TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 65, Issue Special III, November, 2022

THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTERS CLOTHING

Daniel Onuț BADEA, Alina TRIFU, Oana Roxana CHIVU

Abstract: *Personal protective equipment (PPE) is essential for firefighters to ensure their safety and health because they encounter complex conditions while performing their duties. The most serious of these conditions is thermal exposure, which may result from radiation, convection, hot liquid, steam. Inefficient protection in a fire scenario can cause injury and fatality. The best approach for firefighters to mitigate burn injuries and reduce the risk of death, is to apply high-performance PPE. This paper presents the results of a laboratory simulation performed to study the thermal responses of firefighter's clothing. There are three types of heat transfer: conductive heat, convected heat and radiation heat. The study was conducted using various combinations of essential requirements (flame propagation, convective heat transfer index, radiation heat transfer index, resistance to residual tensile material exposed to radiant heat, tensile strength, tear resistance) and is a review of the influence of various factors on the performance of thermal protective clothing, to predict the thermal protective performance of 3 pieces of firefighter's clothing. By employing these key essential requirements against thermal resistance, the multiple linear regression model was developed for predicting the thermal protective performance of those pieces of firefighters clothing.*

Key words: *Thermal protection, firefighter's clothing, heat exposure, performance of thermal protective clothing.*

1. INTRODUCTION

Firefighters encounter complex environments and conditions while performing their duties within a wide range of possible hazards. Thermal exposure, which may result from radiation, convection, hot liquid, steam is the primary possible hazard exposure for firefighters.

Personal protective equipment (PPE) and textile-based equipment are critical for firefighters to ensure their safety and health. Ineffective protection in a fire scenario with multiple hazards can cause injury and fatality.

The best approach for firefighters to mitigate burn injuries and reduce the risk of death is to apply high-performance PPE. Standardized test methods are available for measuring the thermal protective performance of fabrics used in firefighters' clothing.

2. TYPES OF THERMAL EXPOSURES

Thermal exposure, which may result from radiation, convection, hot liquid, steam, and/or hot solids, is the primary possible hazard exposure for firefighters. During the combustion of structural materials, firefighters can encounter thermal hazards including collapsing fireground debris, hot liquid, and molten materials. In a fire scene, cool water from a hose can quickly become hot water, and then steam. Steam and wet air cause more serious burns because more heat energy can be stored in water vapor than in dry air.

The protection expected through clothing is multidimensional. For traditional clothing, the expectation is basically social and determines its effectiveness from modesty and cultural value to fashion discerning consumers. However, for protective clothing, values are determined on a specific protection performance, limiting cultural or fashion perspective, and even compromising comfort.

For firefighting garments, the main concern is protection against heat, which can be experienced from any uncomfortably hot object or direct/indirect contact with the flame. The human body can control its internal temperature at a certain level when an external or internal condition changes. Specific central and peripheral nervous systems continuously sense the temperature instability in the body and try to maintain a balance through biological action [1].

However, under extreme weather conditions, the body needs protection for survival. One of the most important functions of clothing is to protect a wearer against extremes of environmental temperature either heat or cold [2]. The measure of the insulation of a material is its thermal resistance. It is defined as the temperature difference between the two faces divided by the heat flux and has the unit of Km^2W^{-1}. The heat flow can be any form such as conductive, convective, or radiative. Textiles are generally low heat conductive. Hence, convective and radiative heat resistance are primary concerns for designing firefighting protective clothing.

The temperature between the thermal liner and the firefighter's undergarment can reach from 48°C to 62°C before receiving burn injuries [3]. It has been identified that the pain threshold of human skin is around 44°C [4]. When the skin temperature exceeds this threshold, the absorbed energy determines if and how severe burns will be received [5]. The skin receives second-degree burns when skin temperature approaches 55°C.

The essential requirements of thermal protective clothing for good efficiency of the worker, firefighter depend on protection, comfort and other functional properties like tear resistance and abrasion resistance etc. flame propagation, convective heat transfer index, radiation heat transfer index, resistance to residual tensile material exposed to radiant heat, tensile strength, tear resistance.

