COMPARATIVE STUDY OF RADIANT HEAT FLUX DENSITY TRANSMISSION THROUGH FIREFIGHTER PROTECTIVE CLOTHING

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Abstract: *The main purpose of this research is to find out possibility of improvement in thermal protective performance (TPP) of fire fighter protective clothing (FFPC) when subjected to radiant heat flux density of 10 kW/m^2. Enlargement of TPP is related to the increase of time period when subjected to radiant heat flux density may provide surplus time for fire fighter to carry out duties without enduring harmful injuries. Each FFPC specimen constitutes outer shell, moisture barrier and thermal barrier. However, aerogel blanket was also utilized as substitute to thermal barrier because of its excellent thermal insulation property and inflammable nature. Preliminary testing was related to evaluating thermal resistance and thermal conductivity. Later experimentation involves exposure of multilayer FFPC specimen to radiant heat flux density of 10 kW/m^2. It was witnessed that those combinations in which aerogel blanket was utilized deliver higher thermal resistance i.e.0.1748 m^{2}K/W and improved TPP behavior in terms of transmitted heat flux density Q_c (0.70 kW/m^2) and percentage transmission factor (6.70%).*

Keywords: *Fire retardant fabrics, aerogel blanket, thermal insulation, thermal protective performance.*

1 INTRODUCTION

Protection of human body against exterior climate is the most pertinent aspect of clothing, which serves as heat exchange medium between human body and nearby climate [1]. Clothing is responsible for breeding a microclimate between human body skin and surrounding atmosphere to maintain thermal equilibrium of human body [2-5]. Exchange of heat in clothing implicate radiation from one textile substrate layer to other substrate layer, convection of air gap and conduction of air gap and textile substrate layer [6].

In case of absenteeism of stream of air, radiation is the solitary mode of heat exchange between the body and nearby climate [7]. Emission of thermal radiation takes place from all the bodies and expulsion of heat through thermal radiation takes place in the form of infrared rays.

Fire fighter protective clothing (FFPC) is a multilayer fabric layer arrangement providing safeguard to firefighter from hazards of external radiant heat flux, spilling of chemical, flame and delivers thermal equilibrium of human body [8]. Fire fighter protective clothing encompasses outer layer, moisture barrier and thermal barrier [8]. The exterior shell comprises of those substrates which are engineered to have interaction with flame and heat without degenerating or burning i.e. they avoid ignition when have direct connection with flame and must have property of water repellence and water vapor permeability. Mostly fibers like meta aramids (Nomex), combination of meta aramid and par-amid (Nomex III A), polybenzimidazole (PBI), Zylon and some fibers with flame resistant finishes like Proban and Pyrovatex for improving TPP performance. The moisture barrier is located between exterior layer and thermal barrier. This layer is impermeable to water but permeable to water vapors. Its primary objective is to shield the body of fire fighters from blood pathogens and liquefied chemicals. Moisture barrier is hydrophilic membrane obtainable in the market as Goretex, Proline, Cross tech, Action, Neo Guard. The thermal barrier protects human body by blocking the environmental heat and utilizes flame retardant fibers and their blends. It can be laminated woven, nonwoven, quilted batting, lining fabric and knitted fabric and spun laced [8, 9].

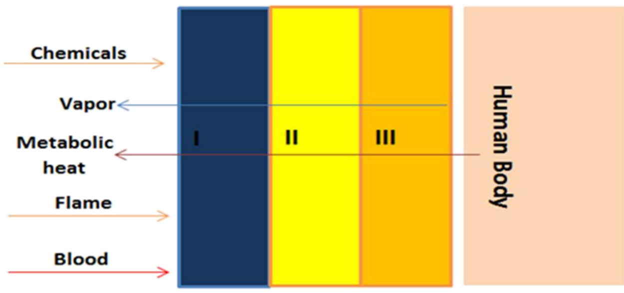


Figure 1 Arrangement of multilayer protective clothing [8, 9]

Time is the pivotal factor in terms of Thermal protective performance (TPP) of FFPC specimen.

Improvement in thermal protective property of firefighter protective clothing may increases the time period for firefighter to accomplish their activities without acquiring major injuries. As a consequence, firefighters can devote more time in hazardous environment saving precious lives and damages caused by fire without injuring themselves [10]. Evaluation of TPP might be conducted by several tests like thermal manikin (full scale methodology) and Heat guard plate and TPP tester (bench scale test) [11] or full scale test methodology like thermal manikin [12].

