Thermal performance of protective clothing (firefighter) under extreme ambient conditions

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ABSTRACT – REZUMAT

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Protective clothing is made up of multiple layers of textile, which include thermal barrier, moisture barrier, chemical protection and heat radiation protection layers etc. This clothing is commonly used by workers working in the chemical industry, blast furnaces, glass industry, industrial boilers and many more. The ambient conditions for these workplaces are humid and hot in which the clothing is designed for the external protection of heat and fluids but the neglected issue is the internal heat and moisture accumulation. This makes the clothing extremely uncomfortable and significantly reduces the workability of the wearer. The multi-layered structure of this clothing causes the body moisture and heat to trap in between layers, which in extreme ambient conditions like working near the furnace or flash fire causes body burns, these "steam burns" are common and considered to be caused by the condensed moisture trapped in the layers of protective garment. This research aims to firstly investigate the moisture flow through hybrid textile layers and its effect on heat transfer and then secondly to see the impact of extreme radiation flux on the moisture flow inside the textile layers and improvement by using Aerogels.

Keywords: *firefighter, comfort, radiation, textile*

Performanța termică a îmbrăcămintei de protecție (pentru pompieri) în condiții ambientale extreme

Îmbrăcămintea de protecție este alcătuită din mai multe straturi de material textil, care includ bariera termică, bariera de umiditate, protecția chimică și straturile de protecție împotriva radiațiilor termice etc. Acest tip de îmbrăcăminte este folosit în mod obișnuit de lucrătorii din industria chimică, furnal, industria sticlei, cazane industriale și multe altele. Condițiile ambientale pentru aceste locuri de muncă sunt umede și fierbinți, iar îmbrăcămintea este concepută pentru protecția externă la căldură și fluide, dar problema neglijată este acumularea de căldură și umiditate internă. Acest lucru face ca îmbrăcămintea să fie extrem de inconfortabilă și reduce semnificativ capacitatea de lucru a purtătorului. Structura multistratificată a acestui tip de îmbrăcăminte face ca umezeala și căldura corpului să rămână între straturi, ceea ce, în condiții ambientale extreme, cum ar fi lucrul în apropierea cuptorului sau combustia spontană, provoacă arsuri corporale, aceste „arsuri cu abur" sunt frecvente și considerate a fi cauzate de umiditatea provenită din condens în straturile de îmbrăcăminte de protecție. Scopul acestei cercetări este de a investiga în primul rând fluxul de umiditate care trece prin straturile textile hibride și efectul acestuia asupra transferului de căldură și apoi, în al doilea rând, de a vedea impactul fluxului de radiații extreme asupra fluxului de umiditate din interiorul straturilor textile și îmbunătățirea acestora prin utilizarea aerogelurilor.

Cuvinte-cheie: *pompier, confort, radiații, textile*

INTRODUCTION

When the body of the wearer of protective clothing is exposed to heat stress, the body reacts by activation of perspiration [1, 2]. The firefighter often works in extreme ambient conditions, which makes the work highly non-comfortable. The perspiration created cannot leave the clothing and often turns to the liquid inside the clothing layers, sometimes this liquid sweat gets the heat from the surrounding can turn to steam, which causes the dangerous phenomena of steam burns to the firefighters [3].

For firefighters, the main concern is heat radiation from the heated body, fire, hot air convection, and direct connection from high-temperature objects [4, 5]. Heat transmission modes including Conduction, convection and radiation have a significant impact on the thermal show of the wearer of protective garments and can cause burn damage. In the case of protection against heat or radiation, the overall structure, material and construction of the garment are very important [6].

Most of the firefighter clothing is made from Aramid fibres like Nomex and Kevlar due to higher melting temperatures and strong mechanical properties.

Human skin can get a different category of skin damage as listed below [6–8]:

I. **First-degree burn**

This is a mild kind of burn that causes damage or rashes to the top layer of the skin, these burns can often lead to scalds. These burns usually do not require medical treatment.

II. **Second-degree burn**

Second-degree burns damage the skin layer called the dermis. The burns need medical treatment; the wounds can swallow and irritate.

