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Faculty of Textile Engineering

THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING

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SUMMARY OF THE THESIS

Title of the thesis:	Thermal Protective Performance of Firefighter Protective clothing
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Abstract

This study is related to the possible improvement in thermal protective performance of firefighter protective clothing when exposed to different levels of radiant heat flux density. Firefighter protective clothing normally consists of three layers: outer shell, moisture barrier and thermal liner. When thermal protective performance of firefighter protective clothing is enhanced, the time of exposure against radiant heat flux is increased, which will provide extra amount of time to firefighter to carry on their work without suffering from severe skin burn injuries. There are several ways to improve thermal protective performance. In this study, Improvement in thermal insulation properties of firefighter protective clothing was made with the help of aerogel blankets. Four different multilayer combinations of firefighter protective clothing were investigated. Two samples have combinations consisting of outer shell, moisture barrier and thermal liner. In other two sample arrangements, aerogel sheet was also employed as a substitute to thermal barrier. Initially, properties like thermal resistance, thermal conductivity were investigated. Later on these combinations were exposed to different levels of radiant heat flux density as per ISO 6942 standard. It was noted that those combinations in which aerogel blanket was used as substitute to thermal barrier acquire greater thermal resistance and have less transmitted heat flux density values. The lower the value of transmitted heat flux density, the better will be thermal protective performance as more amount of time will take for rise in temperature of firefighter's body. This will allow firefighters to perform their duties efficiently and effectively without acquiring significant burn injuries. In another attempt to improve thermal protective performance, the exterior side of outer shell was coated with layer of silver metallic particle through magnetron sputtering technology. Coating of outer shell with silver metallic particles was performed at three level of thickness i.e. $1\mu m$, $2\mu m$ and $3\mu m$ respectively. However, a significant decline was recorded for the value of transmitted heat flux density Q_c (kW/m^2) and percentage transmission factor (percentage TF Q_o) in case of silver coated specimens when subjected to different levels of radiant heat flux density. This indicates considerable improvement in thermal protective performance of silver coated specimen as compared to uncoated specimens. These values of transmitted heat flux density go on further reduction with increase in thickness of coating layer of silver particles. Also the silver coated specimen has lower emissivity values as compared to uncoated specimen indicating better reflective properties. Later on, these specimens were washed as per NFPA 1851 standard for investigating durability of coating and thermal protective performance. It was inferred that there was negligible decline in thermal protective performance of silver coated specimens after different cycles of washing. In the end, Numerical model was employed to predict distribution of temperature for both uncoated and silver coated specimen. This model utilizes appropriate radiant heat transfer equations. When results of uncoated and silver coated fabric assembly obtained from numerical solution were compared, they display similar pattern as observed in the experimental work.

Keywords: Firefighter protective clothing, Thermal protective performance, Thermal insulation and Transmitted heat flux density

Abstrakt

Tento výzkum se zabývá možným zlepšením tepelné odolnosti hasičského ochranného oděvu při vystavení různým úrovním intenzity sálavého tepelného toku. Ochranný oděv hasiče se obvykle skládá ze tří vrstev: vnějšího pláště, bariéry proti vlhkosti a tepelné izolace. Zvýší-li se tepelná odolnost hasičského ochranného oděvu, zvýší se doba expozice proti sálavému tepelnému toku, což poskytne hasiči další čas, aby mohl pokračovat ve své práci, aniž by utrpěl těžká zranění způsobená popálením kůže. Existuje několik způsobů, jak zlepšit tepelnou ochranu. V této studii bylo dosaženo zlepšení tepelně izolačních vlastností hasičského ochranného oděvu pomocí vrstev obsahujících aerogel. Byly zkoumány čtyři různé vícevrstvé kombinace hasičského ochranného oděvu. Dva vzorky mají kombinace sestávající z vnější vrstvy, bariéry proti vlhkosti a tepelné vložky. V dalších dvou uspořádáních vzorků se jako náhrada za tepelnou bariéru použila vrstva aerogelu. V prvé řadě byly zkoumány vlastnosti jako tepelný odpor, tepelná vodivost. Později byly tyto kombinace vystaveny různým úrovním hustoty sálavého tepelného toku podle normy ISO 6942. Bylo zjištěno, že kombinace, ve kterých byla aerogelová vrstva použita jako náhrada tepelné bariéry, získaly větší tepelný odpor a mají nižší hodnoty hustoty přenášeného tepelného toku. Čím nižší je hodnota hustoty přenášeného tepelného toku, tím lepší bude tepelný ochranný faktor, protože zvýšení teploty těla hasiče bude vyžadovat více času. To umožní hasičům účinně a efektivně vykonávat své povinnosti, aniž by utrpěli vážná zranění způsobená popálením. V dalším pokusu o zlepšení tepelné ochranné odolnosti byla vnější strana vnějšího pláště potažena vrstvou stříbrných kovových částic pomocí technologie magnetronového naprašování. Potah vnějšího pláště stříbrnými kovovými částicemi byl prováděn ve třech úrovních tloušťky, tj. 1 μm, 2 μm a 3 μm. U vzorků nepropustných a postříbřených vzorků byl zaznamenán zanedbatelný rozdíl v hodnotách propustnosti vzduchu a relativní propustnosti pro vodní páru. Významný pokles byl však zaznamenán u hodnoty přenášené hustoty tepelného toku Q_c (kW/m^2) a procentního faktoru přenosu (procento TF Q_o) v případě vzorků potažených stříbrem, pokud byly vystaveny různým úrovním hustoty sálavého tepelného toku. To ukazuje na značné zlepšení tepelné ochranné výkonnosti vzorků potažených stříbrem ve srovnání s nepotaženými vzorky. Tyto hodnoty hustoty přenášeného tepelného toku se dále snižují se zvyšováním tloušťky povlakové vrstvy částic stříbra. Také stříbrně potažený vzorek má nižší hodnoty emisivity ve srovnání s nepotaženým vzorkem, což naznačuje lepší reflexní vlastnosti. Později byly tyto vzorky promyty podle standardu NFPA 1851 pro zkoumání trvanlivosti povlaku a tepelné ochranné výkonnosti. Bylo zjištěno, že po různých cyklech praní došlo k zanedbatelnému snížení tepelné ochranné výkonnosti vzorků potažených stříbrem. Nakonec byl použit numerický model k predikci distribuce teploty pro nepotažené a stříbrem potažené vzorky. Tento model využívá rovnice, které jsou vhodné pro přenos tepla sáláním. Porovnáním výsledků měření textilií ošetřených a neošetřených stříbrem s numerickými modely uvedenými v této práci, můžeme konstatovat, že mají shodný trend.

Klíčová slova: Hasičský ochranný oděv, tepelný ochranný výkon, tepelná izolace, hustota přenášeného tepelného toku.

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1. Introduction

Firefighters are always working under constant threat because of hazardous working conditions due to which they need suitable amount of protection against dangerous situations. During thermal exposures, firefighters are subjected to hazardous environments like heated climate, intense thermal radiation and contact with high temperature objects [1][2]. Firefighter protective clothing (FFPC) is multi-layer garment which assures that firefighters are safe from threats like external radiant heat flux, chemical spillage, flame, delivers thermal equilibrium to human body and avoid any possibility of skin burn [3][4]. Firefighter protective clothing comprises of exterior shell, moisture barrier and thermal barrier[5]. The exterior shell comprises of those materials which are developed to have contact with flame and heat without degenerating or burning i.e. they avert ignition when have direct contact with flame and must have property of water repellence and good thermal insulation. Normally, fibers like combination of Nomex and Kevlar (Nomex III A), polybenzimidazole (PBI), Zylon and some flame-retardant finishes like Pyrovatex and Proban are employed for improving protective performance. The moisture barrier is a microporous membrane situated between exterior layer and thermal barrier. This layer is permeable to water vapors but impermeable to liquid water. Its primary objective is to shield the body of fire fighters from liquefied chemicals and blood pathogens. Moisture barrier is offered in the market as Action, Proline, Goretex, Cross tech, Neo Guard. The thermal barrier protects human body by blocking the environmental heat and utilizes flame retardant fibers and their blends. It can be nonwoven, quilted batting, laminated woven, lining fabric and knitted fabric and spun laced [4][6][7].

The primary task of firefighter clothing is to guarantee that the rate of rise of temperature in human skin must be reduced or slowed down in order to provide sufficient amount of time to the firefighter to respond efficiently along with minimization of hazardous injuries to skin [8][9]. This functionality of firefighter clothing is termed as thermal protective performance (TPP), which is considered as the most crucial factor in the performance of firefighter protective clothing. In terms of protective performance of firefighters, time is the main factor. Enhancement in thermal protection increases the duration for firefighter to conduct their activities without any significant injuries. As a result, firefighters can spend more time in substantial risk environment, saving precious lives and reducing damages caused by fire without injuring themselves [10][11][12][13]. Thermal protective performance test determines how well a fabric protects firefighter against second degree burns in case of flash fire. Thermal protective performance is evaluated by several tests like bench scale test (Heat guard plate, TPP tester) [6][7][14][15][16][17] or full scale test methodology like thermal manikin [18][19]. Moreover, properties like thermal conductivity and water vapor resistance can be evaluated by sweat guard hot plate method employing skin model as per ISO standard 11092 [19] and permeation of air of multilayer protective clothing on bench scale can be evaluated by Air permeability tester. Apart from those equipments, if size of sample is small or cutting of the sample is not permitted, equipment like Alambeta and Permetest can also be employed to evaluate thermal resistance, thermal conductivity and water vapor permeability respectively. The protective property of clothing materials against radiant heat can be measured according to ISO 6942 EN 366 [10][17][20][21][22][23].

2. Purpose and aim of the thesis

1. Evaluation of thermal insulation properties of firefighter clothing specimens.
2. Improvement in thermal insulation properties of firefighter protective clothing with the help of aerogel blanket.
3. Effect of metallic coating on thermal protective performance of firefighter clothing specimens keeping in view the breathability and flexibility of specimens.
4. Impact of metallized coating on emissivity of firefighter clothing specimens and influence of washing on thermal protective performance of both uncoated and silver coated specimen.
5. Implementation of Numerical model for prediction of temperature distribution for both uncoated and silver coated specimen.

3. Overview of the current state of the problem

Scientists are making lot of attempts for the enhancement of thermal protective performance of firefighter clothing. There are several approaches for incrementing thermal protective performance of firefighter protective clothing i.e.

i. By increasing thickness of firefighter protective clothing [24][25].

The thickness of fabric has significant impact on thermal behavior of textile substrate. This might be due to reason that increment in thickness of textile substrate influence the porosity of fabric due to consequent enhancement in fabric volume [26]. However, if increase in thickness can cause significant increase in corresponding weight of textile substrate, it might make thermal protective performance counterproductive[27].

ii. By increasing air gaps between different layers of protective clothing [28]

The other approach is to increase the thickness of air gap to certain degree for increasing thermal protective capability of firefighter protective clothing (FFPC) owing to good thermal insulation property of static air. However, the size limit of air gap between layers is very critical otherwise it may result into natural/forced convection reducing thermal insulation property FFPC assembly.

iii. By application of Phase change materials to thermal barrier of firefighting clothing specimens [29].