For last three decades, scientists are conducting lot of research for enhancement of TPP of FFPC. One approach is to employ silica based aerogel or aerogel blankets in FFPC assemblies. It is produced from gel by exchanging liquid phase with gaseous phase and has very low mass and porous structure [13]. There are several types of aerogels. Among various type of aerogels, silica based aerogels have very remarkable properties because of inflammable nature and lesser thermal conductivity than static air in same environmental conditions. Silica based aerogel is hydrophobic in nature with specific surface area around 1000 m^2/g having porosity greater than 90%. The thermal conductivity (λ) of silica based aerogel is approximately 0.015 W/(m.K) [14]. All these attributes allow silica aerogels a promising contender for utilization in firefighter protective clothing (FFPC) as thermal barrier. The main objective of this research is to escalate TPP of FFPC specimen. Several multilayer FFPC combinations were made. Each combination consists of outer shell, moisture barrier and thermal barrier. These specimens were characterized by Alambeta, and then finally evaluated by X637 B machine (ISO 6942-2005 standard) for determining transmission of heat through multilayer protective clothing assemblies at 10 kW/m^2 to figure out TPP of these multilayer clothing assemblies.

2 MATERIALS AND METHODOLOGY

All FFPC specimens were supplied by Kivanc group turkey and Vochoc company Czech republic. Pyrogel 2250 blanket was supplied by Aspen Aerogel Company. This layer was used as substitute layer to thermal barrier. Two different outer shells, one moisture barrier and one thermal liner were employed. Four different arrangements of FFPC assemblies were made. These combinations were made by superimposing outer shell, moisture barrier and thermal liner of the fabric without any stitching and lamination.

3 EXPERIMENTAL WORK

The evaluation of thermal resistance, thermal conductivity and thickness of monolayers and multilayers clothing arrangement was done with the help of Alambeta. It is a patent of prof. Lubos Hes and I. Dolezal which was manufactured by Sensora Company [15]. Radiant heat flux density transmission through FFPC arrangement was carried out by X637 B machine as per ISO 6942 standard.

3.1 Alambeta

Alambeta is computer-controlled device utilized to determine thermal characteristics of textile substrates. It is non-destructive equipment [16] comprises upper hot plate affixed to thin heat power sensor which falls down and have contact with surface of FFPC substrate positioned on lower cold plate. The computer records flow of heat due to temperature gradient between upper heated plate and specimen on cold plate. Temperature of upper plate is kept at 32°C and lower plate is kept at ambient temperature i.e. around 20°C. All measurements in same fabrics are recorded and serve for automatic calculation of mean value and variation coefficient.

Table 1 Specifications of multilayer clothing arrangement

Layer	Fabric Code	Component	Weave type	Fabric weight [g/m²]	Thickness [mm]
Exterior shell 1	E1	70/28/2% Meta-aramid/Para-aramid/Antistatic	Rip stop	200	0.74
Exterior shell 2	E2	100% cotton	Twill	280	0.88
Moisture barrier	MB	PU membrane laminated to nonwoven	Nonwoven	120	0.94
Thermal barrier	TB	40/30/30% Aramid/Viscose/FR icastar	Needle punching nonwoven	380	3.424
Aerogel blanket	P	Silica based aerogel with reinforced polymers (OPAN)	Nonwoven	380	2.85

Table 2 Combinations of clothing assemblies

Sr #	Fabric arrangement in multilayer clothing assembly	Fabric Code	GSM [g/m²]	Thickness [mm]
1	Exterior shell(E1) + Moisture barrier (MB) + Thermal barrier (TB)	Specimen 1	700	5.100
2	Exterior shell (E2) + Moisture barrier (MB) + Thermal barrier(TB)	Specimen 2	780	5.262
3	Exterior shell (E1) + Moisture Barrier (MB) + Aerogel blanket (P)	Specimen 3	700	4.538
4	Exterior shell (E2) + Moisture Barrier (MB) + Aerogel blanket (P)	Specimen 4	780	4.676

3.2 *Relative water vapor permeability (RWVP) percentage*

PERMETEST was employed to determine relative water vapor permeability. It is patent of prof. Lubos Hes (non-destructive method) and was developed by Sensora company under steady state conditions as per ISO 11092 standard and this method is also non-destructive method [17]. The higher the value of relative water vapor permeability, the lesser will be the water vapor resistance and there will be better thermal comfort [18]. Five measurements were taken for each specimen.