III. **Third-degree burn**
This is deeper skin damage and causes inner tissues to be impacted by the heat. Usually, the skin gets charred due to extreme heat.
All this protective clothing is made with packed hybrid layers to protect the wearer against the external hazardous fluid or heat, these multilayers are impermeable and non-breathable which causes great discomfort and even body burns. There are contradictory results, which state the increase and decrease in heat protection due to the presence of moisture in the textile layers [9–12]. The radiation heat protection is the most important factor for this clothing and it will tested with Aerogels can provide better protection with a delay in the time for heat to reach the wearer.

AEROGELS (HISTORY TO ITS APPLICATION IN FIREFIGHTER CLOTHING)

In 1930 Kistler discovered the Silica-based Aerogels in which he substituted the liquid phase with the gaseous phase as a 3D structure. Aerogels are commonly cloud-like materials having a similar projection instead of solid material. Aerogels are commonly prepared by the Sol-Gel process [13] which is shown in figure 1.
These Silca-based Aerogels are 90–96% air and the rest is Silica dioxide. This gives them unique characteristics of solid with extreme thermal protection due to their pore structure and presence of trapped air. The interlocked pores range from 5–90 nm with an average diameter of less than 40 nm. This structure provided ideal conditions for thermal protection and normally the thermal conductivity is less than that of air under some conditions [15]. The use of this material in garments, boilers and home insulations is new and demands further investigations.

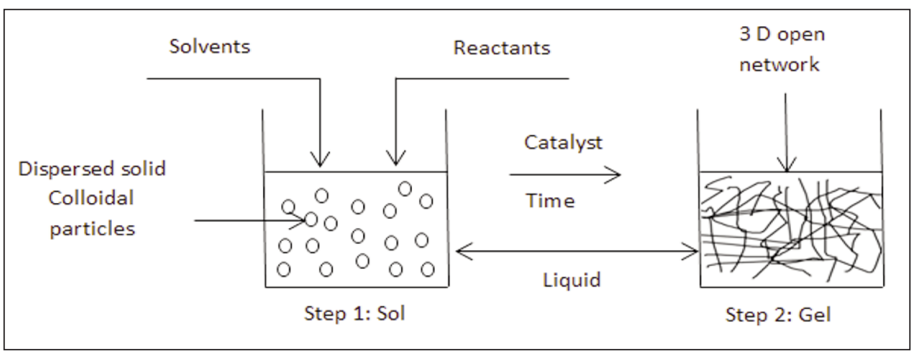

Fig. 1. Preparation of Sol-Gel [14]

OBJECTIVES OF THE RESEARCH

The objectives of the research project are:
- To understand moisture management of sweat for multilayer protective clothing like firefighter clothing.
- To improve thermal protection using different thermal and moisture barrier combinations.
- To analyse the effect of radiation heat protectors on the outer layer.
- Using the experimental and theoretical results to propose a better combination of textile layers for the protective clothing.

METHODOLOGY

To analyse the performance of firefighter clothing, the most common sandwich structure of the garment is selected and each layer of it is also purchased from the company Vochoc (Czech Republic). Another addition is the Aerogel layer which is famous for its high thermal resistance is also selected for the experiment to see the effect of the different combinations of layers on the overall protection of the firefighter clothing.
Table 1 shows the properties of each layer of the firefighter clothing. Two top layers, and one layer of Moisture protector, thermal barrier and the Aerogel layer are selected for the experiment. Each layer will be further combined to see the overall performance of moisture transport and radiation protection.
The samples are then tested under the Radiant heat flux equipment X637 B working according to ISO 6942 standard. In this experiment, the radiation heat flux of different intensities is directed to the sample. This can be from 10 kW/m^2 to 40 kW/m^2. This