In recent years, scientists are employing Phase change materials (PCMs) on thermal barrier for increasing thermal protective performance of FFPC. PCMs provide protection from heat in passive way by absorbing heat from external heat flux [29]. Furthermore, the impact of phase change materials (PCMs) was for very short duration of time.

iv. By Lamination of Aluminum foil on outer surface of firefighter protective clothing [30]

For thermal stability and better thermal protective performance, Aluminum foil was employed on outer surface of firefighter clothing especially when they are subjected to high radiant heat flux density. However, this might cause issues in breathability of the firefighter protective clothing [30].

4. Alternate methodologies

To overcome this issue scientists are trying their level best to find some appropriate solutions by utilizing some alternate insulating materials or flame/heat resistant coating stuff for improvement of thermal protective behavior. For the last ten years, aerogel based insulating substrates are being used in applications like aerospace, defence and construction. Among all these aerogels, silica based aerogels have remarkable insulation and flame proof properties. Silica based aerogel is hydrophobic substrate having porosity greater than 90 percent and specific surface area of nearly 1000 m^2/g. The thermal conductivity of silica based aerogel is approximately 0.015 [W/(m.K)][31][32]. All of these characteristics make silica based aerogels a favorable candidate for utility in firefighter protective clothing as thermal barrier. Silica based aerogels are available on commercial basis as Nanogel particles by Cabot corporation and as aerogel blankets by Aspen aerogel [32] [33].

For enhancing thermal protective performance, metallic foil of Aluminum bonded to outer shell of firefighter protective clothing are utilized because of good reflective property, inflammable nature and high melting point [30]. A significant improvement in TPP was witnessed but at the expense of breathability as exterior shell was totally covered with metallic foil. Consequently, scientists come with the idea of utilizing metallic particles for coating of textile substrate which can improve thermal protective performance without having significant difference in air permeability and water vapor permeability. Metallic particles of silver, aluminum oxide and titanium dioxide have high melting point and good reflective property. For impregnation of these particles on textile substrate, a physical vapor deposition (PVD) technique called magnetron sputtering was employed. In case of metallic particles, silver is one of the metals which have high melting of 962^{o}C along with outstanding reflective property [34][35]. In consequence, silver particles can be a good prospect for utilizing as deposition layer on exterior side of outer shell. As a result, the layer of coating is certain micrometer thick, and unlike PCM [29], the impact for enhancement might be witnessed for longer duration of time and arrangement of clothing assembly was easy as compared to that of arrangement of clothing assembly involving increment of air gap size.

5. Equipment used for testing

5.1 Sweating Guarded Hotplate

Sweating guarded hot plate M259 B by SDL Atlas company was employed to evaluate thermal resistance R_{ct} [m^2K/W] and water vapor resistance R_{et} [m^2Pa/W] of textile substrate in steady state conditions. Sweating guarded hot plate works on principle of “skin model”. This instrument work as per standard of ISO 11092 [36].

5.2 Air permeability

Air permeability tester FX 3300 Labotester III (Textest Instruments) was utilized to evaluate air permeability as per CSN EN ISO 9237 standard. The test pressure was maintained at 200 pascals on an area of 20 cm^2 ($l/m^2/sec$) [10][37]

5.3 Radiant heat transmission machine

ISO 6942 method B was used to evaluate transmission of heat through the material of single layer or multi-layer assembly. The size of specimen was 230 mm × 80 mm and shall be taken from the area more than 20 mm away from the edge of the textile substrate and must not have any defects. All the specimens must be conditioned for at least 24 hours at temperature of 20°C and have relative humidity of 65 percent. The test shall be performed in room which must be free from any current of air. The temperature of room shall be maintained between 15 °C and 35 °C [38]. 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 as shown in figure 1. The face of calorimeter shall be coated with thin film of an optically black paint. Heating arrangement consist of six carbide rods, a moving frame assembly constantly cooled by water flowing in cooling pipes along with movable screen. At first, calibration is performed when moveable screen is withdrawn and reverted to point when rise of temperature was reached to 30 °C and incident heat flux density Q_o is measured.

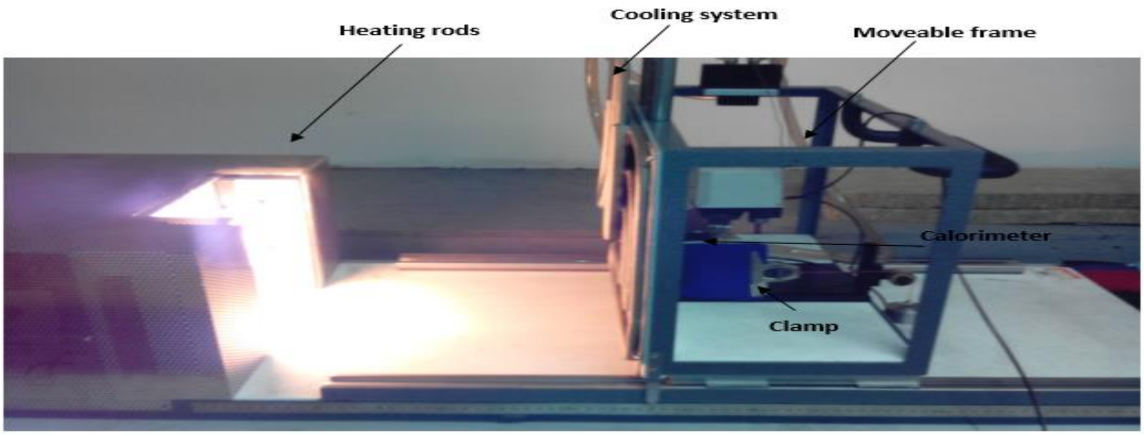


Figure 1: *Radiant heat flux density machine*

Afterwards, specimen is affixed to one side plate of specimen holder and held in contact with the face of the calorimeter, applying a mass of 200 g. The movable screen is withdrawn, and the starting point of the radiation is recorded. The movable screen is returned to its closed position after a temperature rise of about 30 °C has been reached. The 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 (*percentage TF* Q_o) and transmitted heat flux density Q_c. At least three specimens must be tested to get the average value of transmitted flux density Q_c [38].

Incident heat flux density is evaluated by following equation.

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

R = rate of rise of the calorimeter temperature in the linear region in $^oC/s$, M= Mass of copper plate in kg, C_p = Specific heat of copper 0.385 kJ/Kg ^oC, a = the absorption coefficient of the painted surface of calorimeter, A = Area of the copper plate in m^2

The transmitted flux density, Q_c in kW/m^2 is evaluated by the following equation:

$$Q_c = \frac{M C_p}{A} \times \mathrm{K} \quad (2)$$

$$K = \frac{12}{(RHTI\ 24 - RHTI\ 12)} \quad (3)$$

K = Rate of rise of the calorimeter temperature in $^oC/s$ in the region between a 12^oC and 24 ^oC rise.
RHTI 12 = threshold time in [sec] when temperature of calorimeter increases in 12^oC.
RHTI 24 = threshold time in [sec] when temperature of calorimeter increases in 24^oC [38].
Equation 4 delivers percentage transmission factor *[%] TF* Q_o for incident heat flux density level Q_o

$$[\%]\ TF\ Q_o = 100.\frac{Q_c}{Q_o} \quad (4)$$

5.4 Scanning Electron Microscopy

Scanning electron microscopy is utilized to study surface morphology of firefighter specimens inculcating silver deposited layers. SEM micrographs are taken by using Zeiss Ultra plus scanning electron microscope [39].

5.5 Stiffness / Bending moment

TH-4 (Tuhomer) was employed to evaluate the bending moment of uncoated and silver coated firefighter protective clothing specimen. This instrument evaluates the bending moment of textile substrates by CSN 80 0858 standard. The size of specimen was 5 cm × 2.5 cm [40]. Bending properties describes stiffness of fabric. Stiffness is the ability of material to resist deformation when force is applied on it. The instrument TH-4 measures force required to bend specimen by 60 degree. This can be explained by following equation:

$$M_o = F \times K \quad (5)$$

M_o is the bending moment [mN.cm]
F is the force applied in mN
K is constant whose value is 0.52[40]

5.6 Emissivity

Emissivity of specimen was evaluated by ASTM E 1933 – 99a standard (non-contact method) through Fluke Ti 25 Infrared camera [41]. Emissivity is the radiant energy emitted from surface of normal object to that emitted by black body at same temperature.

$$\varepsilon = \frac{W_{obj}}{W_{bb}} \tag{6}$$

Where W_{obj} is the energy emitted from surface of object and W_{bb} is the energy emitted from black body [42].

5.7 Washing

Washing was done in Miele washing machine in accordance with NFPA 1851 standard. The temperature was maintained at 30 ºC along with 400 RPM for two hours and 10 minutes [43].

6. Research Methodologies

For investigation of thermal protective performance of firefighter protective clothing, different type of research studies are performed, which are as under:

I. Improvement in thermal insulation properties of firefighter protective clothing with the help of aerogel blanket
II. Effect of metallic coating on thermal protective performance, emissivity, washing resistance, breathability and flexibility of firefighter protective clothing specimen

6.1 Improvement in thermal insulation properties of firefighter protective clothing with the help of aerogel blanket

In this experimental work, improvement in thermal insulation properties of firefighter protective clothing with the help of aerogel blankets. Aerogel layer was used as substitute layer to thermal barrier. Two different outer shells, one moisture barrier and one thermal liner were employed as stated in table 1. Four different combinations of clothing assemblies were prepared as mentioned in table 2 respectively.

Table 1: *Specifications of multilayer clothing arrangement*

Layer	Fabric Code	Component	Weave type	Fabric weight [g/m^2]	Thickness [mm]
Outer layer 1	O(1)	75 %Nomex-23% Kevlar -2 %Antistatic P-140	Twill	240 ±2.4	0.84±0.02
Outer layer 2	O(2)	Proban (100 % cotton)	Twill	300 ± 3.4	0.98±0.02
Moisture barrier	M	PTFE membrane laminated to non woven Nomex	Nonwoven	128 ± 1.5	0.94±0.01
Thermal liner	T	Liner:50/50 Nomex /FR Viscose Thermal part: Para-aramid	Nonwoven	380 ± 2.9	3.424±0.03

Aerogel blanket	P	Silica based aerogel emebedded in oxidized polyacrylonitrile nonwoven sheet	Nonwoven	400 ± 3.5	2.85±0.02

Table 2: *Combinations of clothing assemblies*

Sr #	Fabric arrangement in multilayer clothing assembly	Fabric Code	Thickness (mm)	GSM (g/m^2)
1	Outer shell (1) + Moisture barrier+ Thermal liner	A	5.20 ± 0.05	748 ± 3.1
2	Outer shell (2) + Moisture barrier + Thermal liner	B	5.34 ± 0.07	808 ± 3.5
3	Outer shell (1) + Moisture Barrier + Aerogel sheet	C	4.63 ± 0.06	768 ± 2.9
4	Outer shell (2) + Moisture Barrier + Aerogel sheet	D	4.77 ± 0.04	828 ± 2.8

Temperature on surface of fabric when placed at certain distance from heating source is given by following table.

Table 3: *Incident temperature on surface of specimen when exposed to different heat flux density*

Heat flux density	10 kW/ m²	20 kW/ m²	30 kW/ m²	40 kW/m²
Incident temperature on surface of specimen	220 ºC	292 ºC	390 ºC	495
Distance of specimen from heating source	37.1 cm	25.1 cm	19.7cm	16.5 cm

The main purpose of this experimental work was to enhance thermal protective performance of firefighter protective clothing. For this purpose four combinations of high performance fabrics were made. Each corresponding combinations were characterized by Sweating guarded hot plate. Afterwards, these combinations were evaluated by X637 B machine (ISO 6942 standard) for determining transmission of heat through multilayer protective clothing assemblies at 10 kW/m^2, 20 kW/m^2, 30 kW/m^2 and 40 kW/m^2 to evaluate the thermal protective performance in terms of transmitted flux density Q_c and percentage transmission factor (percentage TF Q_o).