3.3 *Radiant heat transmission machine*

The radiant heat testing equipment X637 B is employed to investigate radiant heat flux density through material or material assembly according to ISO 6942 standard [16]. The apparatus consists of six carbide rods serving as radiation heat source, a small curved copper plate calorimeter, a moveable test frame having cooling device and specimen holders. The size of the sample was 230×80 mm which is placed on the face side of calorimeter and subjected to a specific level of radiant heat and time for temperature acceleration of 12°C and 24°C in the calorimeter was determined and conclusions are mentioned in the form of radiant heat transmission index (*RHTI 12* and *RHTI 24*) and the percentage heat transmission factor (*% TF* Q_o) [19]. Before experimentation, all specimens were pre-conditioned for 24 hours at temperature of 20°C and have relative humidity of 65% [19]. Five specimens are required for testing at each level of heat flux density. At first the calibration of the instrument is done and incident heat flux density is evaluated from the following equation.

$$Q_o = \frac{C_p R M}{a.A} \quad (1)$$

where: A = area of the copper plate [m^2], a = the absorption coefficient of the painted surface of calorimeter, M = mass of copper plate [kg], C_p = specific heat of copper 0.385 kJ/Kg°C), R = rate of rise of the calorimeter temperature in the linear region in °C/s.

Afterwards, the specimen is mounted on face of calorimeter by applying mass of 200 g. The time t_{12} for accomplishing temperature rise of 12°C and time t_{24} for acquiring 24°C are recorded in calorimeter in seconds and expressed as *RHTI 12* and *RHTI 24* [19]. The transmitted flux density, Q_c [kW/m^2] is evaluated by the following equation:

$$Q_c = \frac{M C_p 12}{A.(t_{24} - t_{12})} \quad (2)$$

where: $\frac{12}{(t_{24}-t_{12})}$ = mean rate of escalation of the calorimeter temperature [°C/s] in the region between 12 and 24°C rise where t_{12} designates time to attain increase of 120±0.1°C rise in temperature` t_{24} means time to attain increment of 24±0.2°C

Percentage age heat transmission factor, [*% TF* Q_o] for incident heat flux density level is explained by equation 3:

$$\% TF\ Q_o = 100.\frac{Q_c}{Q_o} \quad (3)$$

4 RESULTS AND DISCUSSION

4.1 *Evaluation of thermal resistance and thermal conductivity*

Thermal conductivity, thermal resistance and thickness were evaluated by Alambeta for monolayer and multilayer protective fabric assemblies and the outcomes are shown in Figure 2 and Figure 3 respectively.

