METHODS

2.1. Development of Polyester Yarns

The development process involved four color variations, three UV stabilizers from different suppliers, and three flame-retardant (FR) additives. Polyester yarns were produced using melt spinning, and samples were collected for further analysis.

2.2. Physical Properties

The mass (g/m²) and thickness (mm) of the fabrics were measured according to ISO 2062 and TS EN 9073-2 standards.

2.3. Performance and Durability Testing

- Flame Retardancy Tests: Conducted according to NF P92 504-503-505 standards, with Limiting Oxygen Index (LOI) measurements between 35-50.
- UV Resistance & Color Stability: Evaluated through ISO EN 105 B04 - Xenon arc fading lamp test.
- Phenolic Yellowing Resistance: Tested as per ISO 105 X 18, achieving a gray scale rating of 4 or higher.

2.4. Mechanical Properties

- Tensile Strength & Elongation: Measured following ISO 2062 standards.

3. RESULTS AND DISCUSSIONS

The performance characteristics of flame-retardant (FR) and non-FR polyester yarns were assessed under outdoor exposure conditions. The results indicate that FR-treated polyester yarns experienced greater degradation over time compared to non-FR variants, primarily due to the impact of chemical additives.

- Non-FR polyester samples retained 50% of their strength after 1,500 hours.
- FR-treated samples lost more than 50% of their strength after 1,000 hours.
- Higher concentrations of UV stabilizers enhanced colorfastness but slightly reduced tensile strength.

These findings suggest that while FR additives improve safety properties, they also accelerate mechanical degradation under prolonged exposure. Future work will focus on optimizing formulations to balance both durability and flame-retardant efficiency.

4. CONCLUSION

This study successfully developed UV-stabilized, flame-retardant, and recycled polyester yarns suitable for outdoor textile applications. The optimized formulations demonstrated significant resistance to UV degradation and color fading, making them promising candidates for sustainable and long-lasting textile solutions.

Future research will aim to further enhance durability, improve chemical resistance, and explore new polymer modifications for even greater performance under extreme environmental conditions.

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DO TRUNK AND THIGH COOLING USING WET SHEETS AND ICE PACKS EFFECTIVELY REDUCE BODY TEMPERATURE IN A HOT AND HUMID ENVIRONMENT?

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Abstract: *This study aimed to investigate the effectiveness of evaporative body cooling using wet sheets with ice gel packs on alleviating heat strain for military personnel in a hot and humid environment. Nine young males participated in two environmental conditions (33°C, 30%RH vs. 33°C, 70%RH). Rectal temperature, skin temperatures, heart rate, thermal sensation, thermal comfort, and sweat sensation were measured for 90 min (cooling intervention applied during the last 30-min). The results showed that mean skin temperature at the end of the cooling period was $1.6 \pm 0.9^{\circ}\text{C}$ higher than at rest for the 70%RH condition, but $0.6 \pm 1.1^{\circ}\text{C}$ lower for the 30%RH condition ($P < 0.001$). Chest temperature at the end of the cooling was $0.3 \pm 1.4^{\circ}\text{C}$ lower (70%RH) and $4.9 \pm 1.8^{\circ}\text{C}$ lower (30%RH) than at rest ($P < 0.001$), thigh temperature was $2.2 \pm 1.4^{\circ}\text{C}$ higher for the 70%RH condition and $1.3 \pm 2.1^{\circ}\text{C}$ higher for the 30%RH condition ($P < 0.001$). Rectal temperature, heart rate, skin temperature on the forehead, forearm, hand, calf, and foot, thermal sensation, thermal comfort, and sweat sensation showed no significant differences between the two humidity conditions.*

Keywords: *Heat strain, wet sheet, military personnel, evaporative heat loss, hot and humid environment.*

1. INTRODUCTION

Exertional heat illness poses an increasing threat to individuals engaging in physical activity under heat stress, such as farmers, the elderly, athletes, military personnel, and firefighters. Studies have evaluated various body cooling strategies, including misting fans, cooling towels, wet sheets with fans, cooling vests, and arm immersion in cold water (DeGroot et al., 2013; Klous et al., 2022; Sefton et al., 2016; Young et al., 1987). To identify the most effective body parts for cooling using wet sheets, Baek et al. (2023) examined the effects of whole-body cooling, trunk/thigh cooling, and trunk/thigh cooling with ice packs using wet sheets. Among the three cooling methods, trunk/thigh cooling with ice packs was found to be the most effective to alleviate heat strain. However, the effectiveness of evaporative cooling using wet sheets may be influenced by air humidity levels. Therefore, we investigated the effectiveness of evaporative body cooling using wet sheets and ice gel packs in alleviating heat strain for military personnel in a hot and humid environment.

2. MATERIALS AND METHODS

Nine healthy male subjects (25 ± 2 y in age, 175 ± 5 cm in height, 73 ± 10 kg in body weight, 23.8 ± 2.8 kg·m⁻² in BMI, and 1.88 ± 0.14 m² body surface area) participated in the following two environmental conditions: 1) 33°C & 30%RH and 2) 33°C & 70%RH (IRB No. 2310/003-010). The sheet was chosen through pilot tests considering physical properties (polyester 100%, 1,896 s·5 mL⁻¹ in drying rate, 10,637 g·m⁻²·24 h⁻¹ in moisture permeability, 2,100 mm·s⁻¹ in air permeability, 1.79 m²·Pa·W⁻¹ in vapor resistance, <1 s in water absorption time, 76.8 [wale] and 98.4 [course] stitch·5 cm⁻¹ in gauge, 0.55 mm in thickness, and 134 g·m⁻² in weight). The sheet (100 cm wide × 120 cm long) was soaked using room temperature water ($20 \pm 1.8^{\circ}\text{C}$) and stored in an insulated box (20°C and 73%RH inside the box). Subjects wore brief, short-sleeve T-shirts, summer combat uniform (long-sleeve shirts and ankle-length pants), a bulletproof vest, pile socks, and a helmet with running shoes (total mass 11.7 – 12.0 kg without shoes). A trial consisted of a 10-min rest followed by a 50-min exercise, and a 30-min cooling intervention with the trunk/thigh covered

by a wet sheet with four ice gel packs (12 cm × 18 cm; 230 g each). After completing the 50-min exercise on a treadmill, subjects lay down on a mat in the climate chamber. Thirty pieces of wet sheets were prepared for the 30-min cooling treatments, and every wet sheet was replaced every 1 min. The ice gel pack remained attached to the skin surface on the axilla and inner thigh for the entire 30-min without replacement. Skin temperatures (the forehead, chest, forearm, hand, thigh, calf, and foot), rectal temperature, heart rate, and psychological responses (thermal sensations of whole body, trunk/thigh, and arm/leg, thermal comfort, and sweat sensation) were continuously measured.

3. RESULTS AND DISCUSSION

Heart rate and rectal temperature showed no significant differences between the two humidity conditions. Rectal temperatures decreased by approximately 1.1°C during the 30-min cooling period in both 30%RH and 70%RH conditions. At the end of the cooling period, the mean skin temperature decreased by $4.9 \pm 0.4^\circ\text{C}$ (30%RH) and $3.3 \pm 0.6^\circ\text{C}$ (70%RH) compared to the value at the end of exercise, with a significant difference observed between the two conditions (Figure 1A, $P < 0.001$). The mean skin temperature at the end of the cooling period was $0.6 \pm 1.1^\circ\text{C}$ lower than the rest under 30%RH, but $1.6 \pm 0.9^\circ\text{C}$ higher under 70%RH ($P < 0.001$). The chest skin temperature at the end of the cooling period was $4.9 \pm 1.8^\circ\text{C}$ lower (30%RH) and $0.3 \pm 1.4^\circ\text{C}$ lower (70%RH) than the rest period (Figure 1B, $P < 0.001$). Thigh temperature at the end of the cooling period was $3.2 \pm 1.0^\circ\text{C}$ higher under 70%RH and $1.3 \pm 2.1^\circ\text{C}$ higher under 30%RH ($P < 0.001$). No significant differences between the two humidity conditions in the following skin temperatures, the forehead, forearm, hand, calf, or foot, were found. There were no significant differences in thermal sensation (whole body, trunk/thigh, and arm/leg), thermal comfort, and sweat sensation between the humidity conditions.

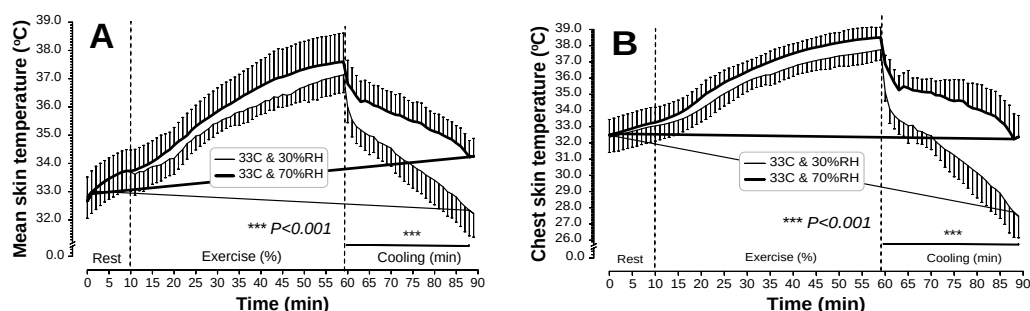


Figure 1. Time courses of mean skin temperature (A) and chest temperature (B).

4. CONCLUSION

The results suggested that the ambient humidity level in hot environments did not affect rectal temperature, heart rate, or psychological responses. However, chest and thigh temperatures showed greater cooling effects with wet sheets for the 30%RH condition compared to the 70%RH condition, which induced a significant difference in mean skin temperature. We confirmed that body cooling using wet sheets had greater evaporative efficiency in a hot and dry environment than in a hot and humid environment. Further investigations are needed to assess potential rebound effects after cooling.

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TESTING OF FUNCTIONAL CHARACTERISTICS OF CHEMICAL AND FIREFIGHTER PROTECTIVE CLOTHING

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Abstract: *Protecting of first responders against toxic compounds in the ambient environment requires protective equipment that must meet various functional requirements in terms of material properties and ensemble integrity as well as user practicality and work comfort. This article describes testing of material properties of protective textiles against permeation of chemical agents, testing of integrity of protective ensembles in toxicologic chamber and testing of thermal strain induced by protective ensembles in climatic chamber. The laboratory tests serve as a baseline assessment for possible improvements of firefighter or NBC (nuclear, biological and chemical) protective suits in terms of protection against the permeation and penetration of toxic compounds underneath the protective clothing.*

Keywords: *Protective ensembles, toxicologic chamber, climatic chamber, hazardous substances.*

1. INTRODUCTION

Personal protective equipment (PPE) is essential mean for first responders dealing with mitigation of a variety of emergency situations including events with risk of hazardous agents release or fires producing complex cocktail of combustion products depending on the burning material and environmental conditions. The PPE provide a barrier between the user and the harmful environment. The PPE ensemble consists of separate parts as protective clothing, respiratory protection and other garments. Such ensemble should meet the requirements as the entire system – good barrier material against toxic vapours or air-born particles may still result in body exposure in case of poor design of clothing in terms of overall integrity. Besides, the perfect barrier provided by PPE significantly influences the body heat exchange and consequently may lead to heat stress with undesired effects on user's physiology, health and safety.

In current study, based on our long-time experience with evaluation of NBC suits, we focused on evaluation of protective properties of firefighter suits in terms of permeation and penetration of hazardous chemical agents – combustion products – underneath the suit. We also determined thermal-insulation properties of firefighter suits currently used and induced heat stress.

2. MATERIALS AND METHODS

2.1 Material Testing – Permeation of Chemical Substances

The characteristics of protective materials during permeation of chemical substances in liquid or vapour state including volatile organic compounds (VOCs) or polycyclic aromatic compounds (PAHs), surrogates or real chemical warfare agents (CWA) can be measured using a multi-channel automatic sampling system Carousel 2000© with GC-FID evaluation (Vaněk et al., 2024). Based on the results, the breakthrough time (BT) is determined – the time interval of reaching the threshold level of the contaminant after the permeation onto the reverse side of the material. In this study, we measured 1-layer wildland firefighter suit (FR1) and four various 3-layer structural firefighter emergency suit (FR2, FR3, FR4, FR5) and three fire-protection hoods (H1, H2 and H3) with filter layer as a protective barrier against particles.

2.2 PPE Ensemble Integrity Testing in Toxicologic Chamber

The PPE ensemble integrity tests were performed in toxicologic chamber with volunteers carrying out physical activities as body and arm swings, squats, walking in place. The volunteers worn protective ensembles with protective mask or SCBA and indication underwear (long-sleeve t-

shirt, underpants, hood) and the toxicologic chamber was filled with model gas. The penetration of model gas under the tested PPE created colour change on the indication underwear. This methodology is an original way of determination and visualization the place and pathway of the leakage including dosage evaluation. The method is worthy for the PPE designers particularly as it reveals the „weak“ sites of the PPE design, as well as for the PPE users to show the most problematic parts to be aware of during the proper donning.

2.3 Heat Stress and Physiology Strain Testing in Climatic Chamber

The tests of physiologic strain were performed in a climatic chamber with 5 volunteer acclimatized probands – 3 men and 2 women wearing the protective ensemble FR3 and performing physical activity (walking on a treadmill) under defined ambient conditions (35 °C, 10–15 % rel. hum.), see figure 1. Monitored values were heart rate (HR), body core temperature (RT) and skin temperature (tsk). Maximum tolerable time achieved in the test by each volunteer (achieving RT 38.5 °C or on proband's demand) was determined (Lunerova et al. 2023). Thermal-insulation properties of the protective ensembles were measured by means of 34-zones Newton thermal manikin in climatic chamber at Brno University of Technology, Czech Republic, see figure 2, according to procedures described in ISO 15831 and in (Toma et al., 2021).



Figure 1. Proband in in climatic chamber at 35 °C, walking on treadmill



Figure 2. Measurement of I_T and R_{eT} using 34-zones thermal manikin Newton at BUT, Czech Republic

3. RESULTS AND DISCUSSION

3.1 Material Testing – Permeation of Chemical Substances

In this study, we describe the results for naphthalene permeation (as a representative of PAH) through construction materials of firefighter suits FR1, FR2, FR3, FR4, FR5, see figure 1, and fire-resistant hoods – H1, H2 and H3, see figure 2. All tests demonstrated were under static conditions.

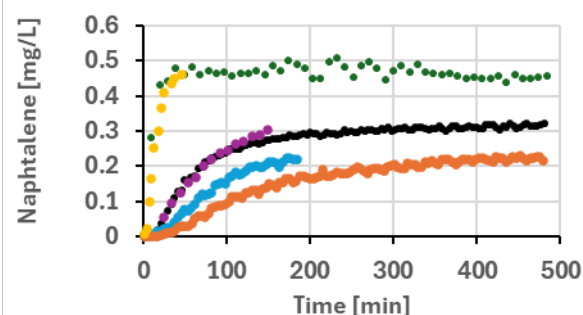


Figure 3. Naphthalene permeation through material: blank ● (separator – PE foil), 1-layer FR1 ●, 3-layers FR2 ●, FR3 ●, FR4 ● and FR5 ●

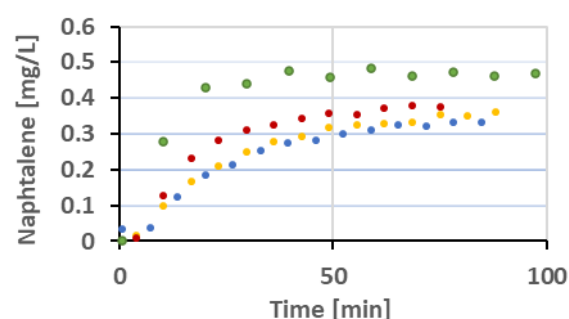


Figure 4. Naphthalene permeation through material: blank ● (separator – PE foil), hood H1 ●, H2 ● and H3 ●

The results presented on figures 3 and 4 demonstrate that material of firefighter suits provide short-term protection against permeation of chemical agent which may be present in combustion products. The material of wildfire firefighter suit FR1 showed naphthalene breakthrough time BT below 2 min, regarding the 3-layers suits FR2, FR3, FR4 and FR5, the BT was within 10–15 min. Regarding the fire-protection hoods, the BT was below 2–5 min for all hoods tested.