6.2 Effect of metallic coating on thermal protective performance, emissivity, washing resistance, breathability and flexibility of firefighter protective clothing specimen

In this research, outer shell of firefighter clothing was coated with silver particles through magnetron sputtering. Each specimen combination consists of three layers i.e. outer layer, moisture barrier, thermal barrier. The exterior portion of outer layer of each specimen was coated with silver particles at 1 μm, 2 μm and 3 μm thickness. There are 4 different combinations and their specification along with arrangement is mentioned in table 4 and table 5 respectively.

Table 4: *Specification of samples*

Sr #	Name of Sample	Code	Material specification	Weave Design	Fabric weight [g/m^2]	Thickness [mm]
1	Outer shell	O	70% Conex, 23 % Lenzing FR, 5% Twaron, 2 % Beltron	Rip stop	225 ± 2.1	0.44±0.01
2	Outer shell (1 μm thickness)	O (1)	70% Conex, 23 % Lenzing FR, 5% Twaron, 2 % Beltron	Rip stop	234± 1.8	0.441±0.02

3	Outer shell (2 μm thickness)	O (2)	70% Conex, 23 % Lenzing FR, 5% Twaron, 2 % Beltron	Rip stop	246 ± 2.2	0.442±0.03
4	Outer shell (3 μm thickness)	O (3)	70% Conex, 23 % Lenzing FR, 5% Twaron, 2 % Beltron	Rip stop	255 ± 2.1	0.443±0.02
5	Moisture Barrier	MB	Face fabric, 50 %/50 % Kermel / viscose FR, PTFE membrane	Non-woven	120 ± 1.8	0.55±0.01
6	Thermal Lining	TB	Thermal: Para Aramid Inner futter: 50% Meta aramid, 50% viscose	Non-woven	200 ± 2.3	1.8±0.02

Table 5: *Arrangement of Fabric assemblies along with their code*

Sr #	Fabric assembly	Fabric code	Fabric weight [g/m^2]	Thickness [mm]
1	Outer shell (O) + Moisture Barrier (MB) + Thermal barrier (TB)	A	545 ± 3.1	2.79±0.01
2	Outer shell (O1) + Moisture Barrier (MB) + Thermal barrier (TB)	A1	554 ± 3.5	2.791±0.02
3	Outer shell (O2) + Moisture Barrier (MB) + Thermal barrier (TB)	A2	566 ± 2.9	2.792±0.03
4	Outer shell (O3) + Moisture Barrier (MB) + Thermal barrier (TB)	A3	575 ± 2.7	2.793±0.03

6.2.1 Coating of Samples through Magnetron Sputtering

Magnetron sputtering is physical vapour deposition process, where magnetically confined plasma is generated near the surface of target metal. Highly energetic ions with positive charge collide with surface of negatively charged target metal. As a result, atoms are ejected from the target material which then deposit on surface of substrate. Magnetron sputtering employs strong magnetic field to confine electrons near surface of target material (metal). In consequence, efficiency of ionization process and deposition rate is enhanced and plasma is created at lower pressure [44][45].

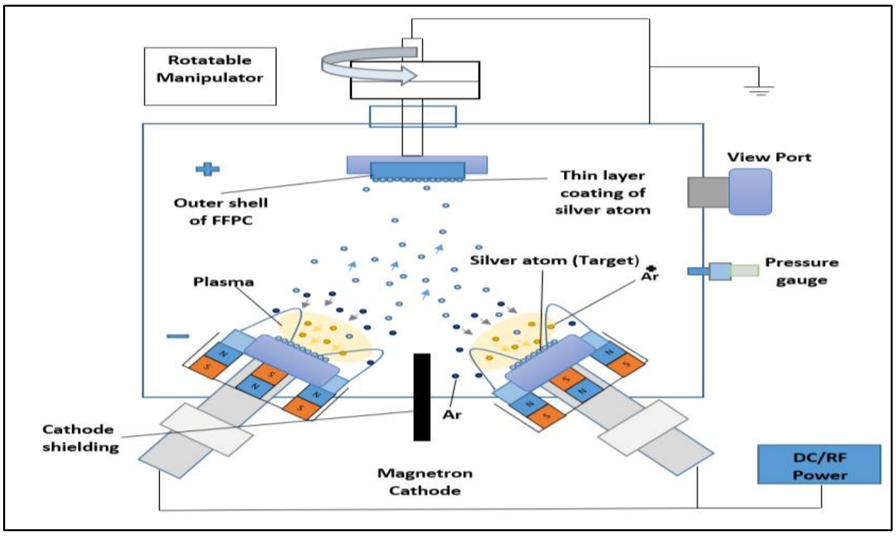
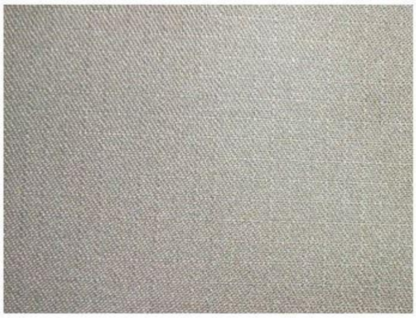


Figure 2: *Schematic diagram of magnetron sputtering* [46]

At first deposition chamber was evacuated at 4 Pascals. The distance between specimen holder and target was maintained at 15 cm. Later on, these specimens were placed in Physical Vapor

Deposition (PVD) chamber. The silver particle layer was acquired by sputtering of pure 99.99 % silver (*Ag*) in the presence of 100 % Argon gas floating at speed of 10 sccm (standard cubic centimeter per minute). At the time of sputtering, the working pressure was maintained at pressure of 1.3 Pascals. The power of magnetron supply was maintained at 615 watt and negative substrate bias voltage was maintained at 300 volts. Physical appearance of uncoated and silver coated specimen after magnetron sputtering is shown in figure 3.

a



b

Figure 3: *Physical appearance of (a) uncoated specimen and (b) silver coated specimen*

All the uncoated and silver coated specimens were then characterized on air permeability tester, Permetest and radiant heat transmission machine. Afterwards, bending moment, emissivity and reflectivity values were evaluated and thermal protective performance was evaluated before and after washing

7. Results and Discussion

7.1 Improvement in thermal insulation properties of firefighter protective clothing with the help of aerogel blanket

Thermal resistance values were evaluated by Sweating guarded hot plate for monolayer and multilayer protective fabric assemblies and their comparison was made in figure 4. Thermal resistance R_{th}, of textile substrate is a function of the actual thickness of the textile fabric and its thermal conductivity. This relationship is given by following equation:

$$R_{th} = \frac{h}{\lambda} \qquad (7)$$

R_{th} is thermal resistance [m^2K/W], where h is thickness of textile substrate. This thermal resistance is inversely proportional to thermal conductivity λ [25]. Thermal conductivity and thermal resistance are not only contingent on thickness of the fabric assemblies and but also on physical and chemical properties of textile substrate [47]. Greater the thickness, greater will be the thermal resistance of the material [48]. However, this is not only the whole scenario, the porosity and density of the textile substrate also plays a vital role in thermal behavior of the medium [48].

Textile materials with closed and small pores are able to trap air inside the substrate. The illustration of this phenomenon is the due to fact that air has a lower thermal conductivity than materials constituting the sample [48]. On the other hand, thermal conductivity enhances with the relative humidity absorbed by the material [49]. Consequently, the thermal conductivity of highly hygroscopic material is more as compared to less hygroscopic substrate.

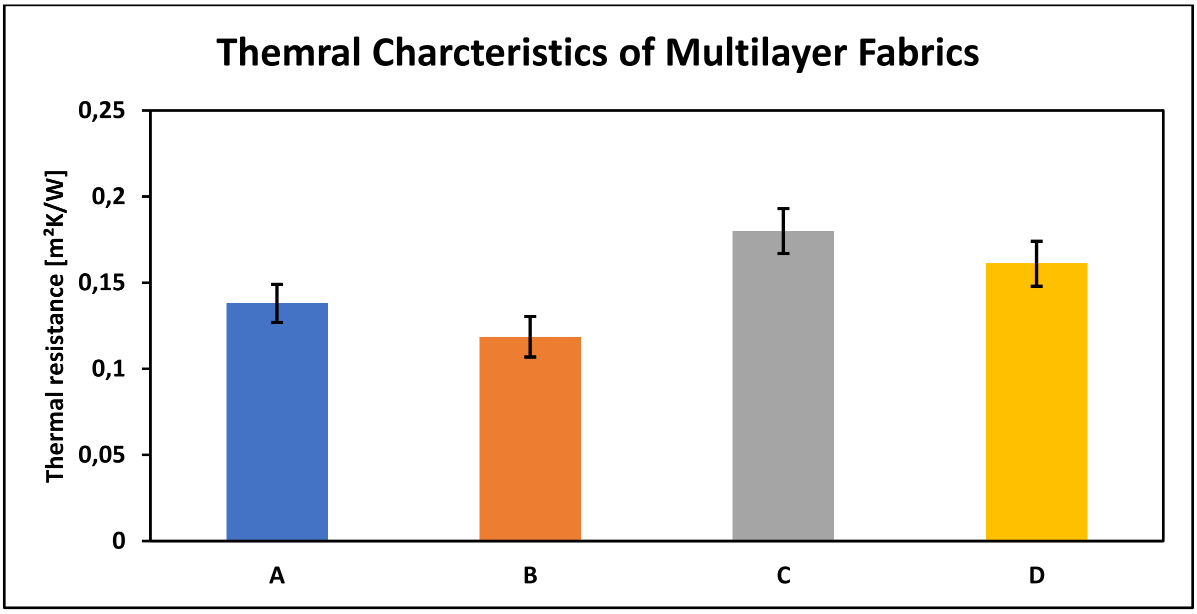


Figure 4: *Thermal conductivity and thermal resistance values of multilayer protective clothing*

From figure 4, it can be noted that a high value of thermal resistance was witnessed in arrangement of multilayer protective clothing having aerogel layer as an alternate to thermal liner (sample *C* and *D*). There might be several reasons. One reason might be that this substitute layer encloses silica based aerogel which has very less thermal conductivity even lower than still air. By means of mass, aerogel is 96 % of air making it least dense man-made substrate [54]. Because of porosity and nanometer pore size, silica based aerogels are highly insulating materials and transmit low thermal energy [50][51][52][53]. In addition to that, convective heat transfer is deterred because construction of aerogel does not allow circulation of air [51][53] .

7.1.1 Evaluation of water vapor resistance

Water vapor resistance R_{et} (m^2Pa/W) was determined by Sweating guarded hot plate equipment. Barker et al mentioned that the influence of moisture on thermal protective performance is a function of exposure conditions, amount of moisture in the turnout system and its permeability and insulation properties [55]. The type of fibers plays a key role in moisture vapor permeability. A careful analysis of figure 5 revealed that more water vapor resistance was witnessed in *specimen C* and *D* utilizing aerogel blanket as compared to specimen *A* and *B*. This might be due to hydrophobic nature of aerogel and presence of closed pores inside the structure of aerogel blanket [50][51][52][53][56].