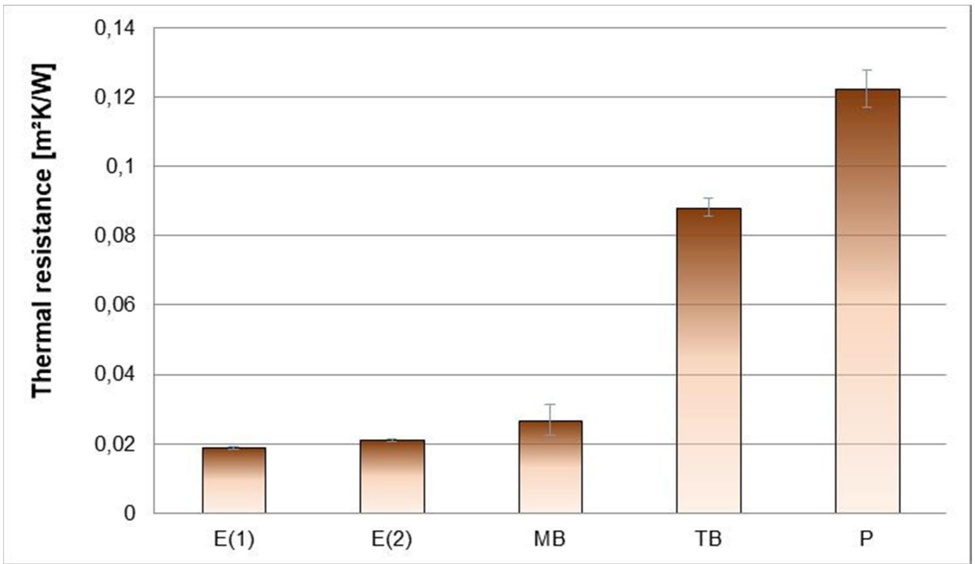


Figure 1 Thermal resistance of single layer fabrics

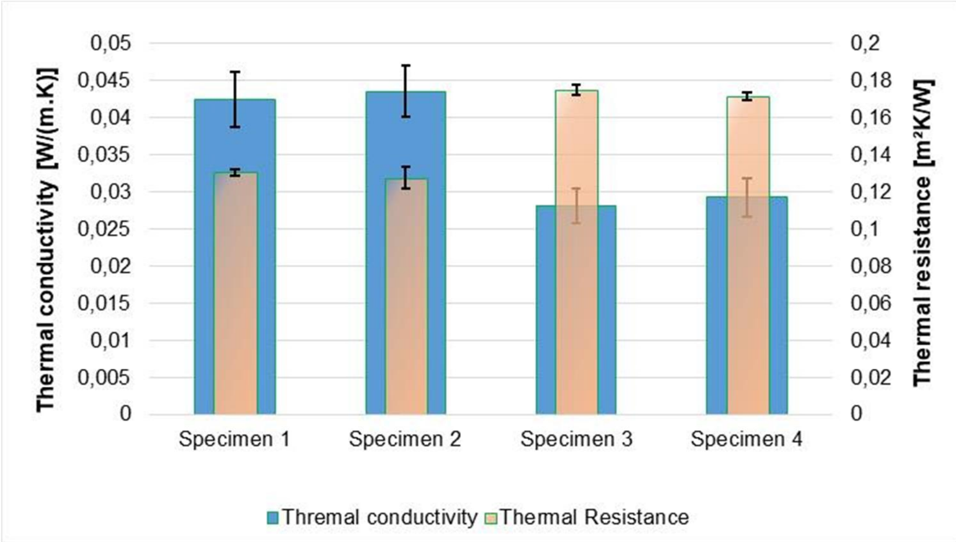


Figure 2 Thermal characteristics of multilayer FFPC specimens

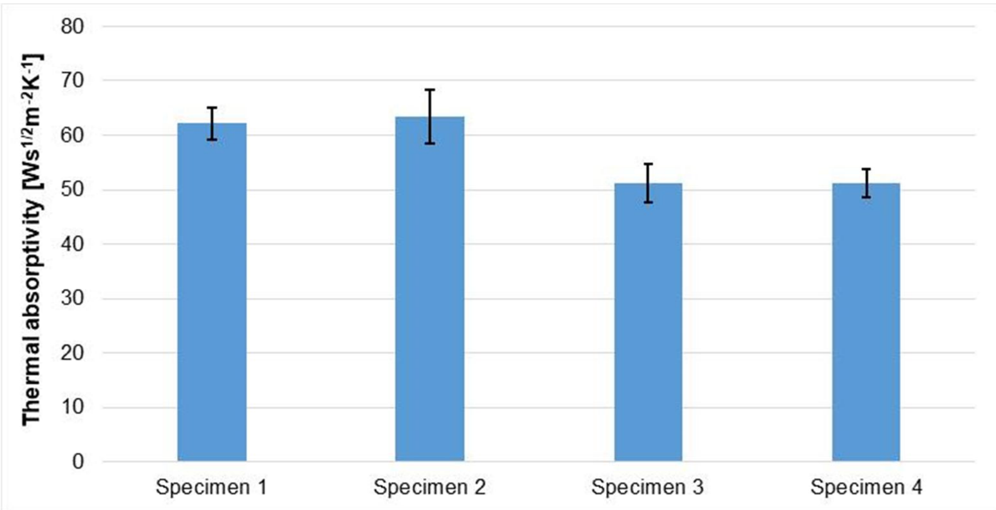


Figure 3 Thermal absorptivity of multilayer FFPC specimens

The relationship between thermal resistance and thermal conductivity is illustrated by following equation:

$$R_{th} = \frac{h}{\lambda} \tag{4}$$

where R_{th} is thermal resistance [m^{2}K/W], h is thickness of specimen and λ is thermal conductivity.

This thermal resistance is inversely proportional to thermal conductivity. Thermal resistance directly proportional to thickness [m] and inversely proportional to thermal conductivity [W/(m.K)]. However, thermal resistance is not only reliant on thickness of specimen but also on physical and chemical characteristics of specimen. Furthermore, the porosity and density of the textile medium have pivotal part in thermal characteristics of textile substrate. Those textile substrates which have closed and small pores are able to enclose static air inside them have high value of thermal resistance as air has very less value of thermal conductivity [20-22].