The paper presents the results of a study that used a combination of essential requirements: flame propagation (assembly of materials with flame applied to outer material, lining and seams), convective heat transfer index, heat transfer index – radiation, resistance to residual tensile material exposed to radiant heat, tensile strength, tear resistance, to predict the thermal protective performances of 3 pieces of firefighter's costumes.

3. METHODOLOGY

The quantitative method is used in this research to find out the relationship between dependent variable and indecent variables.

For this research, different commercially available fabrics for protective clothing used by firefighters were selected and their physical properties were measured in ISO standardized test methods (Table 1).

Occupational barriers were explored based on previous literature. A comprehensive literature review summarizes previous studies on firefighters' experiences in the work environment and issues related to protective clothing. The protective performance of the fabrics was measured in terms of heat transfer performance and systematically tabulated and presented.

4. RESULTS AND DISCUSSION

The emphasis for firefighting clothing is focused on material performance.

This study highlights a series of simulations performed to predict the response of 3 pieces of firefighter's costumes at conductive heat, convected heat and radiation the that may arise during fire exposures. Small scale tests are completed using partial samples of garments.

Various standardized test methods by ISO (International Organization for Standardization) were used under different thermal exposure to measure the protective and comfort performance of the fabrics. Test methods for fire-fighter clothing with the types of testing are outlined in detail in many standards as listed in Table 1. Experimental tests were performed on different types of fabrics used in fire protection clothing to simulate a thermal protection performance test. For this study, different commercially available fabrics used in firefighting workers' protective clothing were selected and measured using the standardized ISO test methods (Table 1). Here, the protective performance of the fabrics is systematically tabulated and presented in Table 2.

Table 1

Standard test methods used to evaluate the protective performance of firefighters protective clothing.

Test standard	Description
ISO 6942:2015	Protective clothing – protection against heat and fire – method of test: evaluation of materials and material assemblies when exposed to a source of radiant heat
ISO 9151:1995	Protective clothing against heat and flame - Determination of heat transmission on exposure to flame
ISO 11612:2008	Protective clothing - Clothing to protect against heat and flame
ISO 14116:2008	Protective clothing - Protection against heat and flame: Limited flame spread materials, material assemblies and clothing
ISO 12127 – 2:2007	Clothing for protection against heat and flame - Determination of contact heat transmission through protective clothing or constituent materials. Test method using contact heat produced by dropping small cylinders
ISO 15025:2000	Protective clothing - Protection against heat and flame: Method of test for limited flame spread
ISO 17492:2003	Clothing for protection against heat and flame - Determination of heat transmission on exposure to both flame and radiant heat
ISO 17493:2000	Clothing and equipment for protection against heat - Test method for convective heat resistance using a hot air circulating oven