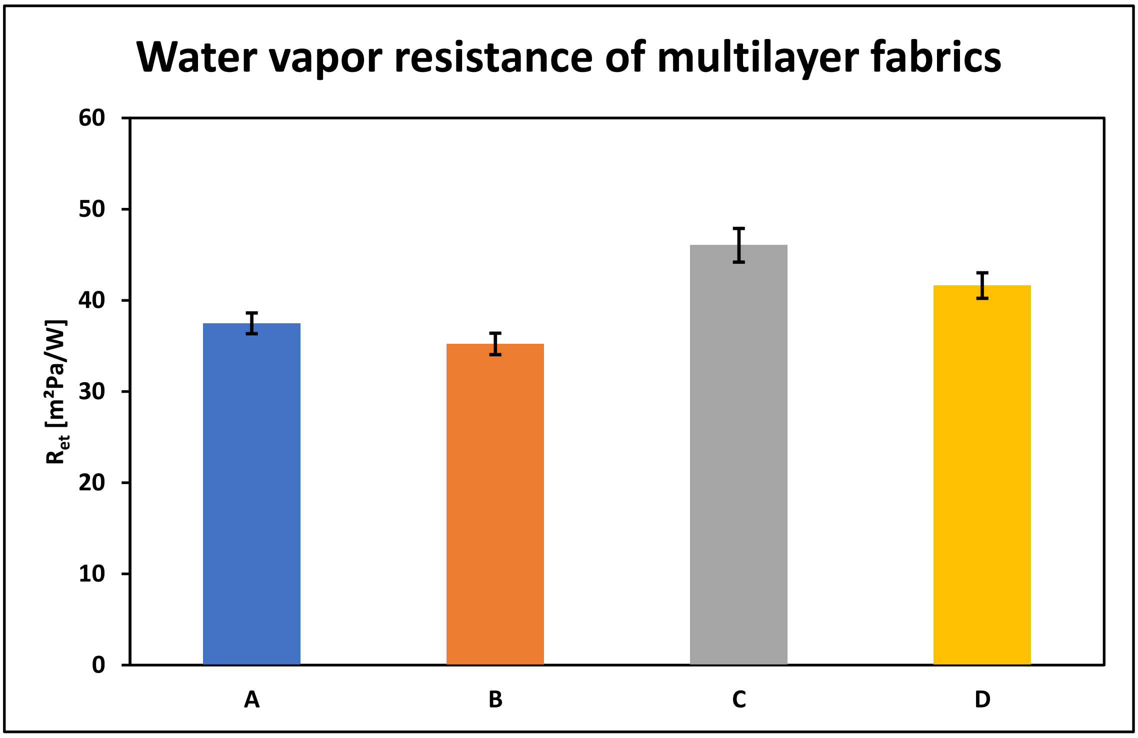


Figure 5: *Water vapor resistance of multilayer protective clothing*

7.1.2 Transmission of radiant heat flux through multilayer protective clothing

Different values of transmitted heat flux density, percentage transmission factor and Radiant heat transmitted index values are shown in table 6. These values were evaluated from radiant heat transmission machine.

Table 6: *RHTI 12 and RHTI 24, Q_o, Q_c and percentage TF Q_o through multilayer firefighter protective clothing specimen*

Sr #	Name of material	Q_o [kW/m²]	RHTI12	RHTI24	RHTI24-RHTI12	Q_c [kW/m²]	Percentage TF Q_o
1	P		54.55 ± 2.828	102.6 ± 2.969	48.05	1.36±0.006	13.6
2	A		58.2 ± 0.424	101.0 ±, 0.015	42.8	1.55±0.014	15.5
3	B	10	74.1±.707	128.65 ± 2.757	54.55	1.212±0.045	12.1
4	C		84.55 ± 0.777	163.35 ± 3.181	78.8	0.839 ± 0.026	8.3
5	D		97.4±6.929	195 ± 2.5738	97.6	0.677±0.132	6.7
1	P		33.25 ± 5.727	54.15 ± 8.273	20.9	3.164 ± 0.390	15.8
2	A		36.7 ± 0.989	57.05 ± 1.343	20.35	3.249±0.056	16.2
3	B		46.7±6.081	58.55 ± 6.293	11.85	5.580±0.100	27.9
4	C	20	44.6 ± 0.457	70.8 ± 2.596	26.2	2.524±0.050	12.6
5	D		58.15±.919	79.956 ± 1.484	21.806	3.033±0.079	15.1
1	P		33.3 ± 0.141	48.75 ± 0.353	15.45	4.280 ± 0.058	14.2
2	A		27.85 ± 0.070	40.35 ± 0.494	12.5	5.290±0.181	17.6
3	B	30	31.4±2.121	38.15 ± 2.474	6.75	9.79±0.516	32.6
4	C		41.5 ± 1.272	61 ± 2.969	19.5	3.391±0.297	11.3
5	D		44.15±1.626	59.8 ± 1.272	15.65	4.225±0.096	14.0
1	P		25.9 ± 0.172	36.1 ± 0.452	10.2	6.522 ± 0.154	16.3
2	A		24.8 ± 0.258	31.3 ± 0.389	6.5	10.235 ± 0.245	25.9

3	B	40	23.7 ± 0.121	28.9 ± 1.35	5.2	12.794 ± 0.489	32.4
4	C		41.4 ± 1.378	57.1 ± 1.14	15.7	4.237 ± 0.354	10.7
5	D		38.2 ± 1.48	52.2 ± 1.25	14	4.752 ± 0.158	11.88

A perusal of table 6 reveals that values of transmitted heat flux density Q_c and percentage Transmission factor *(percentage TF Q_o)* increases sequentially with increase in level of incident heat flux density. It was also noted that minimum values of transmitted flux density Q_c *(kW/m^2)* were observed for the samples having aerogel blanket *(P)* as thermal liner. A similar pattern was also noted in *percentage TF Q_o* values for the specimen having aerogel sheet *(P)*.This might be due to fact that silica based aerogel blanket contains almost 96 percent of air and air is a good insulator blocking the amount of heat passed through the specimen [54]. Moreover, these aerogel samples consist of oxidized polyacrylonitrile polymer which have very good thermal stability and can withstand higher amount of heat flux [57]. The lower the value of transmitted heat flux density, the lesser will be amount of heat passed through fabric assemblies towards calorimeter allowing more time to firefighter to perform their duties before acquiring burn injuries. Table 6 also depicts that greater difference between *RHTI 24* and *RHTI 12,* lesser will be the value of transmitted flux density Q_c *(kW/m^2)* and *percentage TF Q_o* respectively, 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. At 10 kW/m^2, the lowest values of Q_c and *percentage TF Q_o* were witnessed for *specimen C* and *D* utilizing aerogel blanket *(P)*. These values were higher for *specimen A* and *B* having no aerogel blanket. It was also noted that there was minor difference in the values of Q_c and *percentage TF Q_o* values for aerogel sheet *(P), sample A and specimen B* respectively. At 20 kW/m^2, the situation was slightly different i.e. the Q_c and *percentage TF Q_o* values of *specimen B* was significantly higher than rest of the samples and negligible difference for the values of Q_c and *percentage TF Q_o* was witnessed for aerogel sheet *(P)*, *specimen A and specimen D* respectively. The lowest value of *percentage TF Q_o* and Q_c for 20 kW/m^2 was observed for *specimen C.* At 30 kW/m^2, a trend similar to that of 20 kW/m^2 was noted i.e. the least value of Q_c and *percentage TF Q_o* was observed for *sample C* and highest value was observed *sample B*. However, this time there was significant difference in values Q_c and *percentage TF Q_o* for *specimen A* and aerogel sheet *(P)*. At 40 kW/m^2, the orientation of Q_c and *percentage TF Q_o* values were not very different than those witnessed at 30 kW/m^2. *Specimen C* displayed least value of Q_c and *percentage TF Q_o* and again a pertinent differentiation in the values of Q_c and *percentage TF Q_o* for *specimen A* and aerogel blanket *(P)*.

A glance at figure 6 reveals that at 10 kW/m^2 the curve of *specimen D and specimen C* are much flatter as compared to the curves of *specimen B, specimen A* and aerogel layer *(P)* respectively. The flatter 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. However, there was no gap in the curves of aerogel blanket and *specimen A*, which have very close values of Q_c and *percentage TF Q_o*.

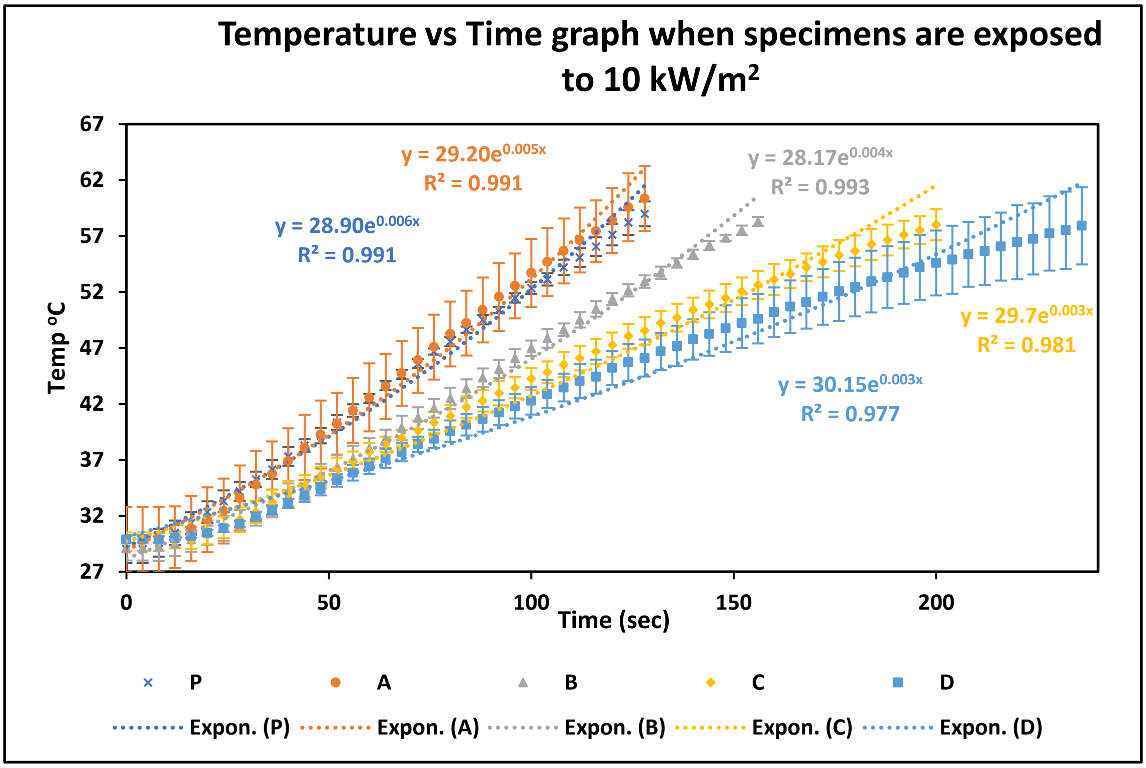


Figure 6: *Temperature of firefighter specimens with respect to time when specimens* exposed to 10 kW/m^2

Figure 6 also depicts clear gap between curves of *specimen B* and curves of *specimen A* and aerogel blanket *(P)*, which is also highlighted from the values of Q_c and *percentage TF* Q_o from table 6. *Specimen C* has improved thermal protective performance as comparison to *specimen A* in terms of radiant heat transmitted index *RHTI 24* by *61.7 percent*. Whereas *specimen D* has improved *RHTI 24* values in comparison with *specimen B* by *51.5 percent*. The maximum value of R^2 and best fitting curves of all specimens was achieved by exponential equations.