3.2 Integrity testing in toxicologic chamber

In the toxicologic chamber, there were 15 tests of various types and combinations of firefighter FR3 emergency and FR1 wildfire suits and fire-resistant hoods H1–H3 and other garments performed, see figure 5. The resulting forms of indication underwear showed coloured pink spots detecting penetration of model gas underneath the FR3 suit around waist and calves, see figure 6, and all over the body underneath the FR1 suit, see figure 7.



Figure 5. Probands in toxicologic chamber



Figure 6. Indication underwear – FR3 suit



Figure 7. Indication underwear – FR1 suit

3.3 Heat stress and physiology strain testing in climatic chamber

In climatic chamber, there were 10 tests performed with firefighter suit FR3 complemented by SCBA or without respiratory protection. The results show that the average tolerable operating time at 35 °C was 67.9 ± 8.6 min with average maximum RT 38.4 ± 0.1 °C.

4. CONCLUSION

For firefighters, the main task of PPE is protection against heat and flames, however the wide range of chemicals that are part of smoke, combustion products, exhaust fumes from engines, fire extinguishers must be also taken into account. Though, the protection provided by currently used firefighter suits against breakthrough of toxic compounds underneath is just few minutes. Solution in the form of complementary supplements similar to current NBC suits may help to increase the protection level of the firefighter suits and contribute to reducing the occupational health risk of firefighters. Provided that the benefits of improved chemical protection of firefighter suits would be in balance with possible decrease in thermal and ergonomic comfort.

ACKNOWLEDGEMENT

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AN IMPROVED THERMOREGULATION MODEL FOR PREDICTING PHYSIOLOGICAL RESPONSE TO OCCUPATIONAL HEAT EXPOSURES

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Abstract: This study proposes an improved thermoregulation model (ITM) to predict the thermophysiological responses to occupational heat exposures. The major improvements include accounting for the effects of high-temperature on metabolic rate and blood flow rate, and the development of a multi-node clothing system. The model is validated in steady-state and transient hot environments, by comparing predicted thermophysiological indicators with experimental data. The results indicate that ITM provides more accurate predictions for physiological indicators than published models. In steady-state conditions, the maximum discrepancies of sweat rate and evaporation rate are 185.80 g/h and 81.75 g/h, respectively, with the root mean square deviations (RMSD) of rectal and skin temperatures are 0.06 to 0.38 °C and 0.39 to 0.51 °C, respectively. In transient conditions, the RMSDs of the same indicators are 0.21 to 0.29 °C and 0.22 to 0.30 °C, respectively. The ITM is useful to estimate thermal safety and thermal comfort in hot environments.

Keywords: Thermoregulation model, hot environment, personal protective equipment, rectal temperature, skin temperature.

1. INTRODUCTION

Core temperature, skin temperature and sweat rate are essential indicators for assessing thermal safety. To accurately predict these indicators, various thermophysiological models have been developed. However, few models are dedicated to occupational exposure in hot environments (Yang, J., et al., 2014), characterized by high temperatures and personal protective equipment (PPE). In this study, we propose an improved thermoregulation model (ITM) by considering the effects of high-temperature and PPEs on thermoregulation mechanisms. Then, the model is validated by comparing predicted thermal responses with experimental data and other models' results in steady-state and transient hot environments.

2. MATERIALS AND METHODS

2.1. Improved Human Thermoregulation Model

The ITM is described in our earlier work (Chen, F., et al., 2022). It is based on the JOS-3 model (Takahashi, Y., et al., 2021) and improved by considering the effect of high-temperature on metabolic rate and blood flow rate. Additionally, a multi-layer clothing system is developed for PPEs and coupled with the model.

2.2. Verification Proposal

The ITM is validated in steady-state and transient hot environment. For steady-state conditions, we compared the predicted rectal temperature, mean skin temperature, sweat rate and evaporation rate with Wang's experimental data and his simulated results (Wang, F., et al., 2010; Wang, F., et al., 2013). For transient conditions, we compared the predicted rectal temperature and mean skin temperature with Yang's experimental data and his simulated results (Yang, J., et al., 2014). Their experimental conditions are shown in Table. 1. The root mean square deviation (RMSD) is used to reflect the differences between the predicted results and experimental data.

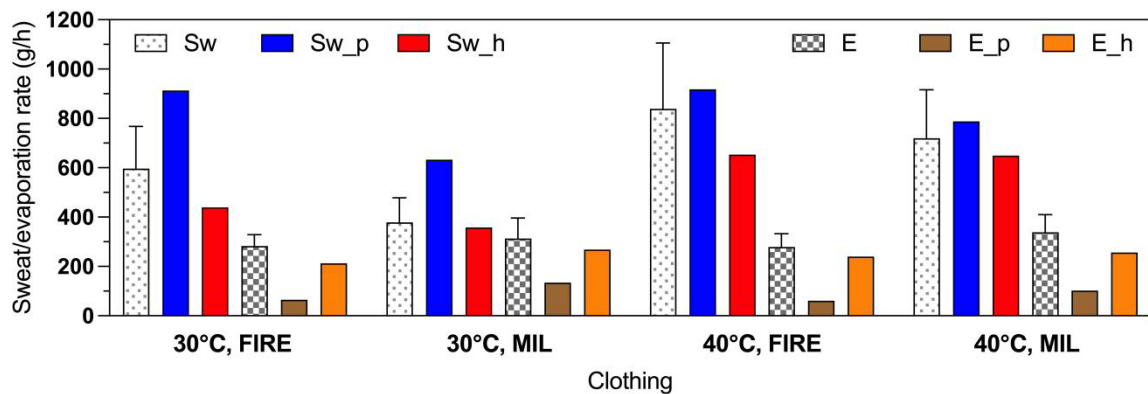
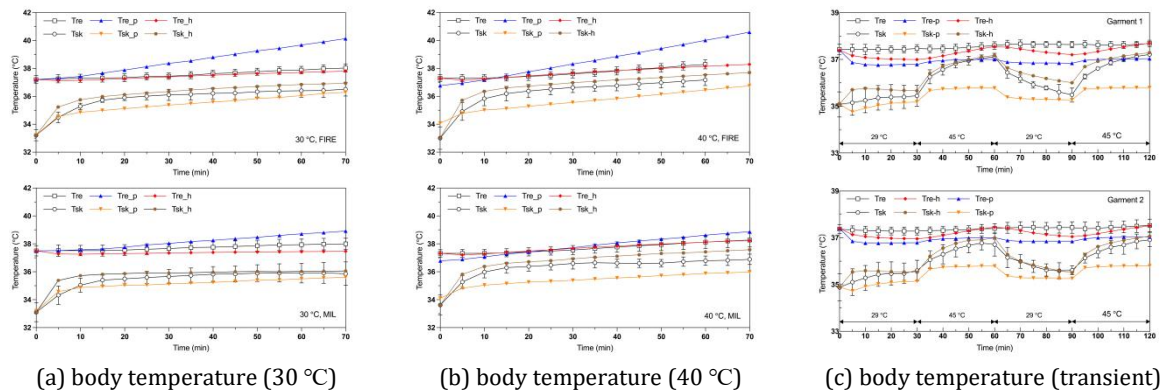
Table. 1 Experimental Conditions

Study	Environmental condition	Clothes	Activity	Measurement
Wang et al.	Ta=30 °C, RH=47% for 70 min	FIRE, MIL	walking at 4.5 km/h	T_{re} , T_{sk} , S_w , E
	Ta=40 °C, RH=45% for 70 min	FIRE, MIL	walking at 4.5 km/h	T_{re} , T_{sk} , S_w , E
	Ta=29 °C, RH=40% for 30 min, Ta=45 °C, RH=40% for 30 min,	garment 1, garment 2	seated	T_{re} , T_{sk}
Yang et al.	Ta=29 °C, RH=40% for 30 min,			
	Ta=45 °C, RH=40% for 30 min			

T_{re} , rectal temperature; T_{sk} , skin temperature; S_w , sweat rate; E, evaporation rate.

3. RESULTS AND DISCUSSION

The measured (T_{re} , T_{sk} , S_w , E) and predicted results ($T_{re,p}$, $T_{sk,p}$, $S_{w,p}$, E_p by other published models, and $T_{re,h}$, $T_{sk,h}$, $S_{w,h}$, E_h by ITM) are presented in Figure 1. By considering of high-temperature on metabolic rate and blood flow, the predicted rectal temperatures by ITM agree well with the experimental data in steady-state and transient environment, with the RMSDs of rectal temperature range from 0.06 to 0.38 °C and 0.21 to 0.29 °C, respectively, significantly lower than those by other published models (0.37 to 1.22 °C and 0.47 to 0.64 °C). The predicted skin temperatures by ITM also show good agreement with the experimental values in both environments, with the RMSDs range from 0.39 to 0.51 °C and 0.22 to 0.30 °C, respectively, significantly lower than those by other published models (0.44 to 0.98 °C and 0.65 to 0.84 °C). This is attributed to the multi-layer clothing model, which can accurately calculate the heat and moisture transfer between skin and environment, leading to better performance. Additionally, the maximum discrepancies of sweat rate and evaporation rate by ITM in steady-state condition are 185.80 g/h and 81.75 g/h, respectively, lower than those by other published model (316.50 g/h and 236.02 g/h).

**Figure 1.** Comparison results by ITM, the published models and experimental data.

4. CONCLUSION

In this study, an improved model (ITM) is developed for occupational heat exposures by considering the effect of high-temperature and PPEs on thermoregulation mechanisms. The ITM is validated by comparing predicted results with experimental data and other published model's results. It's proved reliable in main predicting physiological indicators in both steady-state and transient hot environment, which contributes to evaluating thermal safety and thermal comfort.

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A NEW METHOD FOR EVALUATING THE IMPACT RESISTANCE OF PROTECTIVE GARMENTS BASED ON BODY INJURIES

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Abstract: *This study proposes a new method for evaluating the impact-resistant of protective garments based on human injury scoring. Firstly, a human body-clothing-impactor model is constructed using finite element software to analyze the injury mechanism under various impact conditions (mass 5-15KG, velocity 2-8m/s). The finite element simulation results indicate that even when the material is not penetrated, deformation creates a cavity on the body surface, leading to human injury. The cavity depth ($p<0.05$) and radius ($p<0.01$) are correlated with impact mass, impact velocity, and body curvature, separately. The related fitting equations are developed, and a model of human injury scoring is established based on the cavity ratio and body injury scale.*

Keywords: *Performance evaluation, impact resistance, body injuries, finite element simulation*

1. INTRODUCTION

The impact resistance of protective garments is great importance in protecting human body from impact injuries (Shi, et al. 2024). According to the test standards (EN1621-1, EN1621-2, and EN388), the impact-protective performance of the whole garment is generally estimated based on the material parameters, e.g. the residual impact force and damage area of materials, which can be obtained by experiments and finite element simulations (Zhao, et al. 2021). However, the results obtained by this method may differ from the actual performance. Moreover, in many cases where casualties occur, the protective garments show no significant damage (Sosa & Alessa, 2021). In this study, we establish a new method for evaluating for impact resistance of protective garments, which indicates the effectiveness through body injury scoring.

2. METHODS

2.1 Finite-element model

The body model is divided into three parts, trunk, arms and legs, under the protection of aramid fiber (1.2mm) and Ethylene Vinyl Acetate Copolymer (EVA, 6mm). The impactor is a hemispherical object of 25mm radius (Figure 1). The mass and velocity of the impactor are set to 5-15 kg and 2-8 m/s, respectively. Then, the dynamic response is simulated when a projectile impacts perpendicularly on the surface of protective material, which is direct contact with the human tissue. The impact mechanism is analysed using the finite element software.

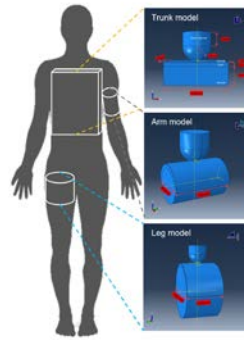


Figure 1. Schematic diagram of human body

2.2 Body injury level

The impact damage to the body is described based on the Abbreviated Injury Scale (AIS), which categorize the human body into 9 primary zones according to injury severity thresholds (Table 1).

Table 1. Injury levels in various parts of the human body

Region	I _{max}	I _{min}
Lung	4	3
Heart	6	5
Liver	6	2
Intestine	4	1
Stomach	4	2
Kidney, Spleen, Pancreas	5	2
Ureter, Bladder	3	1
Vertebral column	6	3
Others	2	0

3. RESULTS AND DISCUSSION

The simulation results demonstrate that impact-induced compression deformation leads to cavity formation within biological tissues (in Figure 2). Based on the regression analysis, it's found that both the cavity depth (h) and surface diameter (D) exhibit significant correlations with the impacting mass (M), impact velocity (V) and body curvature (K). The relationships can be described as Equation (1) & (2). The cavity volume (V_{model}), representing a critical indicator of tissue damage, can be calculated as Equation (3):

$$h = 0.011(K + 1) \times M \times V^2 + 6.687 \quad R^2 = 0.92 \quad (1)$$

$$D = 105.76((K + 1) \times M \times V^2)^{-0.05} \quad R^2 = 0.84 \quad (2)$$

$$V_{model} = 1/3\pi h(3D^2 + h^2) \quad (3)$$

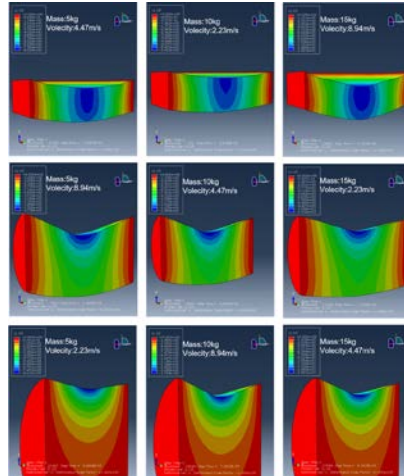


Figure 2. Sectional view of the fitting results

Furthermore, referring to the method of defining blunt trauma in body armor using body injury scores (Liu, et al. 2018), the body injury scoring model is developed based on the volumetric ratio $R(i)$ and body injury levels $S(i)$:

$$R(i) = \frac{V_{model(i)}}{V_a(i)}; S(i) = I_{min} + R(i)(I_{max} - I_{min}). \quad (4)$$

The protective performance can be assessed through injury levels. When $0 \leq S(i) < 1$, it indicates excellent protective performance; when $1 \leq S(i) < 2$, it indicates good protective performance; when $2 \leq S(i) \leq 4$, it indicates poor protective performance; when $S(i) > 4$, it indicates extremely poor protective performance. The overall score is defined by the maximum value of $S(i)$.