Table 1

SAMPLE DESCRIPTION				
Fabric layers	**Serial**	**Composition**	**Weight (g/m^2)**	**Thickness (mm)**
Top layer 1	T1	% 75 Metaaramid-23 Para aramid-%2 Antistatic	220	0.83 (±0.11)
Top layer 2	T2	Proban (100 % cotton)	305	0.97 (±0.2)
Moisture protector	MB	Nonwoven web laminated with polyurethane	115	0.94 (±0.18)
Thermal protector	H	50/50 Meta Aramid /FR Viscose fibres	360	3.40 (±0.14)
Aerogel layer	A	Polymer with Silica aerogel	356	2.82 (±0.2)

radiation is further received by the calorimeter, which shows the heat flux that passes through the samples. The device is first calibrated according to standard and later at different energy powers (10–40 kW/m^2), the samples are tested. The longer time the samples transfer the heat to the receiver the better insulator or thermal resistant it is considered.

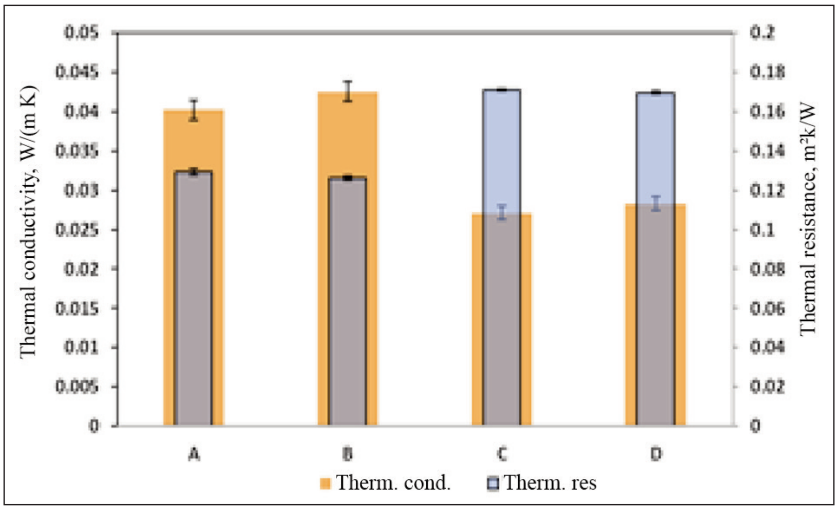

Fig. 3. Thermal conductivity and thermal resistance of layers

RESULTS

All these layers with two top layers will be tested for moisture permeability overall thermal protection and different radiation levels. The combinations made for the testing are shown in table 2.

Table 2

DESIGN OF EXPERIMENT			
Samples	**Assembly layers of fabrics**	**Thickness (mm)**	**Weight (g/m^2)**
A	T1 + Moisture barrier + Thermal protector	5.15 (±0.18)	735
B	T2 + Moisture barrier + Thermal protector	5.29 (±0.2)	801
C	T1 + Moisture barrier + Aerogel layer	4.59 (±0.19)	759
D	T2 + Moisture barrier + Aerogel layer	4.75 (±0.15)	829

Thermal conductivity and connected parameters including thickness were evaluated by Alambeta for single-layer and sandwich fabric assemblies and their corresponding values were mentioned in the figure below respectively. Thermal resistance R_{th}, depends on the thermal conductivity and the thickness of the textile layers. In general greater thickness of textiles brings better thermal protection. Also, the closed pores of air inside the sample make it more resistant to thermal change.

It can be seen in the figure 3 that the thermal resistance of the samples with Aerogel is significantly higher as compared to the classical thermal barrier. Overall thermal performance of the combined layers is suitable for high thermal protection against heat. The samples are further analysed for the water vapour resistance.

Evaluation of water vapour resistance

Sweating guarded hot plate was used according to the standards ISO 11092 to determine the overall moisture transport through textile layers. Higher resistance means that less moisture cannot pass through the fabric, so either it is impermeable or limited channels of water vapour path exist in the textile layers. Commonly the firefighter's clothing is not permeable to moisture or water vapour which makes them uncomfortable to wear during firefighting missions.

The figure 4 shows the overall non-permeable behaviour of the sandwich structure, the minor moisture exchange might be due to the absorption and then release of moisture to the sideways or a few channels of vapour paths through seams etc.