Table 2

The thermal protective performances of three pieces of firefighter's costumes

Trial	Firefighter suit 1	Firefighter suit 2	Firefighter suit 3
Material assemblies	Exterior material: - Fireproof of para and para-aramid fibers and antistatic fibers, fireproof, with a mass of about 220 g/sqm - Thermal insulating and waterproof start - waterproof breathable polyurethane membrane on a layer of 100% aramid fiber nonwoven about 260 g/sqm - Fr aramid fabric and viscose lining, weighing of about 120 g/sqm	- Outer material: - Fabric made of fireproof and antistatic aramid fibers, with a mass of about 210 g/sqm; - Thermal and waterproof layer: breathable membrane 50% aramid fibers + 50% viscous on non-woven backing of about 230 g/sqm - Lining: aramid flame retardant fabric with a mass of about 150 g/sqm;	Outer material: - Meta-aramid fabric with a mass of about 210 g/sqm; - Thermal insulation layer - woven fabric backing on pu membrane of about 230 g/sqm Lining: meta-aramid fabric with a mass of about 150 g /sqm;
Flame propagation. Material assembly with the flame applied to the outer material, the lining and the seams	- No specimen has a burnt top edge or side edges - No test tube shows a hole - After removing the flame, no residual glow spreads from the charred area to the intact area. - No test tube produces molten or burnt debris - Average value of flame persistence: less than 0 s.	- No specimen has a burnt top edge or side edges - No test tube shows a hole - After removing the flame, no residual glow spreads from the charred area to the intact area. - No test tubes produce molten or burned residues - Average value of flame persistence: less than 2 s. - Average value of the duration of the residual incandescence of the flame: less than 2 s	- No specimen has a burnt top edge or side edges - No specimen has a hole in any of its layers - After removing the flame, no residual glow spreads from the charred area to the intact area. - No test tube produces molten or burnt debris - Average value of flame persistence: less than 0 s.
Index convective heat transfer HTI_{24} HTI_{24} - HTI_{12}	HTI_{24}: over 16 s HTI_{24}- HTI_{12}: over 5 s	HTI_{24}: over 16 s HTI_{24}- HTI_{12}: over 4 s	HTI_{24}: over 13 s HTI_{24}- HTI_{12}: over 4 s
Heat Transfer Index - Radiation RHTI24 RHTI24 - RHTI12	RHTI24: over 20 s RHTI24 - RHTI12: over 6 s	RHTI24 over 20 s RHTI24 - RHTI12 over 4 s	RHTI24 over 18 s RHTI24 - RHTI12 over 4 s

Residual tensile strength of material exposed to radiant heat	- Residual tensile strength in the warp direction: 1300 N - Residual tensile strength in the weft direction: 1000 N	- Residual tensile strength in the warp direction: 1200 N - - Residual tensile strength in the weft direction: 780 N	- Residual tensile strength in the warp direction: 1100 N - - Residual tensile strength in the weft direction: 950 N
Thermal resistance	Exterior material - does not initiate combustion - It doesn't melt - Longitudinal contraction: 0%. Shrinkage: 0% Thermal insulation layer - does not initiate combustion - It doesn't melt - Longitudinal contraction: 0% Shrinkage: 0% Lining - does not initiate combustion - It doesn't melt - Longitudinal contraction: 0% Shrinkage: 0%	Exterior material - does not initiate combustion - It doesn't melt - Longitudinal contraction: -1% Shrinkage: -1% Thermal insulation layer - does not initiate combustion - It doesn't melt - Longitudinal contraction: -5%. Shrinkage: -5% Lining - does not initiate combustion - It doesn't melt - Longitudinal contraction: -1.5%. Shrinkage: -1.0%	Exterior material - does not initiate combustion - It doesn't melt - Longitudinal contraction: 0%. Shrinkage: 0% Thermal insulation layer - does not initiate combustion - It doesn't melt - Longitudinal contraction: 0% Shrinkage: 0% Lining - does not initiate combustion - It doesn't melt - Longitudinal contraction: 0% Shrinkage: 0%
Tensile strength	- Breaking force for the outer material in the longitudinal direction (warp): over 1500 N - Breaking force for the outer material in the transverse direction (beat) over 1100 N	- Breaking force for the outer material in the longitudinal direction above 1200 N - Breaking force for the outer material in the transverse direction, over 600 N	- Breaking force for the outer material in the longitudinal direction (warp): over 1200 N - Breaking force for the outer material in the transverse direction (beat) over 1100 N
Tear resistance	- Tearing force for the outer material in the longitudinal direction above 85 N - Tear force for the outer material in the transverse direction over 65 N	- Tearing force for the outer material in the longitudinal direction over 40 N - Tearing force for the outer material in the transverse direction. Over 50 N	Tearing force for the outer material in the longitudinal direction above 85 N - Tear force for the outer material in the transverse direction over 100 N

The results show that the predicted response of the test material was found to favorably agree with experimental measurements. By employing these key essential requirements against thermal resistance, a Multiple Linear Regression (MLR) model was developed for predicting the thermal protective performance of those pieces of firefighter's costumes.

This model can be implemented in the textile industry and academia to predict conveniently the thermal protection performance by using the key properties of the fabric. A group of researchers found that weight, thickness, and thermal and evaporative resistance are the key fabric properties that affect the fabric's thermal protective performance [6].