Impact tests conducted in accordance with the EN1621-1 standard ($M=5\text{kg}$, $V=4.47\text{m/s}$) demonstrate that the investigated material exhibits an average maximum force of 30.05KN and a single maximum force of 32KN, thereby satisfying Level 1 protector requirements. Through the analytical methodology established in this study, the calculated cavity volumes of the material are determined to be $1.93 \times 10^{-4}\text{m}^3$ for the torso region, $2.42 \times 10^{-4}\text{m}^3$ for the arm, and $2.11 \times 10^{-4}\text{m}^3$ for the leg. The impact depth in the trunk region reaches $h=7.78\text{mm}$, which remains below the muscle tissue thickness threshold, thus preventing organ injury. Consequently, the protective performance score of this material when implemented in protective apparel is evaluated at 0.854, in concordance with standardized test outcomes.

4. CONCLUSION

This research revealed the relationship between impact intensity and human body injuries when wearing protective garment, leading to the development of an impact cavity model. Building upon tissue damage thresholds and cavity volume ratios, a performance evaluation methodology was established for protective equipment. It enables comprehensive quantitative assessment of impact-resistant of protective garment and provides optimization recommendations.

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MOBILITY AND THERMAL COMFORT ASSESSMENT OF PERSONAL PROTECTIVE EQUIPMENT FOR FEMALE HEALTHCARE WORKERS: IMPACT OF PROTECTIVE LEVELS AND BODY PHYSIQUE

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Abstract: This study aimed to assess the mobility and thermal comfort of personal protective equipment (PPE) among female healthcare workers, considering wearers' physique and PPE protection levels. Sixteen female subjects (26.3 ± 8.3 y, 161.5 ± 7.3 cm, 57.1 ± 11.0 kg, BMI: 21.9 ± 3.6) representing diverse body types, underwent 4 PPE conditions: L (Low_Plastic gown ensemble), M (Medium_Tyvek 400), H (High_Tyvek 800J with Powered Air Purifying Respirator [PAPR]), and E (Extremely high_Tychem 2000 with PAPR, bib apron, and chemical-resistant gloves). The mobility protocol consisted of 10 different tasks in addition to donning and doffing. The 10 tasks were repeated twice at an air temperature of $24.3 \pm 0.1^\circ\text{C}$, $59 \pm 4\%$ RH. Findings revealed a disproportionate relationship between PPE protection and wearer discomfort. Significant differences in clothing microclimate and total sweat rate were observed between the lowest (L) and highest (E) protection levels ($p < 0.01$), while distinctions among medium levels were inconclusive. Subjective evaluations favoured conditions H and L over M and E ($p < 0.05$), indicating reduced heat, and humidity, increased comfort, and lower exertion. Instances of mobility discomfort, especially in the small body type group, underscored the need for a suitable PPE size system for Korean adult female medical workers. Furthermore, enhancements in gloves, shoe cover, and PAPR hood designs are essential for improving ease of movement and preventing hindrance.

Keywords: Female healthcare workers, personal protective equipment (PPE), comfort, fit, mobility.

1. INTRODUCTION

Personal protective equipment (PPE) plays a critical role in shielding healthcare workers from infectious diseases. However, prolonged use of PPE can lead to heat strain and reduced mobility, issues that have gained attention during global health crises such as COVID-19. In particular, females dominate the workforce in high-risk healthcare environments globally, yet most PPE is designed for male physiques, leading to poor fit and increased risks of discomfort and inefficiency (Janson et al., 2022). Additionally, physiological differences, such as smaller body size and lower $\text{VO}_{2\text{max}}$, make thermoregulation more challenging for females in PPE (Coon & Low, 2024; Cramer & Jay, 2016). Therefore, this study aimed to evaluate the impact of varying protective levels and body physique on the mobility and thermal comfort of PPE, focusing on female healthcare workers who comprise a significant portion of the workforce in high-risk environments.

2. MATERIALS AND METHODS

Sixteen healthy female subjects (age: 26.3 ± 8.3 y, height: 161.5 ± 7.3 cm, body weight: 57.1 ± 11.0 kg, BMI: 21.9 ± 3.6) participated in this study. Subjects were categorized into nine physique groups based on height and BMI. Four PPE conditions were tested: L (Low; plastic gown, total weight of the PPE is 0.61 kg.), M (Medium; Tyvek 400, 0.75 kg), H (High; Tyvek 800J with PAPR, 2.82 kg), and E (Extremely high; Tychem 2000 with PAPR, bib apron and chemical-resistant gloves, 3.14 kg). The common basic items across all 4 PPE conditions were scrub tops and bottoms (short-sleeve top, long pants), bra, panties, socks, EVA clogs, and nitrile surgical gloves. Simulated tasks

included 12 actions: 10 tasks performed by healthcare workers responding to infectious diseases, along with donning and doffing PPE (Figure 1). Environmental conditions were controlled at $24.3 \pm 0.1^\circ\text{C}$ and $59 \pm 4\%$ RH. Measurements included task completion time, clothing microclimate on the chest and thigh, ear canal temperature, total sweat rate, and subjective sensations. Immediately after each experiment, subjects took part in a structured in-depth interview regarding the discomforts associated with each task and PPE item.

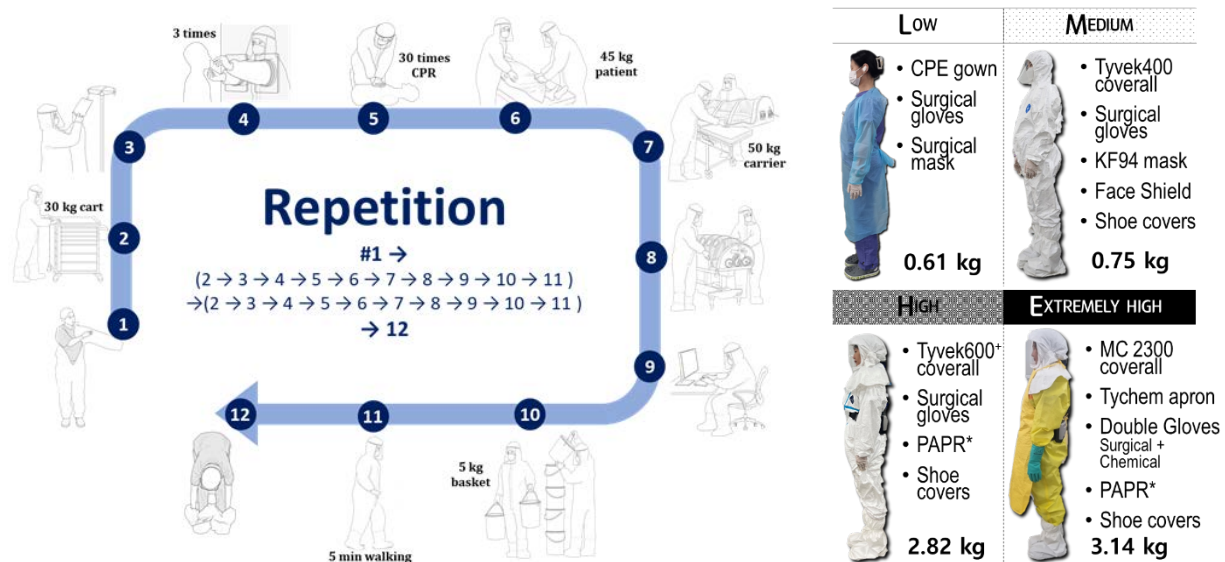


Figure 1. Mobility test protocol of 12 simulated COVID-19 healthcare worker tasks (left) and experimental clothing (right)

3. RESULTS AND DISCUSSION

The experimental results showed that donning and doffing times increased in the order of $L < M < H < E$ ($P < 0.001$), with significant time required for PAPR-related procedures. Higher protective levels, particularly in condition E, resulted in increased clothing microclimate temperature, humidity, and sweat rates ($P < 0.01$). Subjective sensations indicated that conditions $H = L < M = E$ were rated as hotter and more humid (All P s < 0.005). Thermal comfort scores showed a similar trend: $E (-1.8 \pm 0.6) < M (-1.3 \pm 0.9) < H (-0.7 \pm 1.2) = L (-0.4 \pm 0.9)$ ($P < 0.001$). While conditions H and L were more favourable in terms of thermal comfort, medium-level PPE (M) demonstrated inconclusive benefits. Small body types faced significant discomfort and mobility issues, underscoring the inadequacy of current PPE sizing systems. Interviews revealed additional challenges, such as improper glove fit, shoe cover slippage, and PAPR noise disrupting communication.

4. CONCLUSION

The study found that higher protective levels of PPE did not consistently lead to increased discomfort, indicating that wear comfort does not directly correlate with protection levels. This underscores the importance of incorporating comfort evaluation in PPE development. Respiratory protective devices like PAPRs should be distributed based on environmental conditions and individual preferences. Mobility discomfort was more pronounced in smaller body types due to oversized PPE, rather than being linked to higher BMI. Therefore, a tailored PPE sizing system for female healthcare workers, especially for smaller body types, is necessary. Additionally, improvements in the design of gloves, shoe covers, and PAPR hoods are needed to ensure ease of movement and support precision tasks.

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A FOCUS ON SUPERHYDROPHOBIC AND OLEOPHOBIC TEXTILES

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Abstract: Superhydrophobic, oleophobic, and omniphobic textiles have gained increasing attention due to their potential applications in multiple fields. These surfaces, characterized by high contact angles and low sliding angles, are mostly obtained using fluorinated compounds, which have a known environmental and health risks. An alternative solution has been proposed by researchers who have combined surface roughness and low-energy coatings inspired by the lotus leaf. While superhydrophobic textiles can be engineered through several different approaches, achieving superoleophobicity remains challenging due to the low surface tension of oils. This review examines the latest advancements in fluorine-free surface treatments for textiles, emphasizing sustainable approaches to achieving robust liquid repellency.

Keywords: Superhydrophobic, Oleophobic, Omniphobic, Fluorine-free, Textiles

1. INTRODUCTION

Surfaces that can repel both high and low surface tension liquids are used in various fields such as military, protective clothes, medical equipment. Indeed, they present a wide range of applications including self-cleaning, anti-fouling, antibacterial. (Jinlian Hu, 2016)

The wettability, which is the capacity of the liquid to spread over a solid (Marion Callau, 2023), can be characterise according to the contact angle (θ). This angle is formed between the solid-liquid and liquid-air interfaces and can be experimentally measured with a goniometer.

If the liquid is water, a surface can be qualified as hydrophilic when $\theta < 90^\circ$ and hydrophobic when $\theta > 90^\circ$. Other parameters to characterize the wettability of a surface are the angle hysteresis (the difference between the advancing and the critical receding angle)(Kota et al., 2014) and the sliding angle. When a surface displays a contact angle $> 150^\circ$, and a sliding angle $< 10^\circ$ with water or oil it is considered as superhydrophobic or superoleophobic respectively. An omniphobic surface is a surface that repels both low-surface-tension and high-surface-tension liquids (Verma et al., 2023).

Those surfaces have gained an important interest over the last decades, particularly for their applications in the textile industry. Indeed, between the 2000s and the 2020s, the number of papers on hydrophobic textiles increased 100-fold, while those on oleophobic textiles quadrupled (Figure 1).

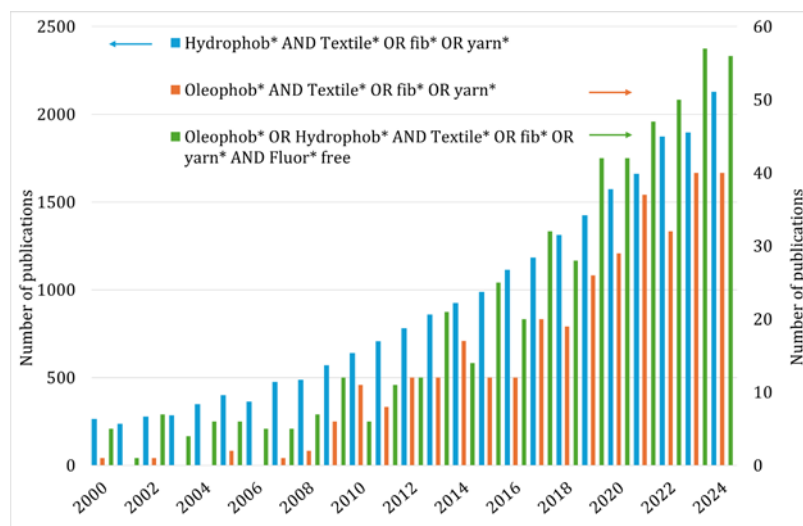


Figure 1. Number of publications with key words “Oleophob* AND Textile* OR fib* OR yarn*”, “Hydrophob* AND Textile* OR fib* OR yarn*” and “Oleophob* OR Hydrophob* AND Textile* OR fib* OR yarn* AND Fluor* free” published since the year 2000, source WebOfScience: 02/2025

Fluorinated compounds are the most used for superhydrophobic textile finishing because of their low surface energy. However, such compounds have been proven to be an environment and health issue as per- and polyfluoroalkyl substances (PFAS) have been found to be persistent, bioaccumulative, and toxic (PFAS Substitution Guide FOR TEXTILE SUPPLY CHAINS, 2022). Moreover, in the literature, there are few hydrophobic treatments and almost no oleophobic treatments research to replace these substances (Figure 2).

This review focuses on the processes used to obtain superhydrophobic, oleophobic and omniphobic textile surfaces at the fabric scale. The aim is to understand how to avoid the use of perfluorinated compounds while achieving/approaching as closely as possible the results that could be obtained with long-chain perfluoroalkyl compounds.

2. FUNCTIONAL TEXTILES

2.1 Preparation of superhydrophobic textiles

A focus on hydrophobic surfaces in the nature highlights the lotus leaf as the most common example of superhydrophobic plant also known as “the lotus effect”. Indeed, the lotus leaf displays a contact angle around 160°, and an angle hysteresis around 4°. Moreover, a look at the structure of this leaf exposes a hierarchical surface structure with convex cells and a layer of hydrophobic wax tubules (Koch et al., 2009). In order to obtain a superhydrophobic surface, there is a need to work on both the surface roughness and the surface chemistry. This property can be obtained by working on a one-step approach (surface roughness and low-surface-energy coating at the same time) or a two-step approach (surface roughness and then low-surface-energy coating).

Surface roughness could be provided by the use of nanoparticles on the substrate (Zaman Khan et al., 2022). As an example, surface modification of natural fibers could be made by two main methods that combine several different approaches which are the coating and the grafting methods (Antoine Ishak, 2023). On the other hand, in the literature it has been shown that synthetic fibers could be modified by physical and chemical methods (which includes grafting and coating methods)(Gashti & Parvinzadeh, 2012).

2.2 Preparation of superoleophobic textiles

In our knowledge, there is no known example of oleophobic plants or animals in the nature. As oils have an extremely low surface tension, it is complicated to obtain a fabric that repels such

liquids. To obtain an oleophobic surface, a focus must be taken on the design parameters of the textile substrate surface. According to Tuteja et al. a re-entrant curvature combined with surface roughness and chemistry can be used to obtain a surface that repel liquids with low surface tension (Tuteja et al., 2007). Shabanian et al. established design parameters to create an oil-repellent textile finish without using perfluorinated compounds. They demonstrated a strong oil repellency by precisely controlling the size, spacing, and surface chemistry of a nylon fabric via an oxygen plasma treatment followed by a dip-coating in a silanol solution (Shabanian et al., 2020).

3. CONCLUSION

In recent years, the interest in superhydrophobic, oleophobic, and omniphobic textile surfaces has significantly increased. Achieving robust oil and water repellency requires to focus on both surface roughness and chemistry by working on a hierarchical dual-sized structure and a low surface tension coating that is not provided using fluorinated compounds. This study reviews strategies to develop high-performance, fluorine-free textile finishes by optimizing material properties and surface structures.