It can be witnessed from figure 7 that at 40 kW/m^2, *Specimen C* curve displays better thermal protective performance as compared to all other curves as curve of *specimen C* was flatter as compared to all curves of other specimen. Thus the fabric assembly having aerogel sheet *(P)* as alternate to thermal barrier has better thermal protective behavior as compared to other samples. This might be due to fact that Infrared radiation that plays a significant role in transference of heat can also be absorbed by aerogel [58][59][53] due to which aerogel blanket offers better thermal stability and insulation as compared to other specimens. *RHTI 24* values for *Specimen C* was increased as compared to *specimen A* by *82.4 percent*. In case of *Specimen D*, *RHTI 24* value was enhanced by *80.6 percent* in comparison with *specimen B*. The maximum value of R^2 and best fitting curves for all specimens was accomplished through exponential equations.

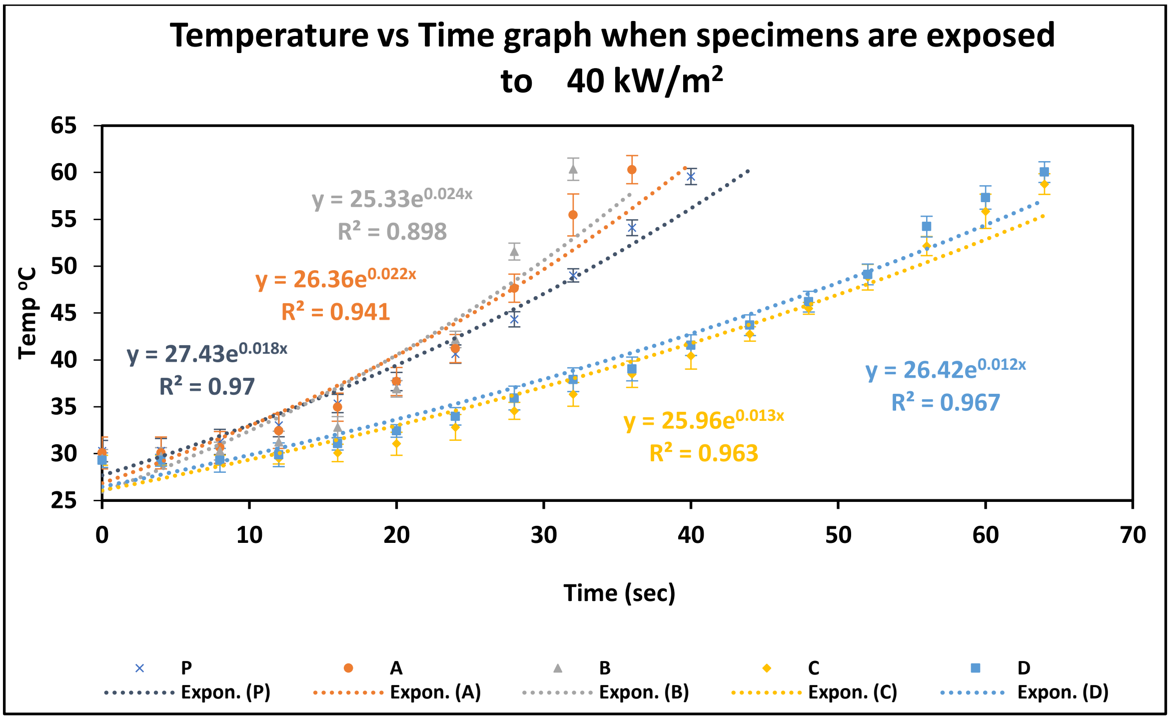


Figure 7: *Temperature of firefighter specimens with respect to time when specimens are exposed to 40 kW /m²*

7.2 Effect of metallic coating on thermal protective performance, emissivity, washing resistance, breathability and flexibility of firefighter protective clothing specimen

7.2.1 Water vapor Permeability

Permetest was utilized to determine Relative water vapor permeability and water vapor resistance of uncoated and silver coated specimens.

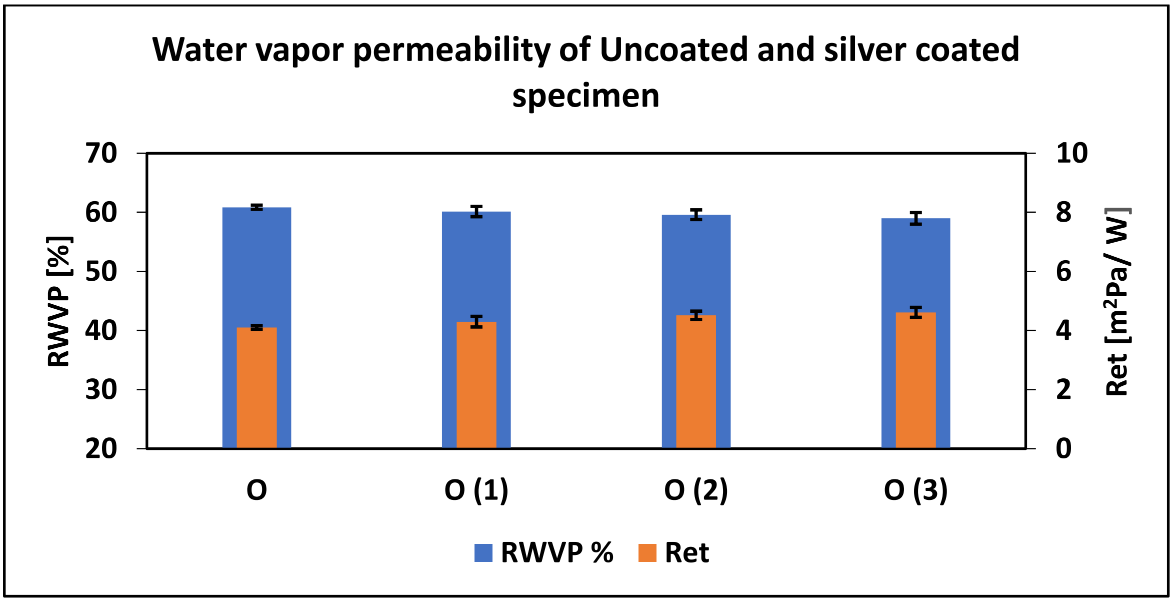


Figure 8: *Relative water vapor permeability percentage and Water vapor resistance of firefighter protective clothing specimen*

During operational activities, firefighter generates lot of sweat which must be evacuated. Therefore, the permeability of water vapor should not be neglected. From figure 8, it was revealed that that outer shell coated with deposition layer of silver particles have slightly less values of relative water vapour permeability percentage and slightly highly values of water vapour resistance. However, this difference was not very conspicuous, which indicates that after coating of silver particles, there is still permeation of water vapour through outer shells and porous structure is not completely blocked by coating of silver particles.

7.2.2 Transmission of radiant heat flux through multilayer protective clothing

The behavior of coated and uncoated specimen when subjected to respective heat flux densities are shown schematically in figure 9 a and 9b respectively.

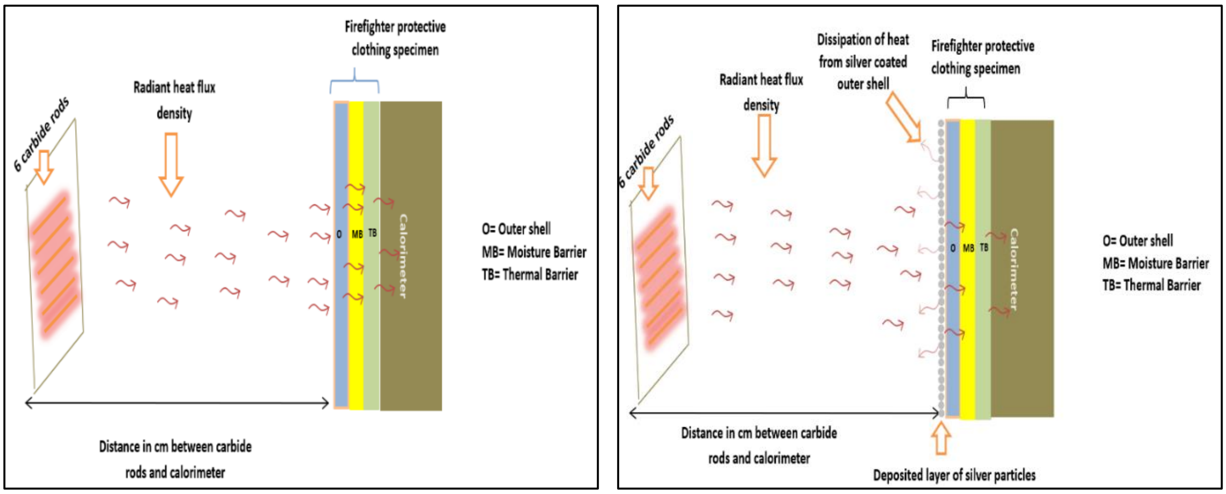


Figure 9: *a Uncoated sample* *b. silver coated specimen*

It is evident from figure 9a and 9b that uncoated specimen is transferring more amount of heat through specimen towards calorimeter and less amount of heat towards surrounding environment climate due to absence silver particle layers. In case of silver coated specimen, less amount of heat Q_c *[kW/ m²]* was transmitted via specimen towards calorimeter. Furthermore, greater amount of radiant heat flux density was dissipated to surrounding climate due to high reflective property of silver particles.

Table 7: *RHTI 12, RHTI 24, Q_c and [%] TF Q_o values of specimen when exposed to 10 kW/ m², 20 kW/ m², 30 kW/m² and 40 kW/m²*

Sr #	Specimen	Q_o [kW/ m²]	*RHTI 12* [sec]	*RHTI 24* [sec]	*RHTI24-RHTI 12* [sec]	Q_c [kW/ m²]	[%] *TF Q_o*
1	A	10	46.3 ± 0.94	77.2 ± 0.92	30.9	2.153 ± 0.001	21.6
2	A1	10	63.3 ± 0.86	110.5 ± 0.72	47.2	1.415 ± 0.003	14.2
3	A2	10	63.5 ± 0.72	113.6 ± 0.79	50.1	1.323 ± 0.001	13.3
4	A3	10	69.0 ± 0.73	124.3 ± 0.62	55.3	1.203 ± 0.002	12.1
1	A	20	28.6 ± 0.84	42.5 ± 0.86	13.9	4.786 ± 0.006	23.93
2	A1	20	35.6 ± 0.74	55.4 ± 0.89	19.9	3.343 ± 0.025	16.71
3	A2	20	35.8 ± 0.87	56.0 ± 0.91	20.2	3.293 ± 0.006	16.46
4	A3	20	37.5 ± 0.81	59.1 ± 0.75	21.6	3.080 ± 0.008	15.4

1	A	30	23.9 ± 0.93	33.2 ± 0.98	9.3	7.154 ± 0.038	23.84
2	A1	30	27.4 ± 0.82	38.9 ± 0.89	11.5	5.785 ± 0.035	19.28
3	A2	30	30.4 ± 0.75	42.5 ± 0.80	12.1	5.498 ± 0.022	18.32
4	A3	30	31.6 ± 0.82	44.2 ± 0.88	12.6	5.280 ± 0.024	17.6
1	A	40	19.3 ± 0.94	26.9 ± 0.89	7.6	8.754 ± 0.05	21.88
2	A1	40	25.2 ± 0.85	34.5 ± 0.88	9.3	7.154 ± 0.022	17.88
3	A2	40	26.1 ± 0.81	35.7 ± 0.79	9.6	6.930 ± 0.58	17.32
4	A3	40	27.7 ± 0.88	38.2 ± 0.91	10.5	6.29 ± 0.018	15.80

An overview of table 7 depicts that silver coated specimen *A1*, *A2* and *A3* have high *RHTI 12* and *RHTI 24* values and low values of transmitted heat flux density and percentage Transmission Factor *[%] TF* Q_o at 10 kW/m^2, 20 kW/m^2, 30 kW/m^2 and 40 kW/m^2 as compared to uncoated specimen. There was further decrease in the values of Q_c and percentage *TF* Q_o with the increase in thickness level of silver deposited layer on outer shell of firefighter protective clothing specimen. This might be due to fact that outer shell has coating of silver particles having high melting point and highly reflective property which not only slow down the amount of heat passing through the specimen but also reflect radiant substantial amount of radiant heat flux density. The lower the values of transmitted heat flux density Q_c *[kW/ m*^{2}*]* and percentage transmission factor, better will be thermal protective performance as less heat will be transmitted towards human body for given period and great time will be required for rise of temperature of 12 °C and 24 °C in the form of *RHTI 12* and *RHTI 24* allowing greater amount of time to firefighters to perform their duties without enduring injuries.