From Figures 2 and 3, it can be witnessed that a greater value of thermal resistance was witnessed in aerogel layer as compared to single layer and arrangement of FFPC specimen having aerogel layer as a substitute to thermal liner i.e. specimen 3 and specimen 4. This might be due to reason that silica based aerogel which has very low thermal conductivity even lesser than still air due to nanometer pore size making silica based aerogels are extremely high insulating materials [14]. Gaseous structure might avert conductive heat exchange [22]. Furthermore, aerogel does not permit circulation of air [22]. Thus, specimen C and D utilizing aerogel layer delivers higher thermal resistance and lower thermal conductivity as compared to specimen A and B.

Thermal absorptivity is the property of textile substrate highlights warm/cool feeling of textile substrate at the moment of connection with human skin. Thermal absorptivity is explained by following equation [23]:

$$b = \sqrt{\lambda \rho C} \tag{5}$$

where λ is thermal conductivity, ρ is density and C is the specific heat of textile substrate.

If thermal absorptivity is high, fabric will deliver cooler feeling. A perusal of Figure 4 revealed, that specimen 3 and specimen 4 having aerogel blanket as a substitute to thermal barrier delivers lesser thermal absorptivity values in comparison with specimen 1 and specimen 2.

4.2 Determination of Relative water vapor permeability

It was explained by Barker et al. [24] that the impact of moisture on thermal protective performance of Firefighter clothing (FFC) is contingent on conditions of exposure, properties of insulation and permeability of FFC and quantity of moisture in the turnout system. A perusal of Figure 5 acknowledged that specimen 3 and specimen 4 having aerogel blanket have low water vapor permeability. This might be due to fact that aerogel blanket has hydrophobic nature and presence of closed pores inside the configuration of aerogel blanket. On the other hand, some permeation of water vapor in specimen 3 and 4 which might be due to the high absorbing capabilities of aerogel, enabling the aerogel blanket enabling it to absorb moisture due to wetting and transport it to environment [25-30].

4.3 Transmission of radiant heat flux through multilayer protective clothing

The temperature of surrounding environment was maintained between 15 to 35°C. The rise of temperature was evaluated at back of specimen's by calorimeter which resulted in two threshold times i.e. *RHTI 12* and *RHTI 24*, Q_c and percentage heat transmission factor (*% TF* Q_o).

Table 3 Incident temperature on surface of specimen when exposed to incident heat flux density of 10 kW/m^2

Heat flux density	10 kW/m^2
Incident temperature on surface of specimen	205°C
Distance of specimen from carbide rods	37.1 cm

A careful examination of Table 4 discloses that transmitted heat flux density Q_c and percentage transmission factor (*% TF* Q_o) that least values of transmitted flux density Q_c (kW/m^2) were observed for the samples having aerogel blanket as thermal liner.

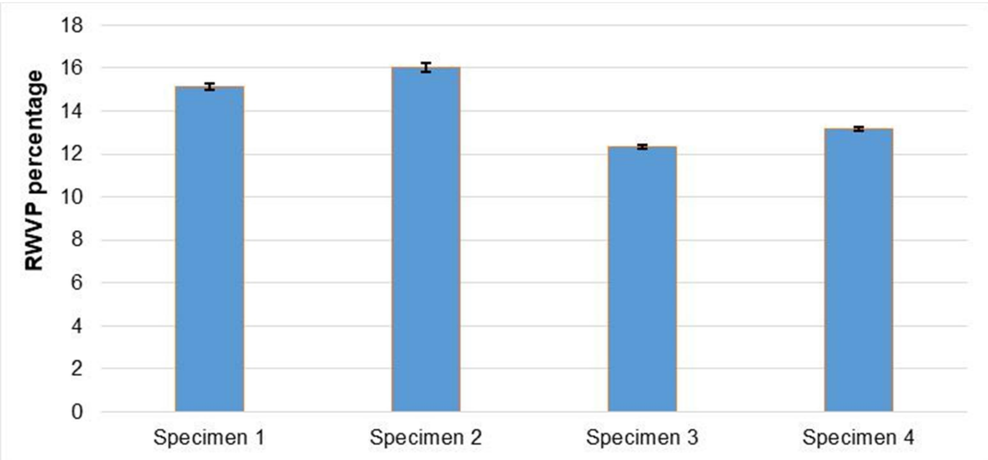


Figure 5 Water vapor permeability of multilayer FFPC specimen

Table 4 Time for rise of 12 and 24°C (*RHTI 12, RHTI 24*), transmitted flux density Q_c and percentage transmission factor (*% TF* Q_o) through FFPC combinations