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MECHANICAL PERFORMANCE AND CAFFEINE RELEASE OF BI-LAYERED POLYVINYL ALCOHOL/POLYCAPROLACTONE NANOFIBERS FOR WOUND DRESSING APPLICATIONS

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Abstract: In this study, a bi-layered nanofiber wound dressing was fabricated to enhance caffeine release while maintaining suitable mechanical properties. Polyvinyl alcohol (PVA) nanofibers loaded with 2% caffeine were electrospun as the first layer, followed by a reinforcing polycaprolactone (PCL) layer. The in vitro transdermal caffeine release was evaluated using Franz diffusion cell, and mechanical properties were assessed via tensile strength (TS) and elongation at break (EAB) measurements. The bi-layered structure achieved a cumulative caffeine release of approximately 41% within 240 minutes, surpassing the release from a single-layer PVA system. The calculated TS (3.83 MPa) and EAB (68%) were within acceptable ranges for wound dressing applications. These findings suggest that a PCL-reinforced bi-layered nanofiber system can provide an effective balance of controlled drug release and mechanical durability for wound healing applications.

Keywords: Caffeine, Polyvinyl Alcohol (PVA), Polycaprolactone (PCL), Bi-layered Electrospinning, Wound Dressing, Mechanical Properties.

1. INTRODUCTION

Wound healing requires protective and bioactive dressings that support tissue regeneration while delivering therapeutic agents in a controlled manner. Electrospun nanofiber-based wound dressings provide high surface area, porosity, and tunable drug release profiles, making them ideal for transdermal delivery applications. Avizeh et al. (2019) reported that caffeine in the PVA nanofibers increased blood vessel formation as a wound dressing. The hydrophilic nature of polyvinyl alcohol (PVA) nanofibers may affect adversely its efficient caffeine release; however, their poor mechanical properties limit their applicability in wound care. Conversely, hydrophobic character of polycaprolactone (PCL) nanofibers may provide a solution. This study aims to fabricate a bi-layered PVA/PCL nanofiber dressing to enhance mechanical integrity while optimizing caffeine delivery. The system was evaluated for caffeine release kinetics using Franz diffusion cells and mechanical properties via tensile strength and elongation at break analysis. The objective was to determine whether the bi-layered system provides a suitable balance of mechanical durability and controlled caffeine release for potential wound healing applications.

2. MATERIALS AND METHODS

2.1 Preparation of Feed Solutions and Bi-Layered Electrospinning

A PVA solution was prepared at 8% (w/w) in acetic acid: water (50:50, v/v) solution. 2% caffeine (w/w) was added to the PVA solution. A PCL solution was prepared at 7.5% (w/w) in acetone: acetic acid (50:50, w/w) solution. The PVA solution and PCL solution were electrospun at the feed rate of 0.6 mL/h and 0.9 mL/h, respectively. The applied voltages were 10 kV and 15 kV for the PVA and PCL electrospinning, respectively. The distance to the collector plate was 10 cm for the PVA electrospinning, whereas it was 5 cm for the PCL electrospinning. To obtain bi-layered nanofibers, first the PVA solution was electrospun, and then the PCL solution was electrospun onto the PVA nanofibers. For mechanical measurements, a PVA solution (8%, w/v) in distilled water and a PCL solution (10%, w/v) in acetic acid were electrospun separately.

2.2 *In vitro* Caffeine Release

In vitro transdermal release of caffeine from nanofiber samples were determined by using a Franz diffusion cell at 37 °C. Given its histological similarities to human skin, approximately 500 µm thick pig ear's skin was used *in vitro* analysis (Pulsoni et al., 2022). The PCL layer of the bi-layered system was placed on the pig ear's skin. Caffeine quantification in a withdrawn sample was performed by a high-performance liquid chromatography (HPLC).

2.3 Mechanical Properties

The mechanical strength of the produced nanofibers was evaluated by analysing the tensile strength (TS) and elongation at break data (EAB) according to the Surendhiren et al. (2020), using a texture analyser. The nanofiber samples were fixed the clamps and stretched at a constant speed of 1 mm/s until 70% of the maximum load was reached, with a pre-load of 0.05N.

3. RESULTS AND DISCUSSION

The cumulative release percentage of caffeine from bi-layered nanofiber samples was approximately 41% after 240 min. This percentage of caffeine release was greater than caffeine release from one-layer PVA nanofiber, which was reported as approximately 37% (Alakaş, 2023).

Texture profile analysis is used to determine mechanical properties, and the results are given in Table 1. The TS and EAB were determined.

Table 1. Texture Profile Analysis of Nanofiber Samples

	Tensile strength (MPa)±sd	Elongation at Break (%)±sd
PVA nanofiber	5.0±0.1	74.0±0.7
PCL nanofiber	1.5±0.4	56.1±9.8

Based on the table, the mechanical properties of the bi-layered system was calculated as follows:

The **total thickness** of the bi-layer system:

$$t_{total} = t_{PVA} + t_{PCL} = 4 + 2 = 6 \text{ mm}$$

Using the **rule of mixtures** (weighted average based on thickness):

1. Tensile Strength of Bi-layered System

$$TS_{bi-layer} = \left(\frac{t_{PVA}}{t_{total}} \times TS_{PVA} \right) + \left(\frac{t_{PCL}}{t_{total}} \times TS_{PCL} \right)$$

2. Elongation at Break of Bi-layered System

$$EAB_{bi-layer} = \left(\frac{t_{PVA}}{t_{total}} \times EAB_{PVA} \right) + \left(\frac{t_{PCL}}{t_{total}} \times EAB_{PCL} \right)$$

t: thickness of the nanofiber layer.

The calculated TS and EAB were 3.83 MPa and 68%, respectively.

4. CONCLUSION

The placing of the PCL nanofiber layer below the PVA nanofiber layer promoted the burst release of caffeine. This may help showing the therapeutic effect of caffeine immediately. In addition to that, the PCL layer, which has hydrophobic character, may decreased the TS and EAB values;

however, the TS and EAB values were still suitable for a wound dressing system. The TS values of dry and wet skin were reported as 5-30 MPa and 1-5 MPa, respectively. On the other hand, the EAB value of skin was 35-120% depending on the hydration level (Blanchard, 2023; Gallagher et al., 2012). Furthermore, the acceptable EAB values of a wound dressing is over 50% to ensure flexibility. As a result, bi-layered nanofiber sample in this study falls within the suitable range for wet skin applications and required flexibility range for wound dressing.

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CUTANEOUS THERMAL SENSATION ACCORDING TO CLOTHING FABRICS AND FOOTWEAR TYPES DURING RADIANT HEAT EXPOSURE TO THE LEG IN A CAR

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Abstract: We examined cutaneous thermal sensation based on the influences of clothing fabrics and footwear types under radiant heat exposure. Seven healthy males wore long-sleeved t-shirts, underpants, socks, long pants with different fabrics (100% cotton, 100% polyester, 100% wool) along with different shoes (slippers, sneakers, leather shoes). Cutaneous warm, hot, and heat pain sensations were measured on the thigh and instep while sitting in a mock-up car ($21.9 \pm 0.2^{\circ}\text{C}$, $50 \pm 1\%\text{RH}$). The surface of a radiant heat panel ($10 \times 30 \text{ cm}^2$) was set to a constant temperature of 135°C . The distance from the leg to the radiant heat panel was maintained at 10 cm. The results showed that cutaneous thermal thresholds on the thigh and instep did not differ significantly according to the pant and shoe types. However, heat flux transmitted through the leg skin and the surface temperature of the pants and shoes varied depending on the conditions

Keywords: Cutaneous thermal sensations, radiant heat, clothing fabrics, footwear types

1. INTRODUCTION

Growing worldwide concerns for the global warming electric vehicles (EVs) are considered as an effective substitute for internal combustion engine vehicles. EVs consumed extra electric energy for convective heating systems in winter. Proximal radiant heating for the passengers is proposed for EVs to optimize electric energy consumption (Gopi et al., 2024). When these proximity and local heaters are applied to EVs, passengers' thermal discomfort or skin burns should be avoided. Radiant heat transmission to the skin through clothing is resisted by the properties of fabrics and the air gap between the skin and clothing is an efficient thermal insulator against external heat (Lu et al., 2013). The influences of fabrics and physical properties of clothing on the cutaneous thermal sensations induced by radiant heat were investigated in this study.

2. METHODS

Seven healthy Korean males (age: 23.8 ± 2.6 y, height: 175.1 ± 4.3 cm, weight: 81.0 ± 10.5 kg, body mass index [BMI]: $26.4 \pm 2.0 \text{ kg}\cdot\text{m}^{-2}$, total body fat: $22.0 \pm 8.2\%$) participated in the following six conditions: three pants and three shoes. Subjects wore long-sleeved t-shirts, underpants, pants, socks, and shoes. Three experimental pants were made of 100% cotton(jeans), 100% polyester, and 100% wool, respectively. Slippers, sneakers, and leather shoes were used for the different three shoe-conditions. All the pants and shoes were in black to minimize of any possible colour effect. Cutaneous thermal sensation was measured while sitting in a mock-up car at an air temperature of $21.9 \pm 0.2^{\circ}\text{C}$ with $50 \pm 1\%\text{RH}$. A radiant heat panel ($10 \times 30 \text{ cm}^2$) was installed in the mock-up car and the surface temperature of the heat panel was set to a constant temperature of 135°C . The distance between the body part and the surface pf the radiant heat panel was maintained at 10 cm. Heat flux (W/m^2) of the skin surface, skin temperature (T_{sk}), surface temperature of the pants and shoes, and response time at the moment when subjects initially felt warmth, hot, and heat pain sensation were recorded. Cutaneous thermal sensations were measured on the left thigh and instep and radiation heat were stimulated up to 60 min unless subjects felt heat pain sensation.

3. RESULTS AND DISCUSSION

Initial skin temperatures on the thigh and instep at rest had no statistically differences among the three types of pants or three shoe conditions (Table 1). Cutaneous warm, hot, and heat pain

thresholds on the thigh and instep did not differ according to the types of pants and shoe. Time to perceive cutaneous thermal sensations on the thigh and instep showed no significant differences among the three pant or three shoe conditions.

Table 1. Thermal thresholds and time to perceive thermal sensation on the thigh and instep

		Thigh (three pant conditions)				Instep (three shoe conditions)			
		Cotton	Polyester	Wool	<i>P</i> -value	Slipper	Sneaker	Leather	<i>P</i> -value
Skin temp. (°C)	Initial	31.8 ± 0.9	31.8 ± 1.3	31.4 ± 0.8	0.714	32.6 ± 2.1	33.3 ± 1.1	32.9 ± 1.0	0.676
	Warm	35.2 ± 1.5	36.0 ± 1.5	35.6 ± 1.8	0.710	35.0 ± 1.9	35.8 ± 0.9	35.1 ± 0.9	0.531
	Hot	38.8 ± 0.5	38.4 ± 1.2	38.0 ± 1.7	0.564	36.4 ± 1.6	36.8 ± 0.7	37.4 ± 1.2	0.403
	Heat pain	38.7 ± 0.6	38.7 ± 0.6	38.4 ± 1.1	0.659	37.0 ± 1.2	37.2 ± 0.5	38.0 ± 1.0	0.218
Response time (s)	Warm	343 ± 265	396 ± 197	333 ± 161	0.860	315 ± 166	482 ± 321	380 ± 227	0.513
	Hot	1734 ± 792	1582 ± 1020	1444 ± 708	0.842	1046 ± 465	1286 ± 875	1367 ± 535	0.680
	Heat pain	2502 ± 970	2611 ± 1053	2178 ± 962	0.740	1754 ± 446	1933 ± 842	1922 ± 729	0.883

Figure 1 showed results from one subject. While the thigh temperature was similar each other among the three pant conditions, the heat flux was the lowest and the pant surface temperature was highest for the cotton condition (Fig. 1a~c). There was no marked difference in heat flux and surface temperature between the polyester and wool conditions.

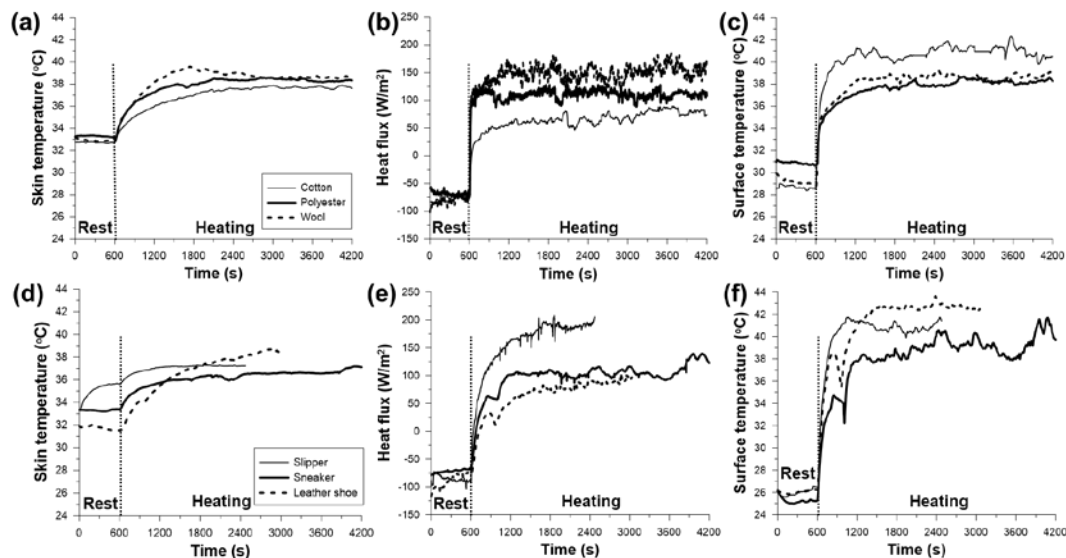


Figure 1. Time courses of thigh temperature (a), heat flux into the thigh (b), surface temperature of pants (c), foot temperature (d), heat flux into the instep (e), and surface temperature of shoe (f) during radiant heat exposure (one subject).

4. CONCLUSION

Cutaneous thermal thresholds and time to perceive thermal sensation on the thigh and instep did not differ among the three pant conditions (100% cotton, 100% polyester, and 100% wool) or the three shoe conditions (slippers, sneakers, and leather shoes), even though the heat flux through the pants (or footwear) and the surface temperatures of the pants and footwear showed differences. These results indicate that cutaneous thermal thresholds are maintained within their intrinsic values regardless of the fabrics of pants and the types of footwear.

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EVALUATING THE IMPACT OF PROTECTIVE GLOVES ON HAND SWEATING IN A HOT HUMID ENVIRONMENT

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Abstract: *Building on previous research into hand sweating patterns for improving space gloves, this study investigates the impact of wearing gloves on hand sweating by comparing the sweating characteristics of hands with and without protective gloves.*

Keywords: *Protective gloves, local sweating, skin hydration, heat stress.*

1. INTRODUCTION

Moisture accumulation is a major issue in protective clothing, as it can lead to skin irritation and reduce thermal insulation, making garments less effective against heat, bacteria, and other hazards. This is particularly critical for healthcare workers, firefighters, chemical workers, and astronauts in spacesuits (Lee & Goh, 2021; Stull, 2000). In space, thermoregulation and moisture management are especially challenging due to the body's altered physiological responses (Greenleaf & Fortney, 1992). During extravehicular activities (EVAs), astronauts rely heavily on their hands for tasks, and hand protection is vital for both dexterity and thermal comfort (Scheuring, 2016). Hand perspiration in bulky gloves leads to discomfort and can contribute to injuries, such as nail trauma (Chappell et al., 2017). However, while studies have mapped sweat distribution across the body, detailed data on hand-specific sweating was lacking (Machado-Moreira et al., 2008).