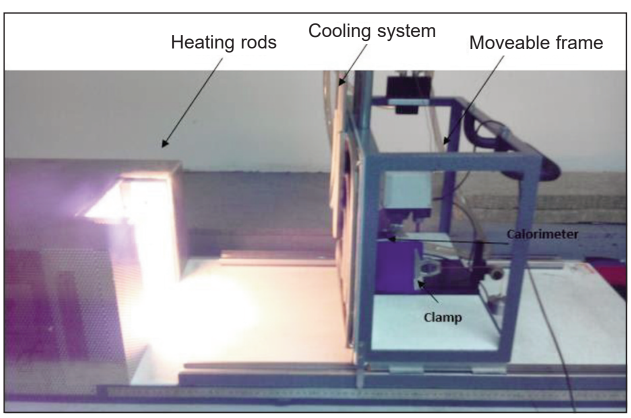

Fig. 2. Radiation heat testing equipment

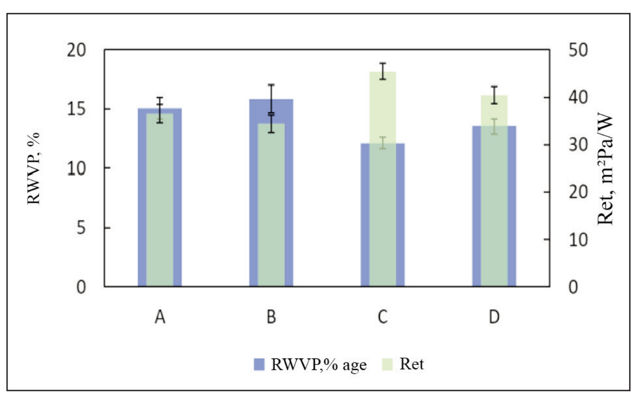

Fig. 4. Water vapour resistance of samples

Table 3

INCIDENT TEMPERATURE ON THE SURFACE OF THE SPECIMEN WHEN EXPOSED TO DIFFERENT HEAT FLUX DENSITY				
Heat flux density (kW/m^2)	**10**	**20**	**30**	**40**
Surface temperature of the samples (°C)	205	292	390	495
Sample distance from the source (cm)	37.1	25.1	19.7	16.5