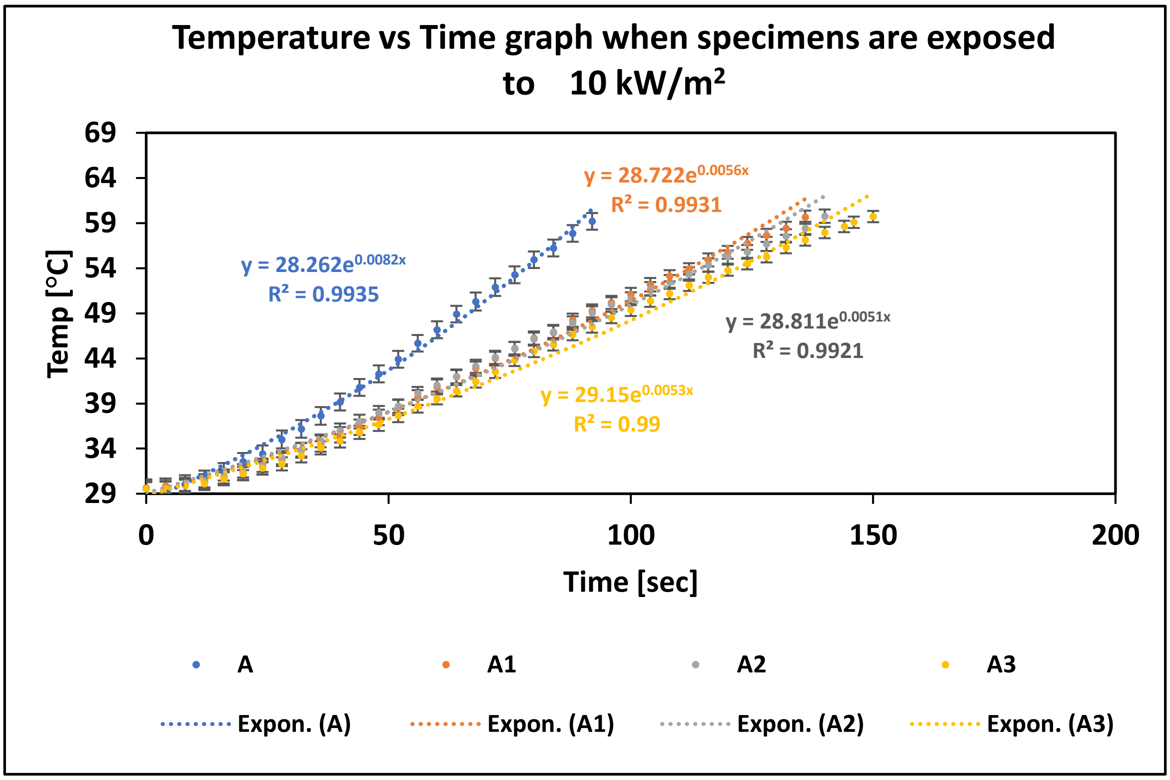


Figure 10: *Temperature of firefighter specimens with respect to time when specimens are exposed to 10 kW/m*^{2}

Figure 10 reveals that curves of all specimens were at same position till 15 seconds. Afterwards, curve of *sample A* started to move in upward position and a slight gap appeared between curve of *specimen A* and rest of specimen curve at 20 seconds which keep on increasing with the passage of time as the curve of *specimen A* becomes steeper than the rest of the curves. The curves of *specimen A1* and *A2* follow same path in almost superimposed position. After 100 seconds, the curve of *specimen A1* becomes slightly upward as compared to curve of specimen *A2* and it remains in upward position till end. The curve of *specimen A3* remains in flat position and gap between curves of *specimen A3* and *A2* started to widen off after 40 seconds and keep on widening till the end. *Specimen A1* has improved *RHTI 24* values with respect to *specimen A* by *43 percent* and highest value of R^2 along with best fitting curves were gained through exponential equations.

A glance of figure 11 reveals, that till first 5 s, all the curves of specimen *A, A1, A2 and A3* are very close to each other. Later on, the curve of specimen *A* moves upward and the gap of curve *A* increases against other curves with increase in time. Till initial 10 s, the curve of specimen *A1, A2 and A3* are neck to neck. Afterwards, the curve of specimen *A1* remains slightly upward and this gap increases with the passage of time. The curves of specimen *A2 and A3* were very close to each other till first 12 s and then curve of specimen *A3* remains in flat position for the rest of experimentation.

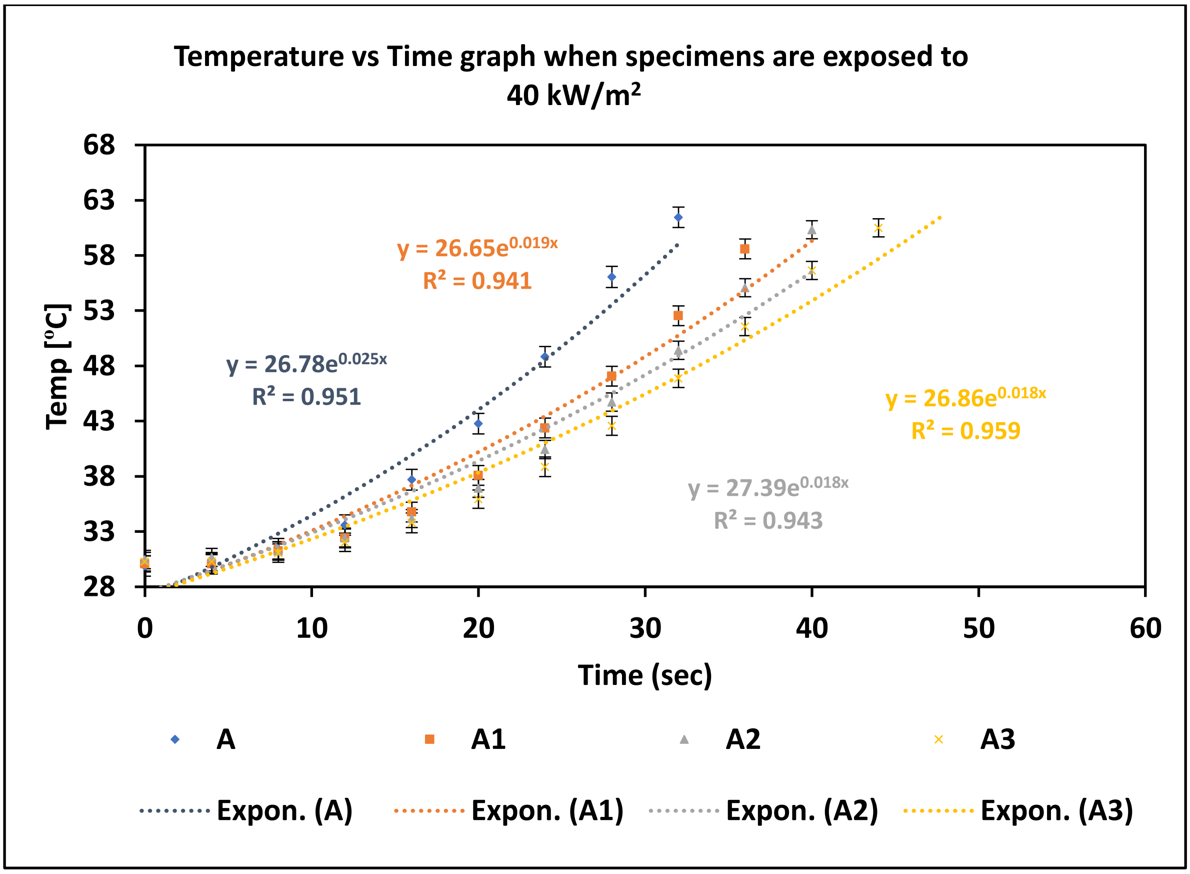
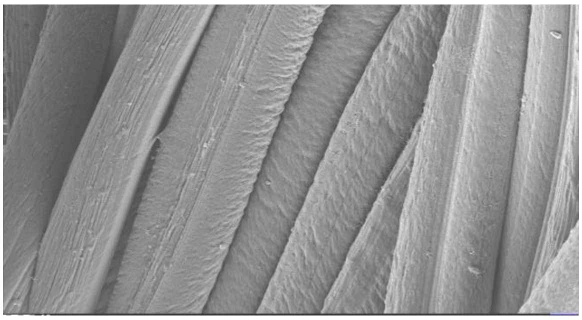


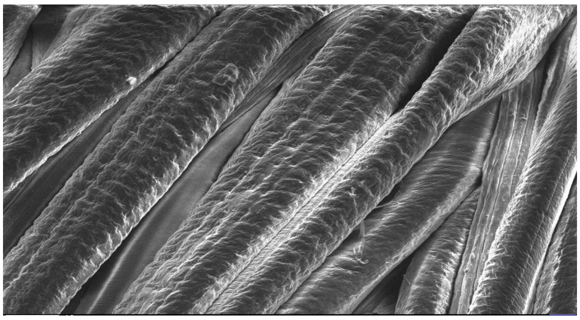
Figure 11: *Temperature of firefighter specimens with respect to time when specimens are exposed to 40 kW/m²*

7.2.3 Scanning Electron Microscopy

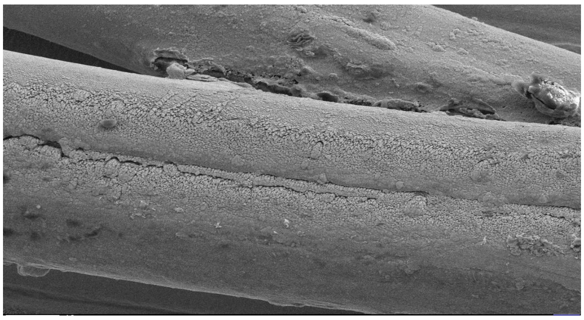
In order to determine impact of radiant heat flux density on surface morphology of uncoated and silver coated specimen, scanning electron microscopic images were taken.