Hand sweating patterns, including sweat rate, skin moisture levels, and activated sweat gland density (ASGD) on both the palm and dorsal surfaces of the hand in a hot, humid environment, were previously studied by the author. However, questions remain about the impact of wearing gloves on hand sweating. This study aims to compare hand sweating patterns with and without gloves. These findings on localized hand sweating could play a crucial role in advancing the design of optimized gloves for heat stress, particularly for specialized applications like space gloves.

2. MATERIALS AND METHODS

Eight healthy right-handed Korean males (26 ± 1.8 y in age, 170.7 ± 4.1 cm in height, 69.4 ± 2.7 kg in weight, 23.8 ± 0.8 kg/m² in BMI) participated in two experiments: 1) wearing glove on both hands (Glove), and 2) without gloves (Hand). A trial consisted of 10-min rest and 60-min passive heating (leg immersion at 42°C water) at an air temperature of 33°C with 60%RH.

Glove simulated multilayer of space glove and included 3 layers: cotton glove, nitrile glove and Kevlar glove. Each glove was weighted right before and after experiment to determine amount of sweat produced by each hand part during heat exposure. While left hand cotton glove was cut into 6 parts (hand, thumb, index finger, middle finger, ring finger, small finger and weighted before and after experiment). Local sweat rate (SKINOS SKN-2000, Japan) and skin temperature were measured in 1-s interval on the 5 sites of the palmar surface of the hand palm (palm, thumb, index finger, middle finger, ring finger). Skin hydration level (MDD 4 meter, Germany) was measured on

the 6 sites of the palm regions (palm, thumb, index finger, middle finger, ring finger, interdigital space (between the index and middle fingers)) (Figure 1).

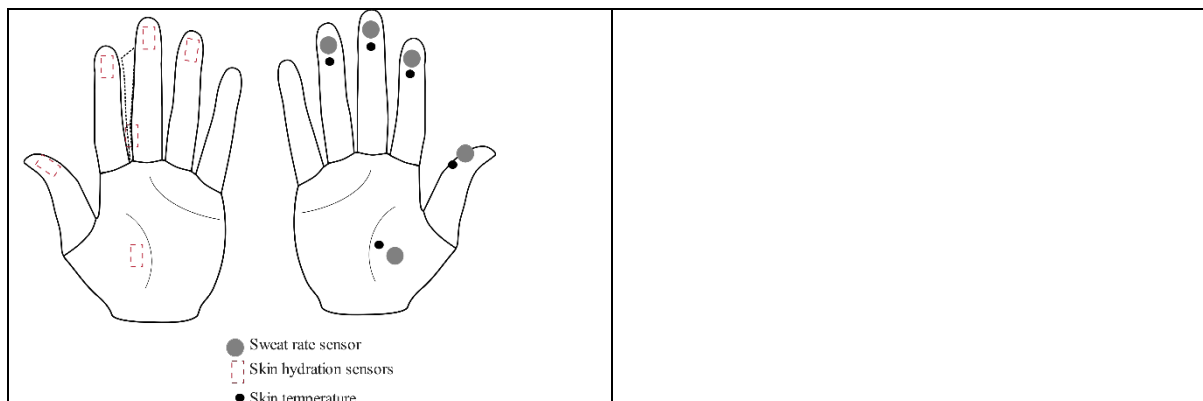


Figure 1. Sensors' attachment during experiment

Body morphological parameters (body weight, total body fat (TBF), total body water, skeletal muscle mass) using a bioelectric impedance analysis (InBody 970, Korea) and hand morphological parameters, including hand surface area, hand volume, and the length and circumferences of the hand and fingers. The perceived onset of sweating, including the time and specific hand part, was recorded.

3. RESULTS AND DISCUSSION

Glove weight, Local sweat rate, Skin hydration, onset of sweating

It was observed by measuring the cotton glove before and after the experiment that the hand (excluding the fingers) sweated the most (+0.57g), followed by the ring finger (+0.0075g), thumb (+0.0062g), small finger (+0.0048g), and index finger (+0.0041g). The right hand sweated 0.0144g more than the left. Additionally, while wearing the glove, the onset of sweating occurred 9.8 seconds earlier. The results above are based on 3 subjects, as the experiment is currently underway. The complete results will be presented.

4. CONCLUSION

In this work, it is aimed to create textile-based hydrogel structures containing superabsorbent with sodium alginate, a natural polymer known to be biocompatible. Sodium alginate is odorless, biocompatible, cost-friendly and has high fluid handling capacity, therefore it is a suitable polymer for the developed product.

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PSYCHO-PHYSIOLOGICAL EFFECTS OF INDUSTRIAL RESPIRATORS WITH DIFFERENT DESIGNS IN A HOT ENVIRONMENT: A PILOT STUDY

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Abstract: This study examined the psycho-physiological effects of various industrial respirators under heat stress. Two subjects participated in the following three mask conditions (3M 8710L, 3M 8812K, and Moldex 4200K) and no mask condition at an air temperature of 33°C with 50%RH. A trial consisted of 60-min (rest, treadmill walking (6 km·h⁻¹), and recovery). Auditory canal temperature, skin temperatures (8 sites), mask microclimate temperature and humidity, heart rate, and subjective perceptions were recorded. Moldex 4200K showed the highest cheek temperature and microclimate humidity even though the inhalation resistance was the lowest, while 3M 8812K exhibited the lowest auditory canal temperature and microclimate temperature during exercise. It seems that the exhalation valve is better to support comfort of wearers than lower inhalation resistance of mask materials. Further studies with more subjects are recommended to validate these findings.

Keywords: Protective mask, thermal strain, thermal comfort, inhalation resistance, exhalation valve

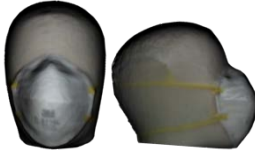
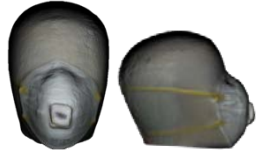
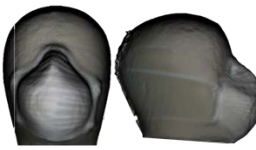
1. INTRODUCTION

The use of personal respiratory protective equipment is essential for workers exposed to hazardous chemicals in industrial environments for their respiratory health and safety. However, during hot summer, workers often experience difficulties wearing masks (Jung et al., 2020), which includes discomfort, a sense of suffocation, and skin irritation caused by face sweat (Kim et al., 2014). The physical effects of masks vary depending on their design (Jung et al., 2021). In order to provide respiratory comfort for workers in hot summer, designing masks that minimize psychological and physiological burdens on workers in harsh working conditions is crucial. This study was conducted as a preliminary study to explore the physiological and psychological responses of wearers when wearing various masks which were commercially available.

2. METHODS

Two healthy male subjects (S1: Age 30, Height 174.4 cm, Weight 71.1 kg; S2: Age 24, Height 170.5 cm, Weight 67.6 kg) participated in the following four experimental conditions: 1) without a mask (Control), and with three different types of masks. The three masks were as follows: A) 3M 8710L, B) 3M 8812K, and C) Moldex 4200k (Table 1). All masks were classified as Second-class respirators. The 3M 8710L featured a cup-style design, the 3M 8812K had a cup-style design with an exhalation valve, and the Moldex 4200k featured a wave design with a larger surface area. The inhalation resistance of masks was measured using a mask inhalation resistance tester (ART-1651, ARTplus Co, Korea; 30 LPM). During the experiments, subjects wore underwear, long pants, long-sleeved shirts, socks, and athletic shoes. All experiments were conducted in a climate chamber set at an air temperature of 33°C with 50%RH. Each session lasted 60 min, comprising 10-min rest (sitting), 30-min walking on a treadmill at a speed of 6 km·h, followed by 20-min recovery (sitting). Auditory canal temperature, skin temperatures [on 8 body sites], mask microclimate temperature/humidity, heart rate, and subjective perceptions (thermal sensation, thermal comfort, sweat sensation, rate of perceived exertion, and respiratory discomfort) were measured.

Table 1. Characteristics of the three masks in the present study

	Type A: 3M 8710L	Type B: 3M 8812K	Type C: Moldex 4200K
Picture of mask			
	Cup-style	Cup-style with an exhalation valve	Wave design with a larger surface area
Inhalation resistance (Pa)	17.6	16.9	8.3
3D-image			

3. RESULTS

We found that Mask C showed the highest cheek temperature and microclimate humidity even though the inhalation resistance was the lowest, while Mask B had the lowest auditory canal temperature and microclimate temperature during exercise. It seems that the exhalation valve (Mask B) is better to support comfort of wearers than lower inhalation resistance due to the wave design. Microclimate humidity during exercise and recovery was lower for Mask C than other mask conditions. Heart rate and subjective perceptions showed similar patterns across the mask conditions.

Table 2. Summary of the auditory canal, skin temperatures, mask microclimate, and heart rate

Condition		Auditory canal temp. (°C)		Mean skin temp. (°C)		Cheek temp. (°C)		Microclimate temp. inside the mask (°C)		Microclimate humidity inside the mask (%RH)		Heart rate (bpm)	
		S1*	S2**	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Control	Rest	36.9	36.9	34.1	34.2	34.7	33.1	32.8	33.0	60	64	88	87
	Exercise	37.2	37.3	35.2	34.7	35.7	33.9	33.7	33.1	59	61	122	119
	Recovery	37.3	37.5	35.8	35.6	36.2	34.1	34.3	33.8	56	66	97	101
Mask A	Rest	37.1	36.8	34.2	34.7	35.9	33.2	35.1	35.6	97	89	88	103
	Exercise	37.2	37.4	35.6	34.6	36.2	33.1	35.2	35.7	87	84	125	136
	Recovery	37.3	37.7	36.0	34.8	36.6	33.7	35.7	36.1	88	87	97	117
Mask B	Rest	37.0	36.7	34.9	34.4	35.9	33.4	35.2	35.2	85	86	94	92
	Exercise	37.1	37.1	35.9	35.1	36.2	33.8	34.8	34.9	87	83	133	122
	Recovery	37.3	37.2	36.0	35.7	36.2	34.2	35.7	35.4	92	87	109	104
Mask C	Rest	37.1	37.0	34.7	34.6	35.5	34.1	35.0	35.2	86	82	94	113
	Exercise	37.3	37.4	35.6	35.4	36.3	35.0	35.1	35.5	80	83	131	140
	Recovery	37.4	37.7	35.8	36.4	36.7	35.6	35.6	35.9	81	82	105	126

S1* and S2** represent subject 1 and 2, respectively.

4. CONCLUSION

The results suggested that the valve design in Mask B facilitated heat exchange with external air, while the wave design structure appeared to aid in moisture release. However, the wave structure may increase thermal burden. As this study was a preliminary experiment involving only two subjects, future studies with more subjects are needed to validate the current results.

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TEMPERATURE VARIATIONS IN DIFFERENT FOOT AREAS DEPENDING ON TOE HEATING LEVELS FOR SMART SHOES DURING EXERCISE

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Abstract: This study aimed to propose the optimal toe heating temperature for smart heated shoes by examining the skin temperatures of various foot regions and shoe microclimates inside the shoes based on different toe heating temperatures in a cold environment. Heating pads were placed inside experimental shoes to heat the toe region under three heating temperatures (46, 48, and 50°C). The results showed that the toe and instep temperatures were higher for the 50°C condition than other conditions during exercise. The sole temperature for the 48 °C condition was, on average, 0.8 °C higher compared to the 50 °C condition. Among the measured regions, the lowest temperature was observed on the heel area. However, there were no significant differences in the skin temperatures of the five regions based on the toe heating levels. The shoe microclimate temperature was lowest for the 48 °C condition, while the shoe microclimate humidity was highest for the 50 °C condition ($P < 0.001$).

Keywords: Diabetic foot ulcer, active heating shoes, foot temperature, smart shoes.

1. INTRODUCTION

The feet, as an extremity of the body, are one of the most frequently reported body parts affected by frostbite or non-freezing cold injuries during outdoor activities in cold environments. In particular, more than 50% of diabetic patients experience diabetic foot complications associated with impaired peripheral circulation and reduced sensory nerve function (Jehan et al., 2013). These conditions prevent them from promptly detecting drops in foot temperature, making them more susceptible to frostbite in the toes. According to Oakley (1984), when the feet remain immobile in cold environments, toe temperature drops the fastest among all foot regions. On the other hand, vigorous movement temporarily increases foot temperature; however, sweat accumulation results in a failure to maintain warmth. Therefore, maintaining the temperature of the toes in cold environments is considered a critical factor for preserving overall foot warmth. Unlike studies on the effect of foot temperature maintenance by heating the soles in cold environments (Shimazaki & Murata, 2015), relatively few studies have addressed the effect of toe heating on foot temperature maintenance. Therefore, the present study aimed to investigate the dynamics of foot temperatures in different regions according to different toe heating levels during exercise in a cold environment.

2. METHODS

2.1 Subjects

Nine male subjects participated in this study [mean $\pm$ SD: 25.2 $\pm$ 2.5 y in age, 177.2 $\pm$ 5.8 cm in height, 80.2 $\pm$ 13.3 kg in body weight, 26.5 $\pm$ 3.4 kg/m² in body mass index, and 23.2 $\pm$ 7.1 in total body fat (%BF)]. There were no subjects with foot frostbite experience, unusual susceptibility to cold, or cold-related cardiovascular diseases.

2.2 Experimental conditions and measurements

All subjects participated in the following three experimental conditions based on toe heating temperatures at 46°C, 48°C and 50°C. Air temperature in a climate chamber was set at -9°C. Airflow in the climate chamber was remained below 0.25 m·s⁻¹. A trial consisted of a 10-min rest on a stool, followed by 60-min walking at 4 km·h⁻¹ on a treadmill and a 10- min recovery in a sitting position on the stool. Subjects wore daily winter clothing, including a padded down jacket with a hood, long sleeve shirts, shorts, long pants, gloves, socks, and running shoes ($I_T=1.69$ clo). Skin

temperatures were measured on the instep, 2nd toe, sole, heel, and anklebone along with the sole temperature on the left foot every 5 s using thermistor sensors and a data logger (LT8A, Gram Corp., Japan). During the 80-min trial, shoe microclimate temperature and humidity on the instep inside the shoe was measured every 5 s.

3. RESULTS

The toe and instep temperatures were higher for the 50°C condition than for the other two conditions (Table 1). In contrast the temperature of the sole was, on average, 0.8°C higher for the 48°C condition than for the 50°C condition (Table 1). The lowest temperature among the five foot temperatures measured was the heel for the three conditions, and the lowest heel temperature was observed for the 50°C heating condition. However, there were no significant differences in the temperatures of the instep, toe, sole, heel, and anklebone according to the toe heating levels. The temperature inside the shoe was lowest for the 48°C condition, while the humidity inside the shoe was highest for the 50°C condition ($P < 0.001$, Table 1). A strong negative correlation was found between the toe temperature and the temperature below anklebone ($r = -0.927$, $P < 0.001$), and a positive correlation was observed between the toe temperature and the humidity inside the shoe ($r = 0.733$, $P < 0.001$).