In this study, two basic fabric properties, weight and air permeability, were considered for the linear regression. These properties can be easily measured by using SR 6142:2007 and SR EN ISO 9237:1999 standards, respectively.

Table 3 shows the key fabric properties for the material assemblies of 3 pieces of firefighter's costumes. The statistical analyses were carried out at a 95% CI; therefore, *p*-values less than 0.05 were considered statistically significant.

Table 3

The key fabric properties for the material assemblies of three pieces of firefighter's costumes

Properties	Material assemblies firefighter suit 1	Material assemblies firefighter suit 2	Material assemblies firefighter suit 3
Weight (g/m^2)	600	590	590
Air permeability (mm/s)	0,835	0,815	0,830

The results showed that this article highlights the main hazards (respiratory hazards, structural hazard, hazardous substances) faced by firefighters when performing workplace-related activities. It is important that policymakers address the need for personal protective equipment as a matter of priority to improve the safety of firefighting workers. Being aware of these challenging barriers is paramount to fire scene safety and will help reduce accidents. Personal safety should be a top priority.

5. CONCLUSION

With the rapid development of the economy (new technologies, materials and new products) and climate change, new dangers have appeared. This has generated various types of fires and sudden disasters.

Starting from this reality, aiming at the development of modern science and technology, using new materials and new techniques, the development of practical protective equipment is pursued to protect users from external influences and danger in the conditions of elevated temperatures and exposure to flame, fire, smoke, and water, in fire scenes.

The paper presents research on the clothing system for protection against heat and flame. The results of the research showed that the user of the examined clothing system would not have sustained injuries dangerous to health and life, which confirmed the protective properties.

We have summarized a series of simulations performed to predict the response of a single layer fabric to the high intensity, short duration convective and radiant heat fluxes that may arise during fire exposures.

In addition to studying the physical characteristics of fabrics used in protective clothing, this paper can be used to determine how fabrics respond to the way and intensity in which thermal energy is applied, as well as how they respond to other environmental factors.

Personal protective equipment (PPE) and textile-based equipment are critical for firefighters to ensure their safety and health. Ineffective protection in a fire scenario with multiple hazards can cause injury and fatality.

The best approach for firefighters to mitigate burn injuries and reduce the risk of death is to apply high-performance PPE. Standardized test methods are available for measuring the thermal protective performance of fabrics used in firefighters' clothing.

It is known as fire scenes are dangerous places. Firefighters today face more than the danger of fire on scene. There are numerous dangers including exposure to asbestos, hazardous vapors, and explosions. Combustion can produce dangerous toxic gases that may cause serious injury.

Future research on thermal protection performance and thermal comfort performance should be simulate to the real fire environment. However, it is very difficult to define the firefighter environment because there are many environmental and physical factors that affect a firefighter's interaction with the fire scene. In addition, future studies must take into consideration the musculoskeletal disorders and the postural analysis of the fireman (as presented in [7-9]). The knowledge and innovation transfer in the ergonomists communities could bring new ideas and solution to the research approach and to practical investigations, too [10].

6. REFERENCES

[1] Li, Y., Wong, A.S.W. 2006, Physiology of Thermal Comfort. Cambridge: The Textile Institute, CRC Press, Woodhead Publishing Limited, 2006.

[2] Slater, K., Textile Progress – Comfort Properties of Textiles vol. 9; Ukponmwan,

J.O. 1993, The Thermal Insulation Properties of Fabrics vol. 24, 1977.

[3] Rossi, R.M., Fire Fighting and Its Influence on the Body, Ergonomics, 46(10), 1017-1033), 2003.

[4] Stoll, A.M., Greene, L.C., Relationship between pain and Tissue Damage Due to Thermal Radiation, Journal of Applied Physiology, 14(3), 373-382, 1959.

[5] Stoll, A.M., Chianta, M.A., A Method and Rating System for Evaluation of Thermal Protection: DTIC Document, 1968.