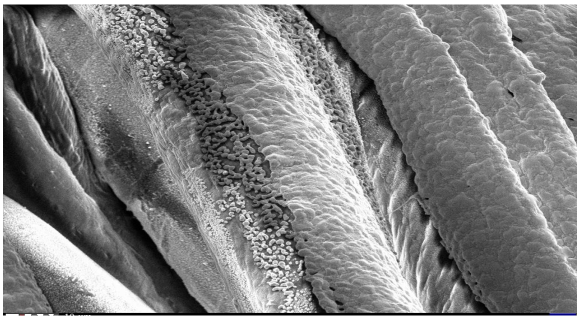
a. Uncoated specimen O



b. Uncoated specimen O exposed to 40 kW/m^2



c. 3 *um* silver coated specimen O3



d. 3 *um* silver coated specimen O3 exposed to 40 kW/m^2

Figure 12: *Scanning electron microscopy images of coated and uncoated samples*

From figure 12 b and d, it was noted that uncoated specimen on being exposed to 40 kW/ m^2 has much darker surface as compared to 3 μm silver coated specimen. This might indicates better thermal stability of silver coated specimen as this specimen is reflecting/dissipating incident radiant heat flux density to surrounding environment. Also in figure 12 d, the presence of silver particles can be witnessed even after exposure to 40 kW/m^2.

7.2.4 Stiffness/ Bending moment

The greater the bending force *F* required to bend the textile substrate at particular angle, greater will be the bending moment which ultimately results into greater stiffness of textile substrate. From above figure 13, it can be witnessed that with increase in thickness level of silver deposition layer, there was slight increase in bending moment values of silver coated specimen. This difference occurs due to coating of silver particles which eventually increase weight of outer shell due to which slightly greater amount of force was required to bend specimen through certain angle.

The greater the bending force *F* required to bend the textile substrate at particular angle, greater will be the bending moment which ultimately results into greater stiffness of textile substrate. From above figure 13, it can be witnessed that with increase in thickness level of silver deposition layer, there was slight increase in bending moment values of silver coated specimen. This difference occurs due to coating of silver particles which eventually increase weight of

outer shell due to which slightly greater amount of force was required to bend specimen through certain angle.

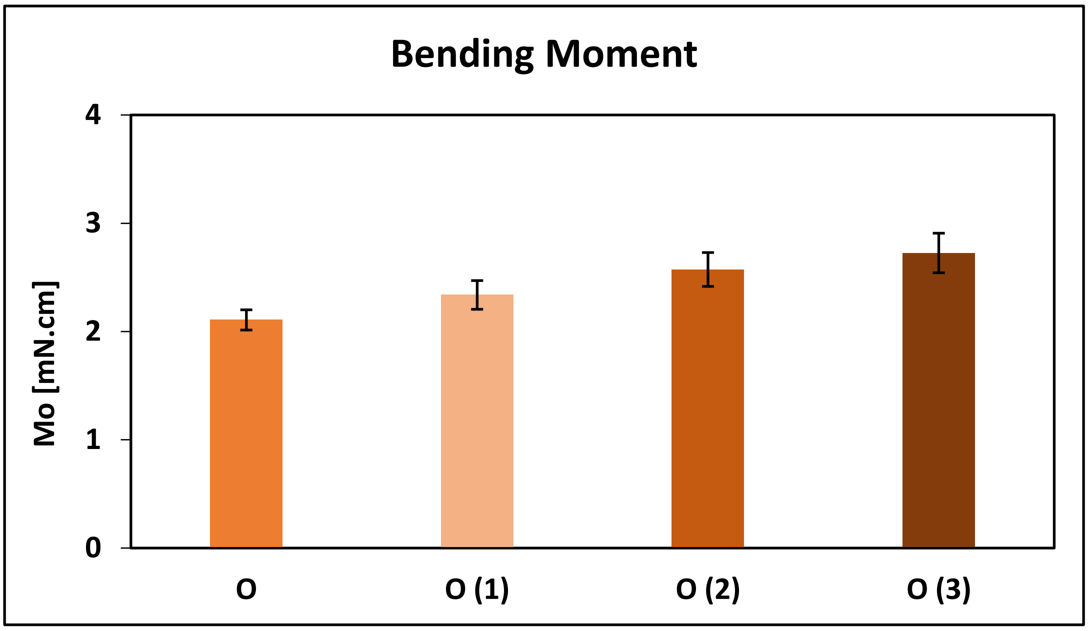


Figure 13: *Bending rigidity of uncoated and silver coated specimen*

7.2.5 Emissivity

Emissivity of surface depends not only on the material but also on the nature of surface i.e. polished and clean metal surface have low emissivity values as compared to rough, oxidized metal surface having high emissivity values. Emissivity is dimensionless number having values between 0 (perfect reflector) and 1 (perfect emitter). Emissivity is also dependent on temperature of surface along with its wavelength and angle. Understanding of emissivity is pertinent for non-contact temperature measurement and transmission of heat calculations.

Table 8: *Emissivity values of hot plate, uncoated specimen and silver coated specimen*

Hot plate	Uncoated specimen	Silver coated specimen
0.98	0.86	0.52

The brighter yellow color in the figure 14 shows emission of more thermal radiation and therefore have higher emissivity values. On the other hand, the light bluish dull colors depict less emissivity values and thus endure good reflective properties [60]. Figure 14 shows, silver coated specimen have good reflective property due to which it is able to dissipate greater amount of radiant heat flux density to surrounding temperature.

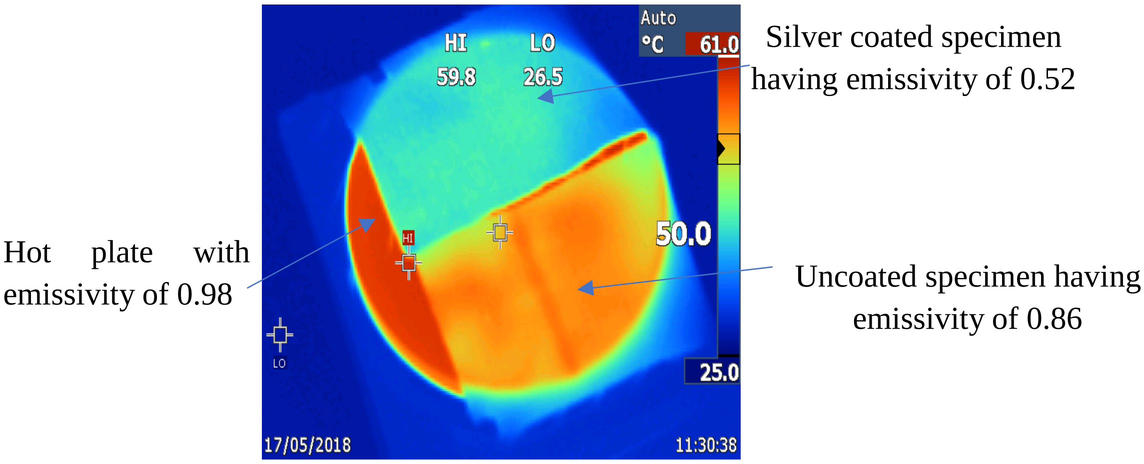


Figure 14: *Thermal images of hot plate, uncoated and silver coated specimen*

7.2.6 Thermal Protective Performance after washing

In order to investigate stability of metallic coating on surface of substrate, silver coated specimen were washed for five cycles as per NFPA 1851 standard [43]. Afterwards, their thermal protective performance was investigated at 40 kW/m^2. Comparison of Q_c and radiant heat transmitted index is shown in table 9.

Table 9*: RHTI 12, RHTI 24, Q_c and [%] TF Q_o values of specimen when exposed to 40 kW/m^2 before and after washing cycles*

Sr #	Specimen	Q_o [kW/ m^2]	*RHTI 12* [sec]	*RHTI 24* [sec]	*RHTI24-RHTI 12* [sec]	Q_c [kW/ m^2]	Percentage *TF Q_o*
1	A 1 (Before washing)	40	25.2± 0.79	34.5± 0.84	9.3	7.15±0.05	17.88
2	A1 (After one cycle)	40	24.12±1.01	33.3±1.16	9.18	7.20±0.117	18.00
3	A1 (After two cycle)	40	24.0 ±1.44	33.12±1.58	9.12	7.25±0.111	18.17
4	A1 (After three cycle)	40	23.8± 1.26	32.65±1.36	8.85	7.47±0.084	18.68
5	A1 (After four cycle)	40	23.5±1.74	32.32±1.84	8.825	7.49±0.085	18.73
6	A1 (After five cycle)	40	23.1±1.69	31.72± 1.79	8.625	7.66±0.089	19.16

From table 9, it was witnessed that silver coated specimen *A1* has slightly high value of *RHTI 12* and *RHTI 24* before washing. It was also observed that value of Q_c before washing for *A1* specimen was slightly low. With increase in number of washing cycle, value of *RHTI 12* and *RHTI 24* started to decline. On the other hand the value of Q_c, started to increment sequentially with increase in number of washing cycles. This might be due to slight deterioration of silver coated layer due to which there was slight decline in TPP of silver coated specimen after washing. A comparison was made for *RHTI 24* before and after washing in order to quantify decrease in *RHTI 24* for specimen A1 when exposed to 40kW/m^2 in figure 15.

It can be seen from figure 15 that there was 3.1 percent and 3.7 percent decline in *RHTI 24* values after one and two washing cycles respectively. However, after three and four washing cycles the decrease in *RHTI 24* was 5.6 percent and 6.03 percent. After five washing cycle there was almost 7.77 percent decrement in *RHTI 24*.

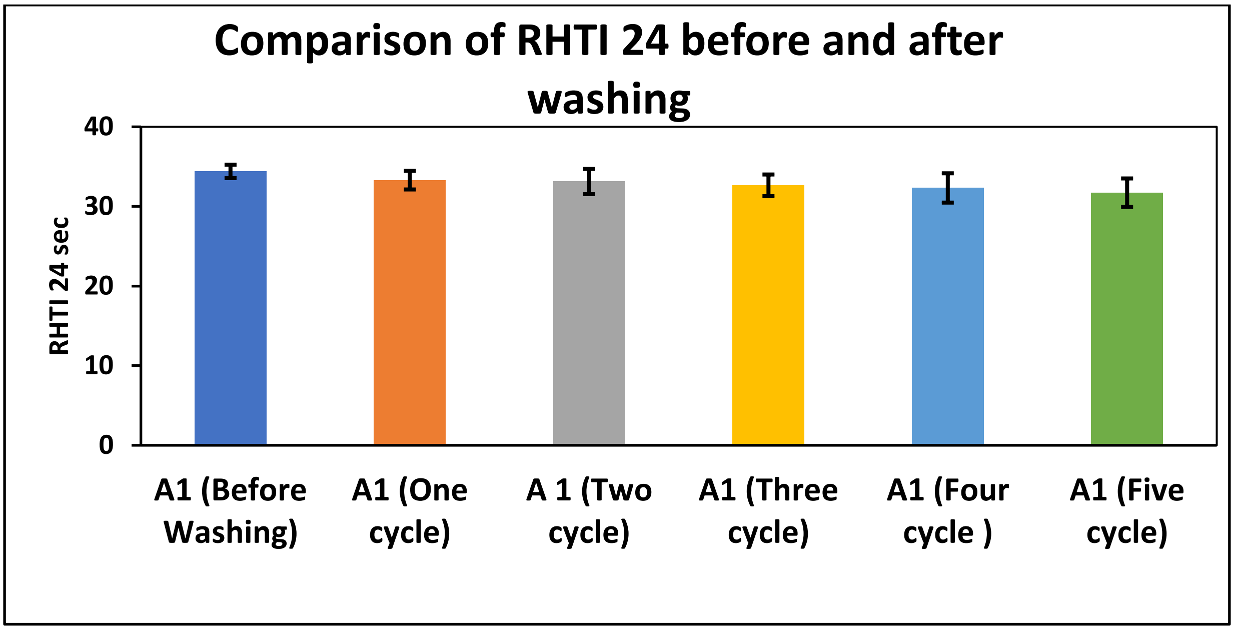
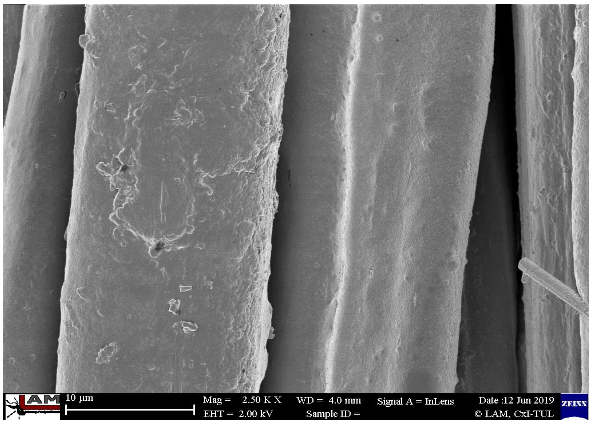