Table 1. Skin temperatures on the foot and shoe microclimate during exercise (unit: °C)

Parameter	Toe heating temperature			P
	46°C	48°C	50°C	
Instep temp._Exercise**(°C)	24.1 ± 4.7	24.1 ± 3.0	24.8 ± 2.9	N.S
Toe temp._Exercise (°C)	22.8 ± 5.8	23.3 ± 5.0	23.8 ± 6.9	N.S
Heel temp._Exercise (°C)	15.8 ± 4.6	16.2 ± 4.6	15.0 ± 3.3	N.S
Sole temp._Exercise (°C)	21.7 ± 4.4	22.4 ± 3.9	21.6 ± 3.9	N.S
Below ankle bone temp._Exercise (°C)	17.8 ± 3.3	18.9 ± 2.7	18.4 ± 3.8	N.S
Shoe microclimate temp._Exercise (°C)	17.3 ^{ab} ± 4.0	15.3 ^b ± 2.6	18.6 ^a ± 2.1	< 0.001
Shoe microclimate humidity.Exercise (%RH)	11.7 ^b ± 5.2	11.2 ^a ± 4.8	12.9 ^c ± 4.6	< 0.05

*a, b, or ab represent statistical differences among the three heating conditions; **Mean for the last 3 min of the exercise.

4. CONCLUSION

While heating the toes inside the shoes, the toe and instep temperatures were highest when the heating temperature was at its peak among the 46, 48 and 50°C. However, the sole, heel temperature exhibited opposite trends compared to the toe temperature, showing the lowest temperature at the highest heating setting. These results may be explained by the redistribution of blood in the foot and increased local sweating for the 50°C heating condition. Therefore, it is important to set an appropriate toe heating temperature that does not induce excessive foot sweating during exercise in cold environments.

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SUSTAINABILITY IN PROTECTIVE CLOTHING THROUGH COMPARATIVE ANALYSIS OF CONVENTIONAL AND ECO-FRIENDLY DENIM FINISHING PROCESSES

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Abstract: *The increasing emphasis on sustainability within the textile industry has driven the exploration of eco-friendly finishing processes for protective clothing. This study investigates the comparative effects of traditional and sustainable denim finishing techniques on high-strength denim fabrics intended for heavy-duty workwear and motorcycle apparel. Three denim fabrics of similar weight and raw material content were subjected to both conventional and ecological finishing processes. Conventional methods included pumice stone washing and sodium hypochlorite bleaching, while sustainable alternatives utilized enzymatic stone washing and ozone bleaching. The results revealed that ecological processes achieved comparable outcomes to traditional methods in terms of tensile strength, tear strength, and overall durability. Specifically, the ecological washing techniques resulted in a 6% increase in tensile strength and higher tear strength in both warp and weft directions, attributed to the reduced abrasive impact compared to pumice stone washing.*

Keywords: *Protective clothing, denim, sustainability, ecological finishing processes*

1. INTRODUCTION

Sustainability in the textile industry is essential for minimizing environmental impact while ensuring social and economic benefits. The sector significantly contributes to pollution, resource depletion, and waste generation, making sustainable practices crucial for mitigating these effects (Kumar, 2020; Fletcher, 2014).

Protective clothing plays a vital role in ensuring safety across various industries, including construction, healthcare, and extreme sports (Slater, 2003). Denim, known for its durability and strength, is widely used in protective apparel due to its high tensile strength and resistance to wear and tear (Kadolph, 2007). Additionally, denim's adaptability to various finishing techniques allows for both functional and aesthetic modifications (DeLong, 1998).

Traditional denim finishing methods, such as stonewashing and chemical bleaching, consume excessive water and chemicals, raising environmental concerns. In contrast, modern techniques like laser printing, ozone treatment, and enzyme washing offer more sustainable alternatives by reducing resource consumption (Periyasamy, 2023).

This study examines the effects of both conventional and eco-friendly finishing processes on high-strength denim fabrics used in protective clothing. The physical properties of the garments, including tear strength, elasticity, rub resistance, tensile strength, and recovery, were analyzed to assess the impact of different finishing methods.

2. MATERIALS AND METHODS

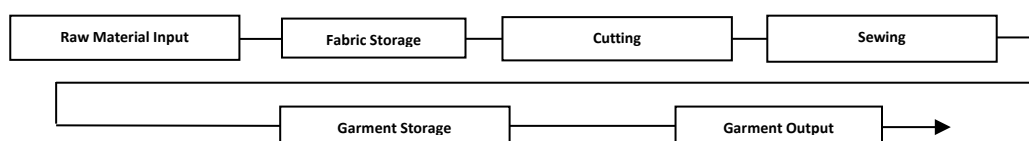
2.1. Fabrication of Denim Pants

This study utilized three high-strength denim fabrics with comparable weight and raw material composition, selected for their suitability in heavy-duty workwear and motorcycle apparel. Fabric weight was measured following the ASTM D3776/D3776M-20 standard (Table 1).

Table 1. Physical properties of the fabrics

Sample Code	Color	Composition (%)	Weaving Type	Width (cm)	Weight (oz/yd ²)
23559	Deep Blue	CO/NY/EL 69/30/1	3/1 Z Twill	150	12,75
25313	Over Dyed	CO/NYCO/EL 69/29,5/1,5	3/1 Z Twill	156	12,5
25763	Deep Blue	CO/NYCO/EL 69/29,5/1,5	3/1 Z Twill	156	12,5

The fabrics were cut and sewn into five-pocket denim pants using standard industrial procedures to ensure production consistency. The pre-finishing production phase is shown in Figure 1.

**Figure 1.** Production phases of semifinished garment

2.2. Finishing Processes

Two finishing processes were applied to denim trousers to compare traditional methods with sustainable alternatives. The stone-washed effect was achieved using conventional pumice stones, mechanically agitating the trousers in a washing machine to create a distressed appearance. Traditional bleaching was performed using sodium hypochlorite (purchased from Rubin Kimya AŞ., Turkey), a strong base (pH 13–13.5) that fades indigo dye pigmentation. After bleaching, sodium metabisulfite (supplied by Akkim Kimya A.Ş., Turkey) was used for neutralization. Pumice stones were provided by Kastone LTD., Turkey. All processes were conducted using Tolkar's industrial washing machine (capacity: 1658 liters) (Figure 2).

**Figure 2.** Industrial finishing machine**Figure 3.** Ozone machine

Enzymes were used as a sustainable alternative to achieve a stone-washed effect. The cellulase enzyme (procured from Asutex SA., Spain) degrades cellulose fibers, breaking the bond between the fiber and dye, creating a distressed appearance without pumice stones. Ozone treatment, a sustainable bleaching method, was applied using ozone gas as a powerful oxidizing agent. This process, conducted with the G2 model device from Jeanologia (Figure 3), reduces water and chemical usage, making it environmentally friendly.

Prior to these treatments, all semi-finished products underwent a rinsing process at 40°C for 5 minutes using 2 g/l amylase and 2 g/l NaOH to remove sizing agents. The experimental plan following rinsing is detailed in Table 2.

Table 2. Experimental plan

Sample Code	Stone Washing	Bleaching	Neutralization
23559-S1 25313-S2 25763-S3	%2 Asucel WF, 60 min, 40°C	100 g/m ³ ozone, 10 min, room temperature	NaOH + H ₂ O ₂ ½, 50°C, 5 min
23559-C1 25313-C2 25763-C3	½ w/w pumice stone, 30 min, 40°C	10 g/l NaClO, 10 min, 50°C	10 g/l Na ₂ S ₂ O ₅ , 5 min

*S refers sustainable process, C refers conventional process

2.3. Analysis of Physical Properties

The finished denim garments were analyzed to assess the impact of each finishing process on their physical properties. The following tests were conducted:

- Tear Strength: Measured using the ISO 13937-2:2000 method.
- Elasticity and recovery: Assessed through the ASTM D3107-07 standard.
- Effect analysis in light cabinet according to ISO 3664:2009 standard
- Dry and Wet Rub: Evaluated using the ISO 105-X16:2016 method.
- Tensile Strength: Measured using the ASTM D5034 method.
- Abrasion: Conducted in accordance with the ISO 12947-2 standard.

3. RESULTS AND DISCUSSION

The developed samples after finishing processes are shown in Figure 4. Evaluation was conducted under standardized lighting conditions (ISO 3664:2009) using a light cabinet. Due to the random fading patterns of denim, spectrophotometric analysis was unsuitable for quantifying stone-washing effects. Visual assessment confirmed that enzyme treatments effectively replicated the abrasion patterns of pumice stone washing.

Comparing conventional sodium hypochlorite bleaching with ozone bleaching, the former resulted in more pronounced bleaching. This difference was attributed to the darker ground color of ozone-bleached samples.



Figure 4. The developed samples after finishing processes

The tensile strength, elasticity, and recovery analysis results of the developed products are shown in Figure 5.

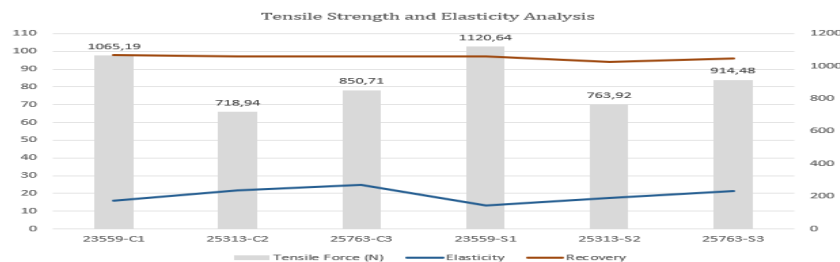


Figure 5. Tensile strength, elasticity and recovery analysis

To assess statistically significant differences between experimental fabric groups (C1 vs. S1, C2 vs. S2, C3 vs. S3), a paired sample t-test was conducted. A composite dataset was created by treating all measured parameters as equally relevant contributors to fabric performance, concatenating values into a one-dimensional array to increase sample size and enhance test robustness. The t-statistic was calculated using the formula:

$$t = \frac{d}{s_d/\sqrt{n}}$$

where d is the mean of differences, s_d is the standard deviation of differences, and n is the number of paired observations. The p-value was derived from the t-distribution's cumulative distribution function (CDF). A p-value < 0.05 led to the rejection of the null hypothesis (H_0), indicating statistically significant differences.

$$p = 2 \times P(T > t)$$

By structuring the dataset in a comprehensive manner and applying a paired t-test, we demonstrated that no statistically significant differences were found among the tested fabrics.

The analysis revealed no statistically significant differences among the tested fabrics. However, ecologically washed samples exhibited 6% higher tensile strength on average, attributed to the abrasion caused by pumice stones in conventional washing. Conversely, conventionally washed samples showed higher elasticity and recovery, likely due to ozone bleaching's impact on the elastane's molecular structure. Tear strength results are presented in Figure 6.

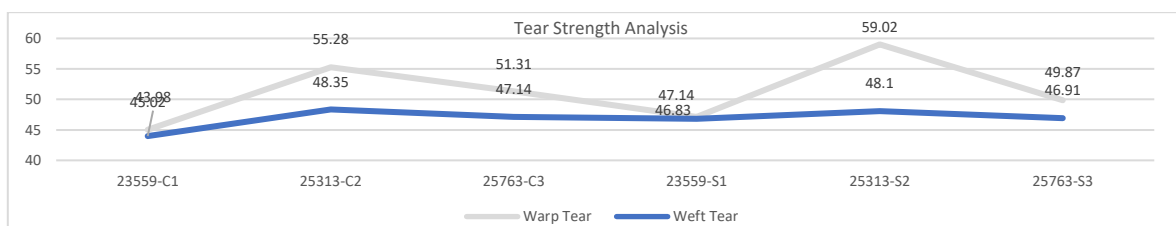


Figure 6. Tear strength analysis

Samples subjected to ecological washing exhibited higher tear strength in both warp and weft directions compared to conventionally washed samples. This increased durability aligns with tensile strength findings and is attributed to the reduced abrasion caused by pumice stones in conventional washing.

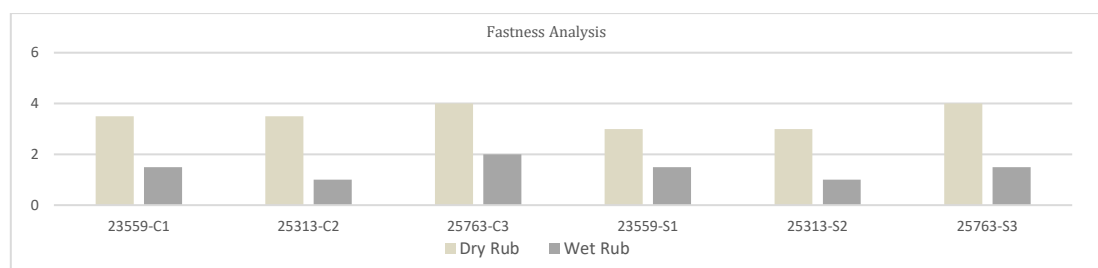


Figure 7. Fastness properties of the samples

Fastness analysis results (Figure 7) showed that ecologically washed samples had lower dry and wet rub fastness than conventionally washed samples. This difference is likely due to the greater efficiency of conventional washing in removing indigo dye from the fabric.

4. CONCLUSION

This study highlights the potential of sustainable denim finishing processes as effective alternatives to traditional methods for protective clothing production. Ecological washing techniques, such as enzymatic stone washing and ozone bleaching, achieved comparable or superior fabric durability and performance. Ecologically washed samples demonstrated higher tensile and tear strength due to reduced abrasion compared to conventional pumice stone

methods. However, lower dry and wet rub fastness indicates a need for further optimization to improve color retention.

These findings emphasize the importance of advancing eco-friendly practices in the textile industry to support sustainability goals. Future research should focus on refining these processes to balance performance and environmental benefits, ensuring their feasibility for industrial adoption.

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ECOFRIENDLY PRODUCTION OF FUNCTIONAL FACE MASKS

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Abstract: *The advanced nanofiber membrane filters produced through electrospinning technology significantly outperform traditional filters, offering enhanced filtration efficiency due to their exceptionally high surface area and ultra-fine inter-fiber pore structure. Bolstered by their environmentally sustainable, biocompatible, and biodegradable nature, alongside inherent antibacterial functionality, these filters emerge as promising candidates to replace conventional polypropylene-based synthetic filters. This study aims to develop an eco-friendly, biodegradable, electrospun functional nanofiber air filter, showcasing its potential as a superior alternative.*

Keywords: *Air filters, eco-friendly, biodegradable, functional*

1. INTRODUCTION

Nanofibers possess extraordinary properties that have drawn significant attention from researchers, including their ultra-fine fiber diameters, high surface area-to-volume ratio, and adjustable porosity (Ramakrishna et al., 2011). These unique attributes make nanofibers particularly well-suited for air filtration applications. Nanofiber layers with diameters below 1 micron can serve as highly effective sieves, capturing particulate matter (PM) of comparable or smaller sizes. The high surface area-to-volume ratio ensures that nanofiber layers remain lightweight while offering numerous contact points to trap airborne particles efficiently. Additionally, the ability to precisely control the porosity of the nanofiber mesh is crucial for optimizing air permeability and effectively filtering out undesirable particles such as dust, pollen, and bacteria. Together, these properties establish nanofibers as an ideal material for advancing air filtration systems.

Among the various methods available for fabricating nanofibers, electrospinning has emerged as the most widely used and versatile technique. This method enables the production of functional materials in a single-step process. The result of electrospinning is a nanofiber mesh deposited onto a collection electrode—a network of randomly oriented nanofibers with a specific thickness and porosity. This mesh serves as an efficient filter layer, showcasing exceptional potential for air filtration applications (Stepanyan et al., 2014).

2. MATERIALS AND METHODS

2.1 Preparation of Functional Face Masks

In this study, the materials listed in Table 1 were utilized to optimize the solution through an environmentally friendly process.