[6] Mandal, S.; Song, G., An empirical analysis of thermal protective performance of fabrics used in protective clothing, The Annals of Occupational Hygiene, 58(8), 1065-1077, 2014.

[7] Gajšek, B., Draghici, A., Boatca, M. E., Gaureanu, A., Robescu, D., *Linking the Use of Ergonomics Methods to Workplace Social Sustainability: The Ovako Working Posture Assessment System and Rapid Entire Body Assessment Method*, Sustainability,1 4(7), 4301, 2022.

[8] Choong, S. W. J., Ng, P. K., Yeo, B. C., Draghici, A., Gaureanu, A., Ng, Y. J., ..., Selvan, H. K. T., A *Preliminary Study on Ergonomic Contribution to the Engineering Design Approach of a Wheel Loader Control Lever System*, Sustainability, 14(1), 122, 2021.

[9] Dufour, C., Draghci, A., Ivascu, L., Sarfraz, M., *Occupational health and safety division of responsibility: A conceptual model for the implementation of the OHSAS 18001: 2007 standard*, Human Systems Management, 39(4), 549-563, 2020.

[10] Szabó, G., Balogh, Z., Dovramadjiev, T., Draghici, A., Gajšek, B., Lulić, T. J., ..., Zunjic, A., *Introducing the ergonomics and human factors regional educational CEEPUS Network*, Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, and Engineering, 64(1-S1), 2021.

Performanța de protecție termică a îmbrăcămintei pompierilor

Echipamentul individual de protecție (EIP) este esențial pentru pompieri pentru a le asigura siguranța și sănătatea, deoarece se confruntă cu condiții complexe în timpul îndeplinirii sarcinilor lor. Cea mai periculoasă dintre aceste condiții este expunerea termică, care poate rezulta din radiații, convecție, lichid fierbinte, abur. Protecția ineficientă într-un scenariu de incendiu poate provoca leziuni și decese. Cea mai bună abordare pentru pompieri pentru a atenua leziunile provocate de arsuri și pentru a reduce riscul de deces este folosirea EIP-urilor de înaltă performanță. Această lucrare prezintă rezultatele unei simulări de laborator efectuate pentru a studia răspunsurile termice ale îmbrăcămintei de protecție pentru pompieri. Există trei tipuri de transfer de căldură: căldură de contact, căldură convectivă și radiantă. Studiul a fost realizat folosind diverse combinații de cerințe esențiale (propagarea flăcării, indicele de transfer de căldură convectiv, indicele de transfer de căldură prin radiații, rezistența la materialul de tracțiune rezidual expus la căldură radiantă, rezistența la tracțiune, rezistența la rupere) și este o trecere în revistă a influenței diferiților factori asupra performanței îmbrăcămintei de protecție termică, pentru a stabili performanța de protecție termică a trei tipuri de îmbrăcăminte. Prin utilizarea acestor cerințe esențiale cheie împotriva rezistenței termice, a fost dezvoltat modelul de regresie liniară multiplă pentru a prezice performanța de protecție termică a acestor 3 tipuri de îmbrăcăminte de protecție pentru pompieri.

Daniel Onuț BADEA, PhD. Student, National Research and Development Institute for Occupational Safety - I.N.C.D.P.M. "Alexandru Darabont" – Bucharest, Personal Protective Equipment Laboratory, 35A Ghencea Blv., Sector 6, Bucharest, Romania, E-mail: dbadea@protectiamuncii.ro, Office Phone: +40213131726

Alina TRIFU, PhD. Student, National Research and Development Institute for Occupational Safety - I.N.C.D.P.M. "Alexandru Darabont" – Bucharest, 35A Ghencea Blv., Sector 6, Bucharest, Romania, E-mail: alinatrifu@yahoo.com, Office Phone: +40213131726

Roxana Oana CHIVU, PhD., Professor, Politehnica University of Bucharest, Faculty of Industrial Engineering and Robotics, virlan_oana@yahoo.co.uk, +40722219498, 313 Splaiul Independenței, Sector 6, RO-060042 Bucharest, Romania.