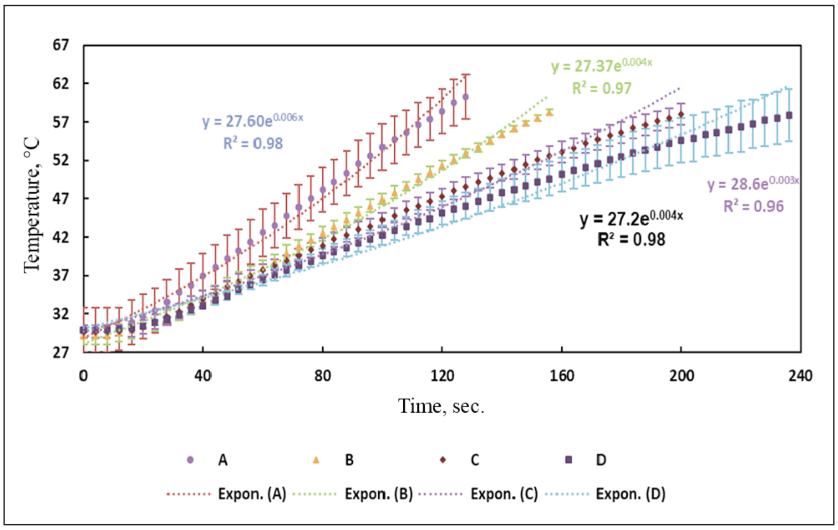

Fig. 5. Heat transmission at 10 kW/m^2

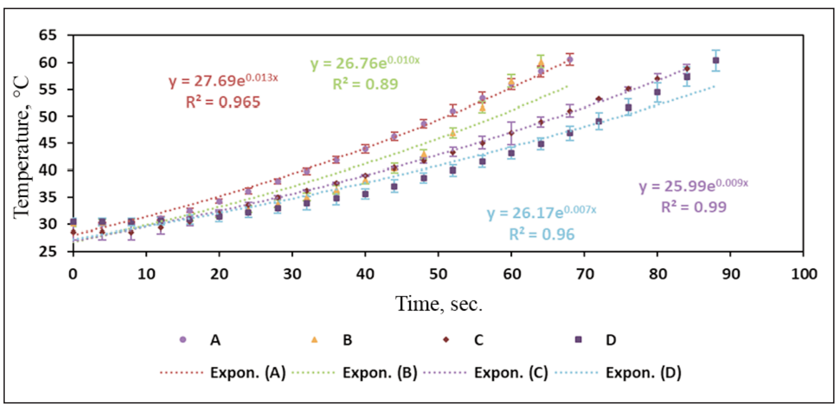

Fig. 6. Heat transmission at 20 kW/m^2

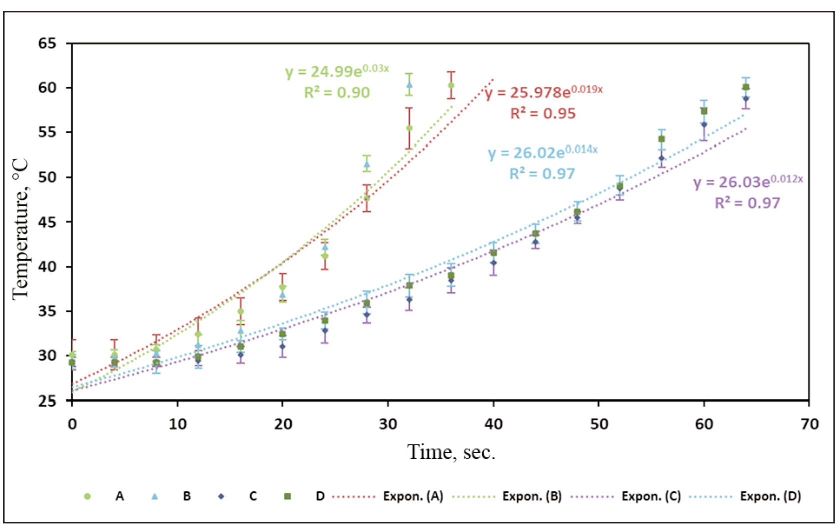

Fig. 7. Heat transmission at 40 kW/m^2

Transmission of radiant heat flux

The most important factor for the protection of firefighter clothing is radiation heat transmission. In this experiment the samples are exposed to different energy levels of radiant heat and the overall transferability of the material is tested concerning time.

The graph shows the radiant heat protection of the samples exposed to different energy levels (10–40 kW/m^2). The lower the curve the better the heat protection, which shows that it takes longer time for the heat to transfer to the other side of the sample. The machine works on the phenomenon of reaching 12 degrees rise and 24 degrees rise of temperature concerning time, so the longer it takes the better the protections. The results show that the C and D samples with Aerogels provide the best protection, the lines are more slowly rising and the difference from the classical samples is quite significant as well. This is mainly due to the better thermal protection of the Aerogels layers, as all other layers are identical in the other samples as well.

The rise is exponential which is common for heat exchange through textile materials. The results show significant improvement in the firefighter clothing with Aerogels in it.

CONCLUSION

It can be concluded from the research that the thermal radiation protection of firefighter clothing is very important and with extreme ambient heat, it is necessary to have proper sandwiched layers to provide the firefighter with maximum time and minimum damage.

The firefighter's clothing performance is mainly judged by the thermal protection from the radiant heat. The results show that firefighter clothing is almost impermeable to moisture or water vapour due to multiple layers sandwiched together with the focus on better thermal performance and comfort not considered. Whereas the samples show quite good radiant thermal protection and the results are very promising when using the Aerogels instead of the thermal barrier. The Aerogel layer provides significant extra protection from the radiation heat and also the time delay makes more time for the firefighter during the extinguishing process. The research needs more work related to ergonomics, durability and the functional behaviour of Aerogels for the thermal protection of firefighters.

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