During the electrospinning process, polymeric solutions are subjected to high voltage, typically in the range of several kilovolts, causing them to accumulate significant electrical charges. These highly charged and energized solutions are then ejected from a needle or nozzle, forming fine jets of polymer strands. As these jets travel through the electric field, they undergo solidification while being drawn toward a target electrode, which is either oppositely charged or electrically neutral. The overall mechanism is illustrated in the schematic shown in Figure 1.

2.1.1. Tables and Figures

Table 1. The materials used for this study

Materials	Purpose
PHB, PCL, PLA etc.	Polymeric material in granule form
Acetic Acid, DMSO, 1-4 Dioxane, THF, DMF etc.	Potential solvents
TBAC, Triton 100X, LiCl	Additives
Lavender oil, Lemon Grass Oil, Cinnamon oil etc.	Functional materials

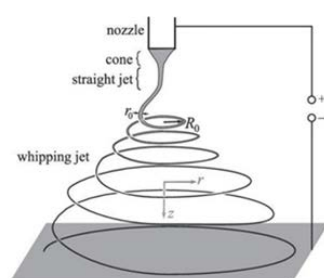


Figure 1. Diagram showcasing the electrospinning mechanism. Ref image from [2].

3. RESULTS AND DISCUSSION

A series of trial recipes have been processed and the samples obtained by a stable and continuous spinning process have been examined under SEM to examine the morphologies.

The candidate solutions that have stable, continuous process were coated on 35 GSM PET spun bonded substrates with varying thicknesses for filtration measurements and some of the samples gave promising filtration results meeting all the requirements of EN149 standard. The SEM image, fiber diameter analysis and the filtration performance of one of the candidate recipe are given below in Table 2 and Figure 2 respectively.

Table 2. The filtration measurements of the membranes with respect to the thickness

Solution Numbers	Filtration Eff (%)	Press. Drop(mbar)	Flow Rate (L/min)
Thickness – 0.5 GSM			
Replicate 1	95.01	1.32	85.2
Replicate 2	95.31	1.34	85.2
Thickness – 0.6 GSM			
Replicate 1	96.13	1.46	84.9
Replicate 2	95.51	1.46	85.3

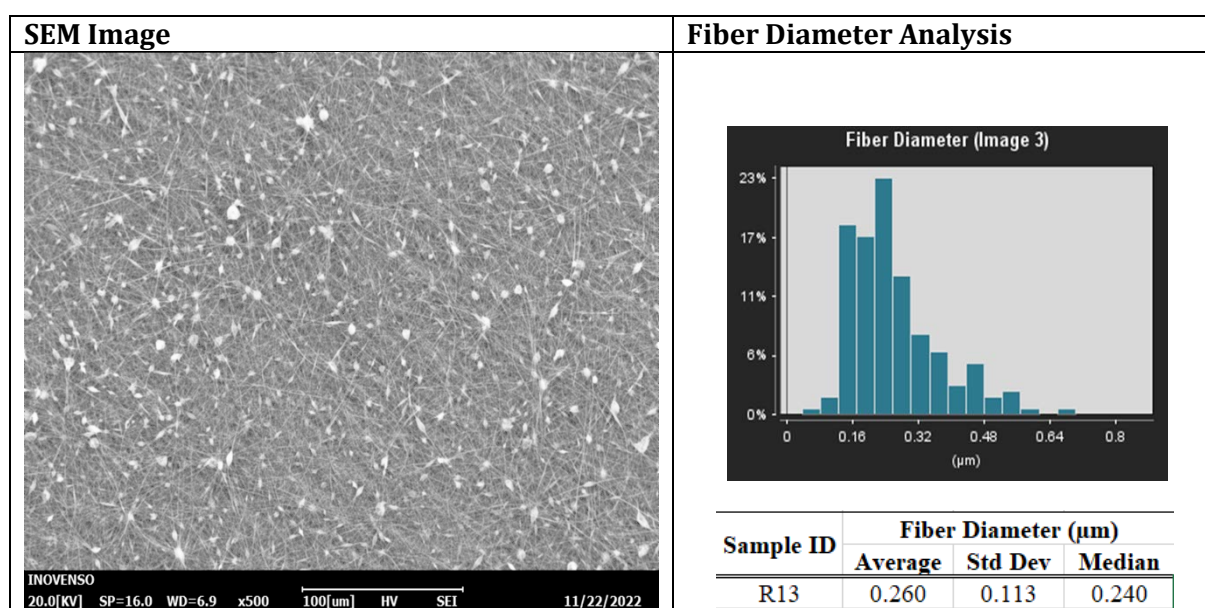


Figure 2. The SEM image and the fiber diameter analysis of a 0.6 GSM membrane

The study will continue with addition of functional materials in the potential membrane recipe and the tests for antibacterial activity will be run to optimize the minimum amount of active ingredient required for the functionality.

4. CONCLUSION

The current commercial masks are made of non-renewable resources and are non-biodegradable. After one-time use, they turn to harmful microplastic disposals, which is destructive towards the environment (Torres et al., 2021). There is a great potential in the manufacturing of air filtration membrane materials using biodegradable, ecofriendly materials modified with multifunctional properties like antibacterial activity etc in the market. In this work, we will manufacture a bio-based air filter which meet all these advantageous properties.

ACKNOWLEDGEMENT

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EVALUATING TOTAL HEAT LOSS OF TURNOUT GEAR AND BALLISTIC VESTS ON FIREFIGHTER HEAT STRAIN

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Abstract: Firefighters perform various high-intensity tasks while wearing heavy and semipermeable protective gear. Therefore, the firefighter turnout gear contributes a significant amount of heat strain during their occupational tasks. Wearing ballistic vests with turnout gear may increase the risk of further serious heat strain to the firefighters as ballistic vests are multilayered and non-breathable, impeding proper ventilation of the metabolic heat and sweat through the fabric to the environment. Therefore, the research outlined an empirical approach to quantify heat strain by assessing the total heat loss (THL) of six firefighting clothing combinations emphasizing on how ballistic vests affect heat transfer in the torso area. Results demonstrated that a substantial decrease in THL occurred when ballistic vest was added to the firefighting gear. This study also investigated the comparative analysis of the tested ensembles to emphasize the need for optimized solutions to balance safety and heat strain mitigation for firefighters.

Keywords: Firefighter, ballistic vest, total heat loss (THL), heat strain.

1. INTRODUCTION

According to the US Fire Administration, only approximately 4% of emergency calls to fire departments in 2020 were related to live fires, and 64% of the reported calls to fire departments were associated with a wide range of non-fire scenarios, including mass shootings, medical emergencies, hazardous materials, search and rescue operations, and civil unrest. Between 2019 and 2024, 122 incidents occurred in the USA where firefighters were shot and killed while responding to non-fire scenarios (Billy, 2024). After firefighters became targets of violence, fire departments requested funds to make ballistic vests standard personal protective equipment (PPE).

Research studies indicate the potential harmful impact on firefighter heat strain when adding additional layers and thickness to the turnout gear (McQuerry et al., 2018). Wearing ballistic vests with turnout gear, therefore, may increase the risk of heat strain to the firefighters (Kunz and Chen, 2005). While each layer in a firefighters' PPE system contributes in a different way to the overall level of protection, all layers also increase the risk of heat strain due to increased thermal insulation. Heat strain is the total reactions of the body when it is exposed to a high-temperature environment that can cause hyperthermia, heat stroke, cardiac failure, etc. Heat strain is correlated to decrease in total heat loss of the clothing system meaning when the body cannot adequately dissipate metabolic heat due to impermeable clothing system in extreme environmental conditions, heat strain occurs. Human body heat dissipation occurs primarily in two ways: wet heat loss caused by a gradient in humidity and dry heat loss caused by a gradient in temperature. The total heat dissipation can be expressed as below

Total heat loss (THL) = Dry heat loss + Wet heat loss

Dry heat loss usually occurs through conduction, radiation and convection. On the other hand, wet heat loss occurs by evaporation (Gao, 2021). THL can be calculated according to ASTM F1868 (part C) by measuring thermal resistance (R_t) and apparent evaporative resistance (R_{et}) (ASTMF1868, 2023). Predicted total heat loss by the thermal manikin can be calculated by using the formula

$$Q_{manikin}(THL) = \frac{T_s - T_a}{R_t} + \frac{P_s - P_a}{R_{et}}$$

Where R_t = Thermal resistance of clothing and air layer in $\text{m}^2\text{°C} \cdot \text{W}^{-1}$; T_s = Temperature of test plate in °C ; T_a = Temperature of air layer in °C ; R_{et} = ensemble total evaporative resistance in $\text{m}^2\text{kPa} \cdot \text{W}^{-1}$; P_s = Water vapor pressure at the test surface in kPa; P_a = Water vapor pressure at the ambient air in kPa

2. MATERIALS AND METHODS

2.1 Test ensembles

In order to quantify the thermal insulation, six combinations of firefighting ensembles were selected: E1) station uniform (Baseline 1); E2) station uniform and ballistic vest; E3) station uniform and turnout suit (Baseline 2); E4) station uniform, turnout suit and ballistic vest worn under the turnout jacket; E5) station uniform, turnout suit and ballistic vest worn over the turnout jacket; E6) station uniform, turnout suit and ballistic vest with hard plates worn over the turnout jacket.



Figure 1. Schematic of test ensembles

2.2 Test conditions

Dry test was conducted to assess the R_t of the clothing ensembles following the ASTM 1291 standard. The mean surface (skin) temperature of the manikin was $35\text{ °C} \pm 0.1\text{ °C}$. The air temperature, relative humidity and wind speed in the test chamber were 15°C , 45-55%, and 0.4–0.5 m/s respectively during the test. Wet test was conducted to measure R_{et} following ASTM F2370 where air temperature and relative humidity were 35°C and 35-40% respectively. Other parameters were similar to dry test. Three tests were conducted for each ensemble to confirm the reliability of the data and the average was calculated to report the R_t and R_{et} of the tested ensembles. These values were used to calculate total heat loss of the ensembles in the torso area.

3. RESULTS AND DISCUSSION

The THL values for E1, E2, E3, E4, E5, and E6 in the torso area were 210.5, 86.9, 66.2, 40, 36.9, and 35.7 W/m^2 respectively. The results evidently depicted a decrease of total heat loss in the torso area with adding layers. THL decreased from 210.5 W/m^2 in E1 (baseline 1-without ballistic vest) to 86.9 W/m^2 in E2 (with ballistic vest added) representing 58.7% reduction. The substantial decrease in THL from E1 to E2 is due to the dense materials (e.g. Kevlar, Nomex, etc.) in ballistic vests that is designed to provide ballistic protection that inherently reduced heat transfer. The further decrease in THL through E3 to E6 demonstrated the compounding effect of additional layers in the firefighting turnout ensemble with ballistic vests. E3 (Baseline 2) has a THL of 66.2 W/m^2 which means multi-layer construction and low permeability of turnout suit materials makes the turnout suit more restrictive for total heat loss compared to the E1 alone and E2. THL decreased by 39.6% compared to baseline 2. THL dropped further to 36.9 for E4- a 44.4% reduction compared to baseline 2. Heat loss reduction between ballistic vest worn under (E4) and over (E5) the turnout jacket is minor ($40.0 \rightarrow 36.9\text{ W/m}^2$). It indicates that the ballistic vest

material itself, regardless of placement, serves as a significant barrier to heat dissipation. For E6, the reduced THL value is 35.7 W/m^2 , a 46.1% reduction from the baseline. It indicates that the presence of hard plates further exacerbates the thermal burden by trapping heat closer to the body.

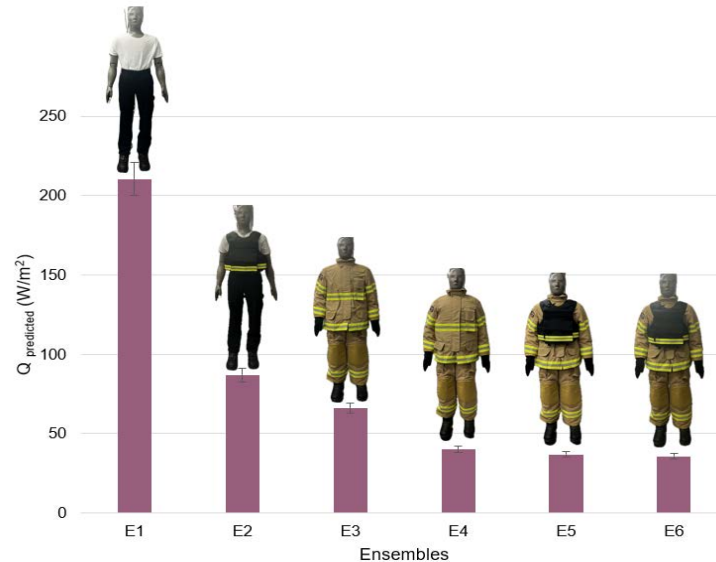


Figure 2. Predicted THL of firefighting clothing ensemble in conjunction with ballistic vest

4. CONCLUSION

The decrease in total heat loss from the ballistic vest and additional layers correlates directly with the potential for heat strain on the firefighters due to the impaired heat dissipation capacity of the ensembles. Lower THL confirms less heat transfer from the body which can lead to an increase in skin temperatures, core temperatures and cardiac output. The increase in these physiological responses can negatively affect the firefighters by causing extreme fatigue, heat-related illness, and degradation in work performance. In daily operations, firefighters undergo rigorous training to maintain readiness for a broad range of emergency scenarios. As part of this preparedness, rapid deployment is critical to ensuring timely response and minimizing risk to both firefighters and civilians. However, the introduction of ballistic vest can influence deployment dynamics by increasing gear-up time by 10 to 20 seconds, depending on the vest design and how it's integrated into existing PPE. This delay, while seemingly minimal, can be significant in high-stakes scenarios where every second counts. Consequently, fire departments must balance the trade-off between enhanced protection against ballistic threats and potential reductions in operational speed. The findings of this study will help fire departments to make informed decisions in selecting the combinations of clothing that will be comparatively more comfortable to mitigate heat-caused health risks and ensure firefighters' wellness.

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PHYSIOLOGICAL AND PSYCHOLOGICAL RESPONSES TO IMMERSION SUITS FOR REPUBLIC OF KOREA AIR FORCE PILOTS

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Abstract: This study evaluated the physiological and psychological responses to immersion suits worn by Republic of Korea Air Force (ROKAF) pilots during simulated conditions. Nine male subjects participated in three different clothing conditions: without an immersion suit (Control), with a conventional immersion suit (Conventional), and with an improved immersion suit (Improved). Experiments were conducted in a climate chamber (24°C, 50% RH; 80-min trial). Results showed that rectal temperature was 0.2°C higher in Conventional and Improved conditions compared to Control ($P < 0.05$), but no difference was found between the two immersion suits. Mean skin temperature was significantly lower in the Improved suit due to chest and back temperatures. Clothing pressure around the neck and wrist was lower in the Improved condition, but microclimate humidity was higher than other conditions. Thermal sensation, comfort, and mobility differed across the three conditions, with subjects feeling hotter and less comfortable in immersion suits compared to the Control condition.

Keywords: Republic of Korea Air Force(ROKAF), immersion suit, thermal stress, pilot, clothing compression.