Sr #	Name of material	Distance [cm]	RHTI 12 [sec]	RHTI 24 [sec]	Q_o [kW/m^2]	Q_c [kW/m^2]	% TF Q_o
1	P	37	54.6±2.828	102.6±2.969	10	1.4±0.005	13.6
2	Specimen 1	37	58.2 ±0.424	101.0±0.015	10	1.6±0.010	15.5
3	Specimen 2	37	74.1±0.707	128.7±0.997	10	1.3±0.050	12.1
4	Specimen 3	37	84.6 ±0.777	163.4±0.897	10	0.9±0.030	8.3
5	Specimen 4	37	97.4±0.898	195±0.672	10	0.7±0.150	6.7

An analogous pattern was observed in percentage *TF* Q_o values for the specimen having aerogel sheet i.e. specimen 3 and specimen 4 respectively. This might be due to reason that aerogel blanket contains almost 96 percentage of air and air is a good insulator delaying the amount of heat that will be exchanged through the specimen [31-33]. Furthermore, these aerogel samples consist of oxidized polyacrylonitrile (OPAN) polymer which has very respectable thermal stability and can endure greater amount of incident radiant heat flux [33]. The lesser the value of transmitted heat flux density, the minor will be quantity of radiant heat transmitted through fabric assemblies giving more amount of time to wearer (firefighter) to conduct their duties efficiently and effectively before acquiring any burn injuries. Table 4 also depicts that greater difference between *RHTI 12* and *RHTI 24*, lesser will be the value of transmitted flux density Q_c [kW/m^2] which indicates that specimen can withstand respected heat flux for longer time period allowing firefighters to perform their duties for longer duration before getting burn injuries.

A careful examination of Figure 6 reveals that the curves of specimen 3 and specimen 4 are more flat than that of the curves of specimen B, specimen A and aerogel layer (P) respectively at 10 kW/m^2. The flat curve indicates that rate of rise of temperature takes place at slower rate with respect to time. This might be due to reason that infrared radiation that performs a pertinent part in transference of heat may also be absorbed by aerogel [26-29] due to which aerogel blanket delivers improved thermal stability and insulation as compared to other specimens. The steep curve highlights, that rate of rise of temperature occurs at higher rate with respect to time, indicating swift exchange of radiant heat towards calorimeter. In consequence, the flatter curve will result in the slower transmission of heat exchange. Figure 6 also reveals that as curve becomes steeper curve, it shows certain increment of thermal conductivity and sudden decline in thermal resistance with the increase of time period [sec] which might be due to deterioration in the structure of FFPC specimen. The less steep the curve, the slower will be rate of increase in temperature, which will give more time of exposure to specimen when subjected to radiant heat flux. The flatter curve also indicates less damage to the corresponding fabric layers of the specimen. This might be due to fact that Infrared radiation that plays a substantial role in transference of heat can also be absorbed by aerogel [26-29] due to which aerogel blanket offers better thermal stability and insulation as compared to other specimens.

The images of specimen before and after exposure of 10 kW/m^2 are shown in Figure 7.

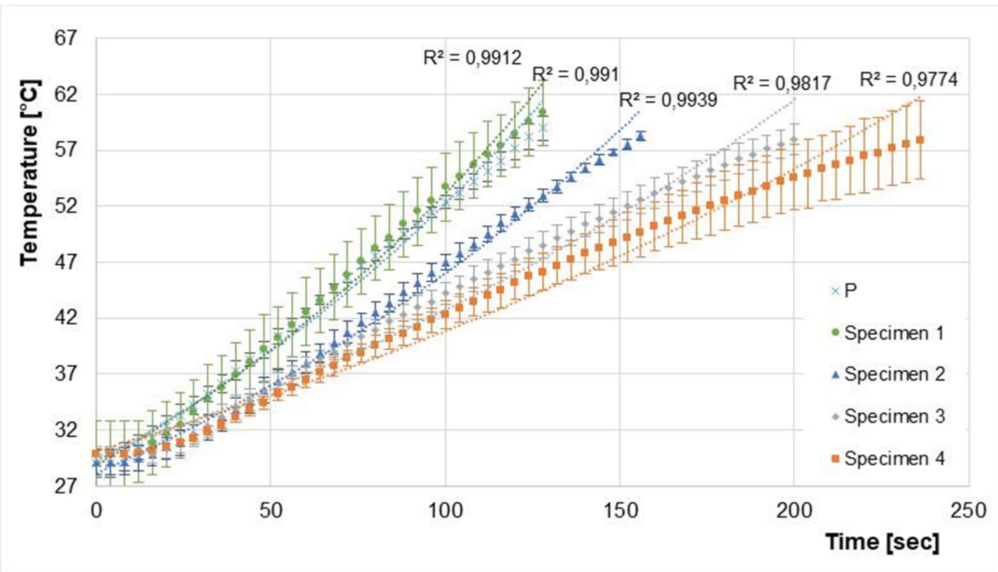
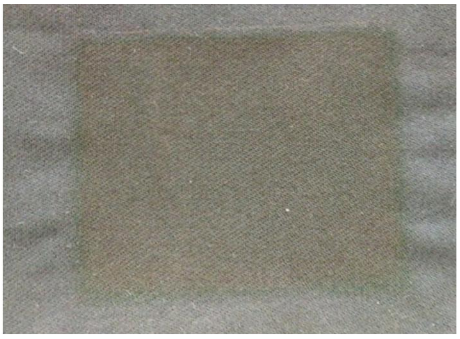