1. INTRODUCTION

Pilots operating over the sea are required to wear immersion suits to prepare for emergency scenarios. Immersion in cold water can lead to hypothermia, defined as a drop in core temperature below 35°C (Golden et al., 1980). Immersion suits are therefore crucial for protecting wearers during unintended immersion. However, the waterproof material of these suits, designed to prevent water penetration, limits evaporative cooling from the body. Consequently, pilots in cockpits may experience thermal discomfort, fatigue, and decreased performance (Nunneley, 1989). Despite these considerations, very few research has been conducted on thermal stress related to clothing requirements for pilots in the Republic of Korea Air Force (ROKAF). This study aimed to evaluate the physiological and psychological responses when wearing the immersion suit for pilots of ROKAF.

2. METHODS

2.1 Subjects and experimental conditions

Nine Korean males (23.0 ± 2.2 y in age, 173.4 ± 7.4 cm in height, 71.5 ± 7.4 kg in body weight) participated in this study. All subjects wore the ROKAF pilot clothing system, consisting of a t-shirt, overall flight suit, anti-G suit, gloves, socks, and boots. Three experimental conditions were tested: (1) without an immersion suit (Control), (2) with a conventional immersion suit (Conventional), and (3) with an improved immersion suit (Improved).

2.2 Experimental procedure and measurements

A climate chamber was set at an air temperature of 24°C with 50% relative humidity. Each experiment lasted 80 min, including 10-min stabilization, 60-min control posture, and a final 10-min recovery. During the last 30 min of the control posture, air was pumped into the anti-G suit to simulate lower body pressure. Four types of motions (extension and flexion, twist rotation,

lateral bending, and reach forward with one arm extension) were assessed before and after the session. Measurements included rectal temperature, skin temperatures (10 sites), total body mass loss, thermal sensation (9-point scale), thermal comfort (7-point scale), humidity sensation (7-point scale), and compression sensation (5-point scale).

2.3 Data analysis

All data were expressed as mean $\pm$ SD. Repeated Measures ANOVA and Bonferroni correction were conducted for parametric variables (Non-parametric: Friedman Test and a Wilcoxon test). A significance was set at $P < 0.05$.

3. RESULTS AND DISCUSSION

Rectal temperature was on average 0.2°C higher in both the Conventional and Improved conditions compared to the Control condition ($P < 0.05$), but no significant difference was observed between the Conventional and Improved conditions (Fig. 1). Auditory canal temperatures, forehead/hand/foot/thigh/calf temperatures, and heart rate showed no significant differences among the three conditions. However, mean skin temperature was significantly lower in the Improved condition ($34.4 \pm 0.5^\circ\text{C}$) compared to the Conventional condition ($34.7 \pm 0.5^\circ\text{C}$; $P < 0.05$). This difference was primarily attributed to significantly lower skin temperatures on the chest and back for the Improved condition. Clothing compression around the neck and wrist was significantly lower in the Improved condition (9.8 ± 4.0 mmHg) compared to the Conventional condition (12.1 ± 7.0 mmHg; $P < 0.05$). No differences among the three conditions were found in skin blood flow on the neck. However, clothing microclimate humidity on the chest area was significantly higher in the Improved condition compared to the Conventional condition. Significant differences were observed in overall thermal sensation, thermal comfort, and humidity sensation among the three conditions ($P < 0.05$). Subjects felt significantly hotter, less comfortable, and more humid in both the Conventional and Improved conditions compared to the Control condition. Clothing compression also differed significantly among the three conditions. In addition, evaluations of head, neck, and arm mobility showed significant differences across all the conditions.

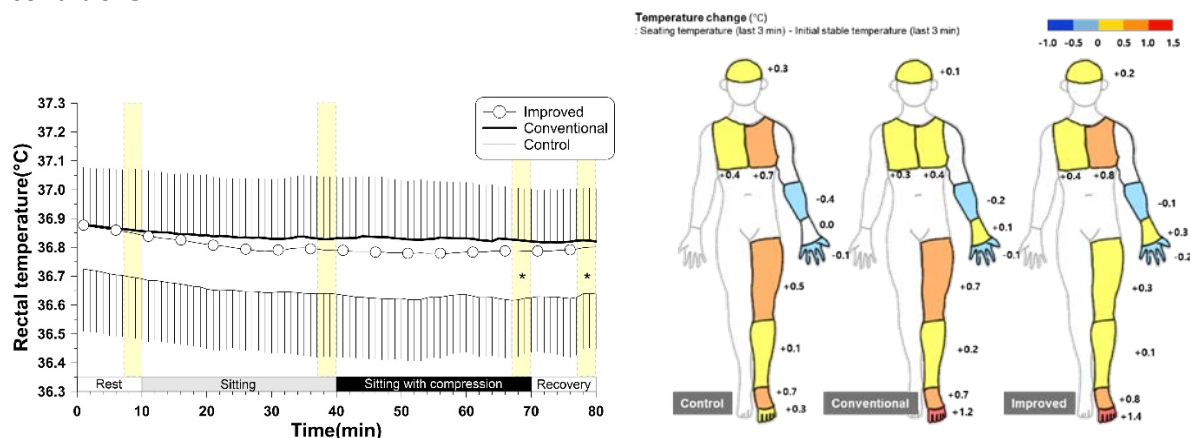


Figure 1. Time courses of rectal temperature (Left) and changes in skin temperatures for the three conditions (Right).

4. CONCLUSION

We compared the improved immersion suit with the conventional design. The improved suit is designed to better accommodate the body shape of Korean pilots while aiming to enhance heat dissipation. Wearing immersion suits significantly influenced core temperature increases but did not induce heat strain. The improved immersion suit demonstrated enhancements in certain thermoregulatory responses, psychophysiological reactions, and mobility compared to the conventional suit. However, considering the higher microclimate humidity observed in the torso region, further design improvements are necessary to reduce inner-layer humidity during

immersion suit usage. These findings highlight the importance of continued innovation in immersion suit design to optimize both thermal regulation and wearer comfort.

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ASSESSMENT OF THE SERVICE LIFE OF FIREFIGHTER PROTECTIVE GLOVES WITH POLYMER COATINGS CONTAINING CARBON FILLERS ON THE EXAMPLE OF CHEMICAL DEGRADATION TESTS

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Abstract: *In this study, the service life of the material intended for firefighter protective gloves was assessed based on chemical degradation tests. The tested material was designed from aramid fabric coated with flame-resistant polymer paste with the addition of carbon filler. The chemical degradation tests were carried out in accordance with the procedure included in the EN ISO 374-4:2019 standard using liquid chemicals listed in the EN 659:2003+A1:2008/AC:2009 standard: hydrochloric acid, 36 % (HCl) and sulfuric acid, 30 % (H₂SO₄). The samples surface after testing was also assessed using a stereoscopic microscope. The results led to the conclusion that the applied flame-resistant polymer coatings are not resistant to the acids used, and hydrochloric acid discolours the surface of the samples. A larger amount of carbon filler in the coating improves puncture resistance but worsens the chemical resistance of the polymer coated glove material.*

Keywords: *firefighters protective gloves, polymer coatings, carbon fillers, chemical degradation.*

1. INTRODUCTION

Firefighter protective gloves are a key piece of equipment for firefighters, designed specifically to protect hands and wrists during rescue and firefighting operations. The minimum requirements for the effectiveness and testing methods of protective gloves for firefighters are specified in the EN 659:2003+A1:2008/AC:2009 standard, including resistance to liquid chemical penetration test. Instead of this method, in order to assess the chemical resistance and durability of firefighter protective gloves we decided to perform chemical degradation tests of selected materials in accordance with the procedure included in the EN ISO 374-4:2019 standard for polymer protective gloves, for the purpose of expanding knowledge about materials with potential application for firefighter gloves. Liquid substances chosen for tests were hydrochloric acid, 36 % (HCl) and sulfuric acid, 30 % (H₂SO₄), which are listed in the EN 659 standard in the section concerning requirements for resistance to liquid chemical penetration test of firefighter protective gloves.

2. MATERIALS AND METHODS

2.1 Materials

The tested materials are aramid fabrics coated with flame-resistant polymer paste applied by the method of tape-casting in 3 variants: polymer paste (S1), polymer paste + 0.5 wt. % carbon filler (S2), polymer paste + 1 wt. % carbon filler (S3), intended for the outer layer of firefighter protective gloves which will be manufactured by the company Andropol S.A. (Poland). The thickness of the polymer paste is 0.15 mm, measured as the space between the material and the polymer dispenser during the coating process (Irzmańska, Boczkowska et al., 2024).

2.2 Chemical reagents

The liquid chemical reagents used to conduct the chemical degradation tests were commercially available hydrochloric acid, 36 % (HCl) and sulfuric acid, 30 % (H₂SO₄). These substances were selected based on the provisions of the EN 659:2003+A1:2008/AC:2009 standard regarding requirements for resistance to liquid chemical penetration test of firefighter protective gloves.

2.3 Chemical degradation

Chemical degradation tests were carried out in accordance with the procedure in EN ISO 374-4:2019 standard (Irzmańska, Litwicka et al., 2024) with minor modifications. Five 20 mm diameter samples were cut from each material, sealed in vials and exposed to 2 ml of liquid chemicals for 1 hour. Five blank samples were also cut out but were not exposed to chemicals. Then the puncture force was measured on a puncture testing machine (SATRA, UK) (Smejda-Krzewicka et al., 2024).

2.4 Optical microscopy

The surface of samples was observed under a stereoscopic microscope with 10x magnification (OPTA-TEC SK series, Poland).

3. RESULTS AND DISCUSSION

The puncture force of three different coated materials intended for firefighter protective gloves was measured before and after one hour contact with diluted hydrochloric and sulfuric acids. The results are shown in Figure 1.

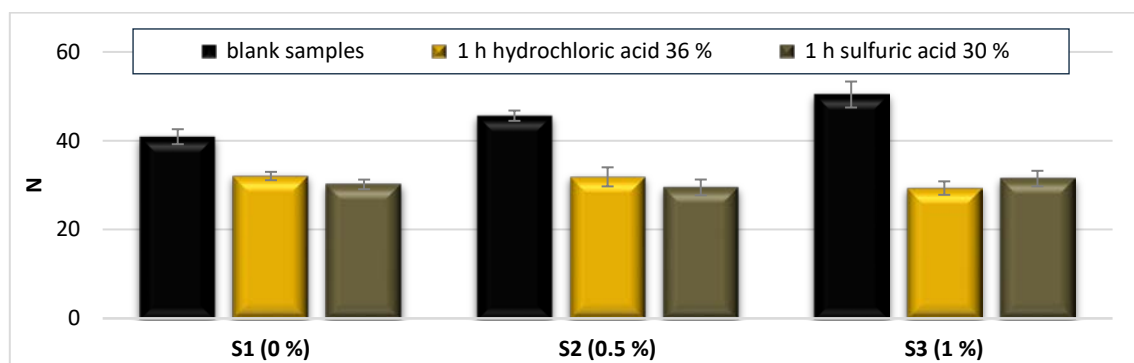


Figure 1. Puncture force for blank samples and samples after chemical degradation with acids measured according to EN ISO 374-4:2019 standard.

The results indicate that the addition of carbon filler in the polymer paste increases the composites puncture resistance (by 22.5 % for 0.5 wt. % of carbon filler (S2) and by 30 % for 1 wt. % of carbon filler (S3)). The composite with flame-resistant polymer coating with addition of 1 wt. % of carbon filler (S3) is characterised by the highest puncture resistance (puncture force of 51 N). The puncture force after one hour contact with tested liquid chemicals decreases for all tested compositions.

The chemical degradation, as the percentage change in puncture force before and after exposure to the liquid chemical, relative to the blank sample, was calculated and is shown in Figure 2.

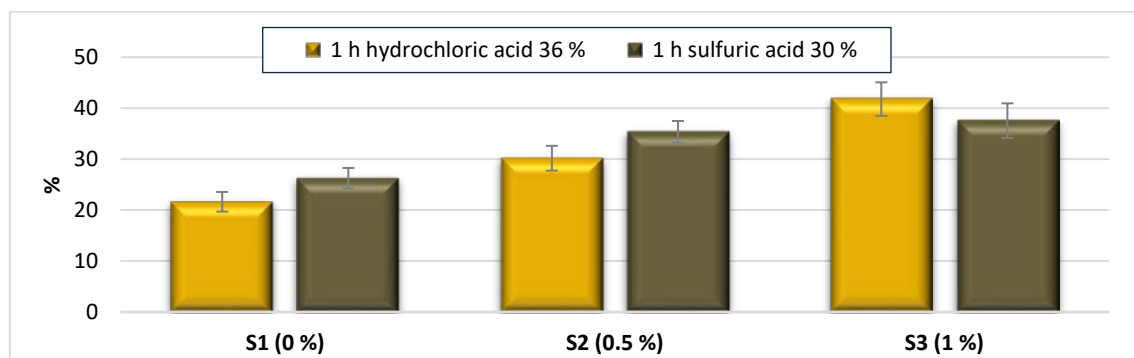


Figure 2. Chemical degradation of samples calculated according to EN ISO 374-4:2019 standard.

The highest chemical degradation ($44.5 \pm 4.8 \%$) was observed in the sample with a coating with the addition of 1 wt. % carbon filler (S3), using diluted hydrochloric acid. The sample with a polymer coating with no addition of carbon filler (S1) showed the lowest chemical degradation under the influence of both acids (less than 30 %). Photographs of the surfaces of unpunctured and punctured samples, taken using a microscope, are presented in Figure 3.

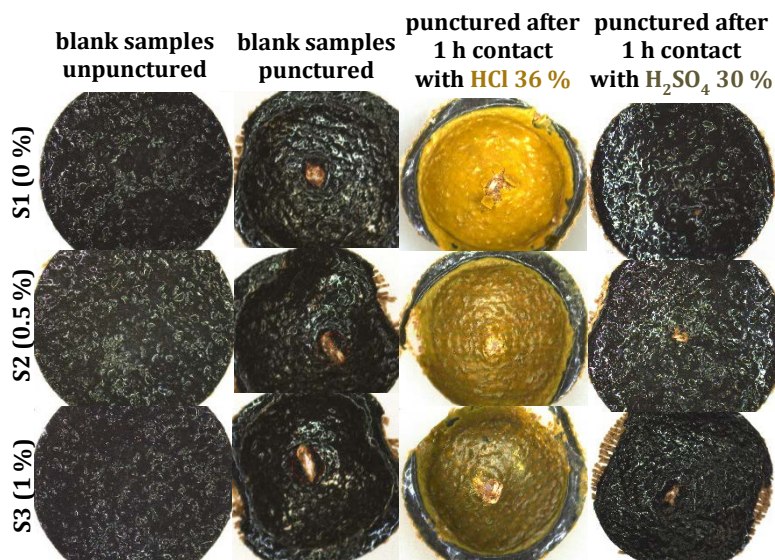


Figure 3. Microscopic photos of the tested materials.

The photos show a significant change in the appearance of the samples surface after degradation with hydrochloric acid.

4. CONCLUSION

The service life of innovative material intended for firefighter protective gloves was assessed based on chemical degradation tests. This test method is not required by the EN 659:2003+A1:2008/AC:2009 standard, but its results may be an additional parameter important in the context of safety and repeated use of firefighter protective gloves. The research allows to conclude that carbon filler applied in the flame-resistant polymer coating on aramid fabric in amount of 0.5-1 wt. % increases the puncture resistance of the samples by 22.5-30 %, but at the same time worsen the resistance to chemical degradation under the influence of acids used in the tests by almost 10 % for 0.5 wt. % and 20 % for 1 wt. %. Major physical changes after degradation with hydrochloric acid were noticed during microscopic observation, confirming the loss of protective properties. The resistance to chemical degradation test together with the resistance to liquid chemical penetration test can provide comprehensive information on the chemical resistance of the polymer coating of firefighter gloves.

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