Figure 4 Heat transmission at 10 kW/m²

Specimen E1 before exposure



Specimen E1 after exposure to 10 kW/m^2

Specimen E2 before exposure

Specimen E2 after exposure to 10 kW/m^2

Figure 7 Comparison of images of outer shell before and after exposure to10 kW/m^2

From Figure 7, it is evident that after exposure to 10 kW/m^2 the color of the fabric became more black which indicated certain damage or deterioration of outer shell after being exposed to radiant heat flux density of 10 kW/m^2.

5 CONCLUSION

It might be deducted that safety of firefighters is contingent on the protective performance of firefighter protective clothing. If this protective performance can upsurge time of exposure of fire fighters against radiant heat flux, it may result in saving precious lives and useful stuff. When FFPC samples were subjected to radiant heat flux density of 10kW/m^2, it was observed that that aerogel layer was employed as an alternate to thermal barrier yield higher thermal resistance and improved thermal protective performance as it delayed the amount of heat transmitted through specimen. The gaseous structure, high percentage of static air, non-flammable nature of silica based aerogel is responsible for its better thermal protective behavior which offers better thermal stability against radiant heat flux density.

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6 REFERENCES

1. Holmer I.: How is performance in the heat affected by clothing? Textile Bioengineering and Informatics Symposium Proceedings 1, 2008, pp. 700-705
2. Das A., Alagirusamy R.: Science in comfort", 2nd ed., Wood Head Publishing, New Delhi, 2011, pp. 4-5
3. Li, Y.: Science in clothing comfort, Layton J.M. (Ed.), Manchester: Textile Institute International, Textile Progress 31(1/2), 2001, pp. 1-138, https://doi.org/10.1080/00405160108688951
4. Thermal comfort (2005a), Environmental Engineering Science 1, 21.07.2005, http://www.esru.strath.ac.uk/Courseware/Class-16293/6-Comfort.pdf
5. Stoecker W.F., Jones J.W.: Refrigeration and air conditioning, 2nd ed., McGraw-Hill, Singapore, 1982
6. Havenith G., Holmer I., Parsons K.: Personal factors in thermal comfort assessment: clothing properties and metabolic heat production, Energy and Buildings 34(6), 2002, pp. 581-591, id:81c53010-c49d-44ae-afe0-0bdaa1c34611
7. Holmer I.: Protective clothing in hot environments, Industrial Health 44(3), 2006, pp. 404-413
8. Lawson J.R.: Fire fighters protective clothing and thermal environments of structural fire- fighting, ASTM Spec. Tech. Publ. 1273, 1997, pp. 334-335
9. Lu J., Kyounga H., Keejong Y.: Effect of aerogel on thermal protective performance of firefighter clothing, Journal of Fiber Bioengineering and Informatics 6(3), 2013, pp. 315-324, DOI: 10.3993/jfbi09201309

10. Holcombe B.V.: The heat related properties of fire fighters protective clothing fabrics, Fire Safety Journal 6(2), 1983, pp. 129-141, https://doi.org/10.1016/0379-7112(83)90058-9
11. Salmon D.: Thermal conductivity of insulations using guarded hot plates, including recent developments and sources of reference materials, Measurement Science and Technology 12(2), 2001, pp. 1-89, DOI: 10.1088/0957-0233/12/12/201
12. Celcar D., Meinander H., Gersak J.: Heat and moisture transmission properties of clothing systems evaluated by using a sweating thermal manikin under different environmental conditions, International Journal of Clothing Science and Technology 20(4), 2008, pp. 240-252, https://doi.org/10.1108/09556220810878865
13. Pierre A.C., Rigacci A.: SiO_2 aerogels (chapter 2), Aerogels handbook, Advances in Sol-Gel Derived Material and Technology, Aegerter M.A., Leventis N., Koebel M.M. (Eds), New York: Springer Science+Business Media, 2011, pp. 21-45, ISBN 978-1-4419-7589-8
14. Pierre A.C., Pajonk G.M.: Chemistry of aerogels and their applications. Chem Rev 102(11), 2002, pp. 4243-4266, DOI: 10.1021/cr0101306
15. Hes L., Dolezal I.: New method and equipment for measuring thermal properties of textiles, Journal of the Textile Machinery Society of Japan. 42(8), 1989, pp. 24-28, DOI:10.4188/transjtmsj.42.8_T124
16. Matusiak M.: Investigation of the Thermal Insulation Properties of Multilayer Textiles, Fibres&Textiles in Eastern Europe 59(5), 2006, pp. 98-112
17. Hes L. Araujo M.: Effect of mutual bonding of textile layers on thermal insulation and thermal contact properties of fabric assemblies, Textile Research Journal 66(4), 1996, pp. 245-250, DOI:10.1177/004051759606600410
18. Matusiak M., Kowalczyk S.: Thermal-insulation properties of multilayer textile packages, AUTEX Research Journal 14(4), 2014, pp. 299-307, DOI:10.2478/aut-2014-0030
19. Meb G.W., P. GmbH P.: Combustion behavior test equipment, Keplerstraße Berlin, 2002
20. Bogusławska-Bączek M., Hes L.: Effective water vapour permeability of wet wool fabric and blended fabrics, Fibres&Textiles in Eastern Europe 97(1), 2013, pp. 67-71
21. Oğlakcioğlu N., Marmarali A.: Thermal comfort properties of some knitted structures, Fibres Textiles in Eastern Europe 64-64(5-6), 2007, pp. 94-96
22. Hes L., Loghin C.: Heat, moisture and air transfer properties of selected woven fabrics in wet state, Journal of Fiber Bioengineering and Informatics 2(3), 2009, pp. 141-149, DOI:10.3993/jfbi12200901
23. Schneider A.M., Holcombe B.V.: Properties influencing coolness to the touch of fabrics, Textile Research Journal 61(8), 1991, pp. 488-494, https://doi.org/10.1177/004051759106100810
24. Barker R.L., Heniford R.C.: Factors affecting the thermal insulation and abrasion resistance of heat resistant hydro-entangled nonwoven batting materials for use in firefighter turnout suit thermal liner systems, Journal of engineered fibers and fabrics 6(1), 2011, pp. 1-10
25. Baetens R., Jelle B.P., Gustavsen A.: Aerogel insulation for building applications: A state-of-the-art review, Energy and Buildings 43(4), 2011, pp. 761-769, https://doi.org/10.1016/j.enbuild.2010.12.012
26. Shahid A., Furgusson M., Wang L.: Thermophysiological comfort analysis of aerogel nanoparticle incorporated fabric for fire fighter's protective clothing, Chemical and Materials Engineering 2(2), 2014, pp. 37-43, DOI: 10.13189/cme.2014.020203
27. Fricke J.: The pore structure determination of aerogels, Springer-Verlag, 4, 1998, pp. 187-195
28. Lee D., Stevens P.C., Zeng S.Q., Hunt A.J.: Thermal characterization of carbon-opacified silica aerogels, Journal of Non-Crystalline Solids 186, 1995, pp. 285-290, https://doi.org/10.1016/0022-3093(95)00055-0
29. Fricke J.: Thermal properties of silica aerogels, Le Journal de Physique Colloques 50, 1989, pp. 4-4
30. Onofrei E., Dupont D., Petrusic S., Soulat D., Bedek S., Codau T.C.: Modeling of heat transfer through multilayer firefighter protective clothing, Industrial Textila 65(5), 2014, pp. 277-282
31. Xu B., Cai J.Y., Finn N., Cai Z.: An improved method for preparing monolithic aerogels based on methyltrimethoxysilane at ambient pressure Part I: Process development and macrostructures of the aerogels, Microporous and Mesoporous Materials 148(1), 2012, pp. 145-151, https://doi.org/10.1016/j.micromeso.2011.08.012
32. Venkataraman M., Mishra R., Kotresh T.M., Sakoi T., Militky J.: Effect of compressibility on heat transport phenomena in aerogel-treated nonwoven fabrics, The Journal of Textile Institute 107(9), 2015, pp. 1150-1158, https://doi.org/10.1080/00405000.2015.1097084
33. Anon. Aspen aerogels. Safety data sheet, pyrogel 2250, 2008