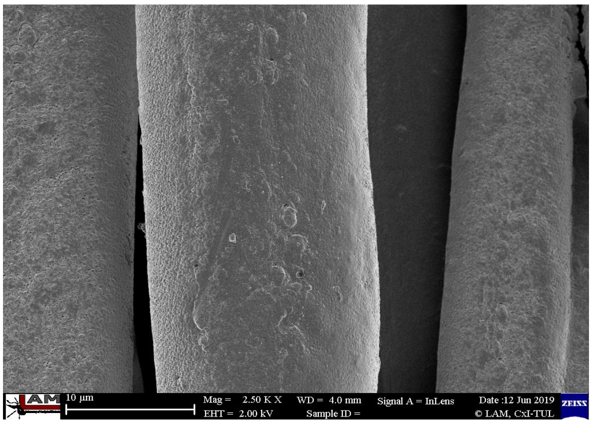
Figure 15: *Comparison of RHTI 24 before and after washing for specimen A1*

7.2.7 SEM images before and after washing

SEM images were taken for further verification of minor decrease in TPP.



a. SEM images of A1 silver before washing



b. SEM images of A1 after 5 washing cycle

Figure 16: *SEM images before and after washing*

It can be clearly seen From SEM images given in figure 16 b that there is retention of metal coating even after several cycles of washing. No evidence of substantial removal of silver coating was witnessed for specimen *A1* in figure 16 b respectively.

8. Numerical model for prediction of temperature distribution

This part of research deals with the Numerical model for prediction of temperature distribution at several positions along with thickness of uncoated and silver coated specimen at different intervals of time. Numerical model implemented by Su et al [61][62] was used with slight modification for estimation of temperature distribution in uncoated and silver coated firefighter protective clothing specimen. In the end, a comparison was made for uncoated and silver coated specimens for rate of rise in temperature at different positions with respect to time interval with the help of Numerical solutions. Radiant heat transmission equations mentioned by Su et al [61][62] and Torvi et al [63] were employed to illustrate radiant heat flux density transmitted towards the firefighter clothing assembly from heat source.

8.1 Specification of materials

The firefighter clothing specimens used in this study were consisted of outer shell, moisture barrier and thermal barrier. These specimens were provided by Vochoc Company, Czech Republic. The specifications of these specimens are given in table 10 below. The outer shell of these specimens was coated with 1 μm coating of silver particles through magnetron sputtering. Two arrangement of fabric assemblies as given in table 11 were made from these samples.

Table 10: *Specification of samples*

Sr #	Name of Sample	Code	Material specification	Weave design	GSM [g/m^2]	Thickness [mm]
1	Outer shell	O	70% Conex, 23 % Lenzing FR, 5% Twaron, 2 % Beltron	Rip stop weave	225±2.1	0.44±0.01
2	Outer shell (1 µm thickness)	O (1)	70% Conex, 23 % Lenzing FR, 5% Twaron, 2 % Beltron	Rip Stop Waeave	234±1.8	0.441±0.02
3	Moisture Barrier	MB	Face fabric, 50 %/50 % Kermel / viscose FR, PTFE membrane	Non-woven	120±1.8	0.55±.01
4	Thermal Barrier	TB	Thermal: Para Aramid Inner futter: 50% Meta aramid, 50% viscose	Non-woven	200±2.3	1.8±0.02

Table 11: *Arrangement of Fabric assemblies along with their code*

Sr #	Fabric assembly	Fabric code	Fabric weight [g/m^2]	Thickness [mm]
1	Outer shell (O) + Moisture Barrier (MB) + Thermal barrier (TB)	A	545±3.1	2.79±0.02
2	Outer shell (O1) + Moisture Barrier (MB) + Thermal barrier (TB)	A1	554±3.5	2.791±0.03

These specimens were exposed to a 10 kW/m^2 heat flux. In order to determine temperature distribution between multilayer clothing assembly, two K-type thermo couples were placed between outer shell and moisture barrier, and moisture barrier and thermal barrier as shown in Figure 17. Thermocouple 1 measures temperature of outer shell and thermocouple 2 measures temperature of the moisture barrier.

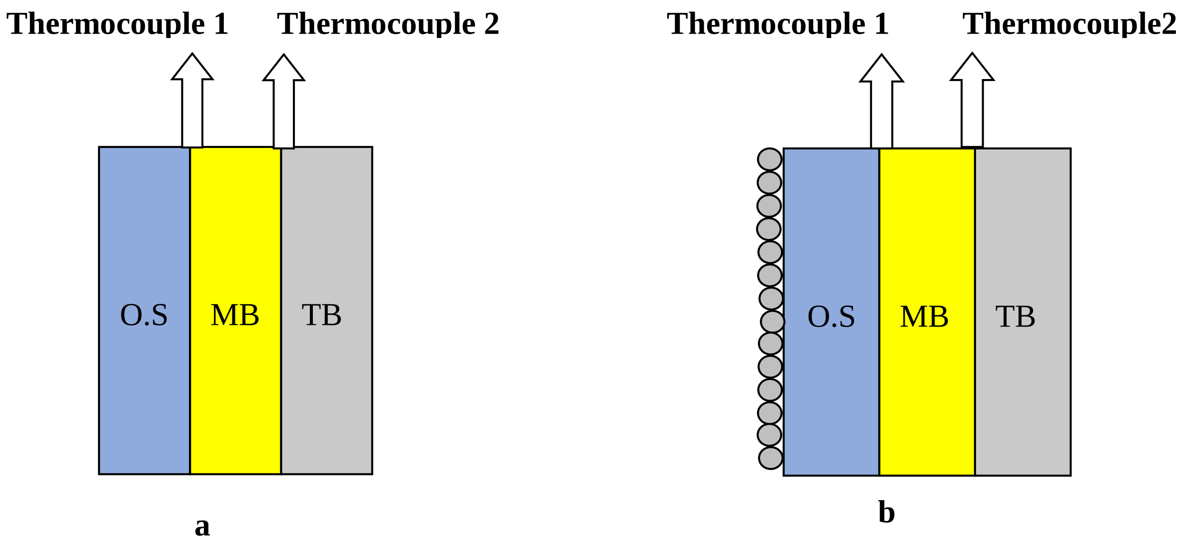


Figure 17: *a. Uncoated specimen* *b. silver coated specimen*

In order to simplify explanation with theoretical equations, following assumptions have been made:

i. Transmission of heat takes place in one dimension only
ii. Transfer of mass is negligible
iii. Radiation only penetrates through exterior shell of multilayer assembly as almost 95% of incident energy is in the form of radiation that is absorbed after covering a distance equivalent to the outer shell thickness
iv. Optical characteristics like transmissivity, reflectivity and absorptivity are assumed constant [61][62][63].

Two specimens of multilayer clothing assemblies are used in the form of uncoated and silver coated specimens in this research work. Initial temperature of room was 301.45 K ± 3 K Temperature versus time graph for uncoated and silver coated specimens are shown in figure 18 and figure 19 respectively.

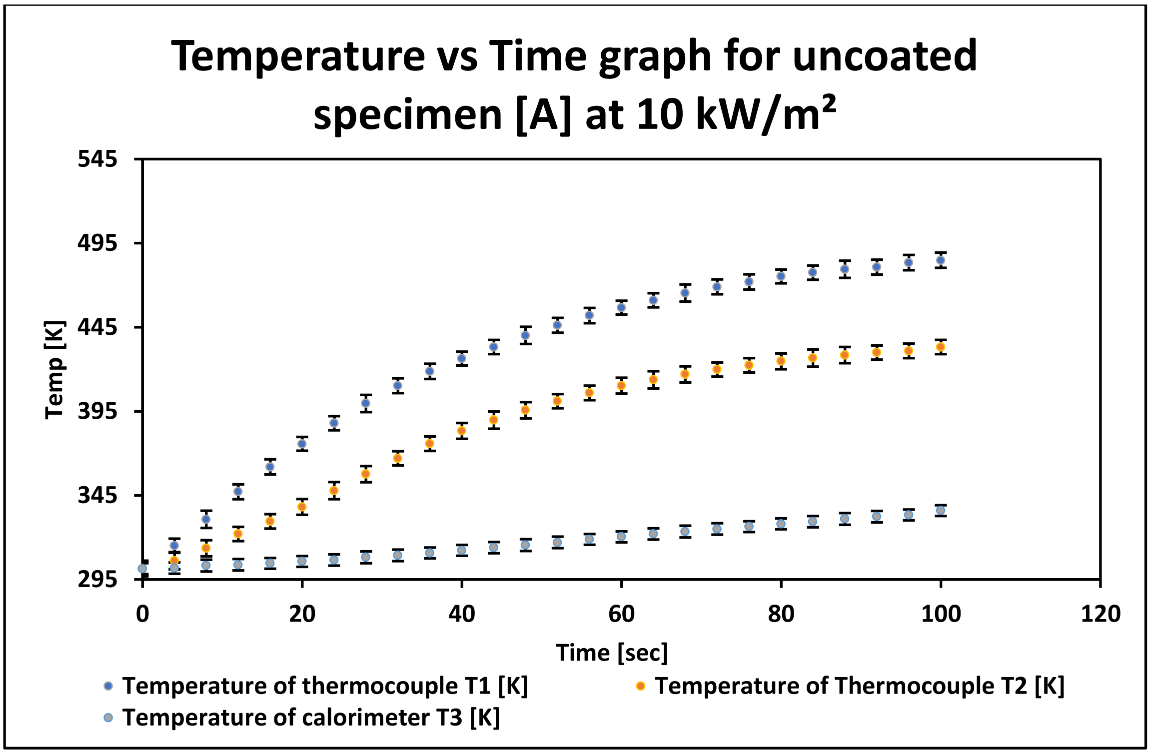


Figure 18: *Temperature of uncoated specimens with respect to time when specimens are exposed to 10 kW/m²*

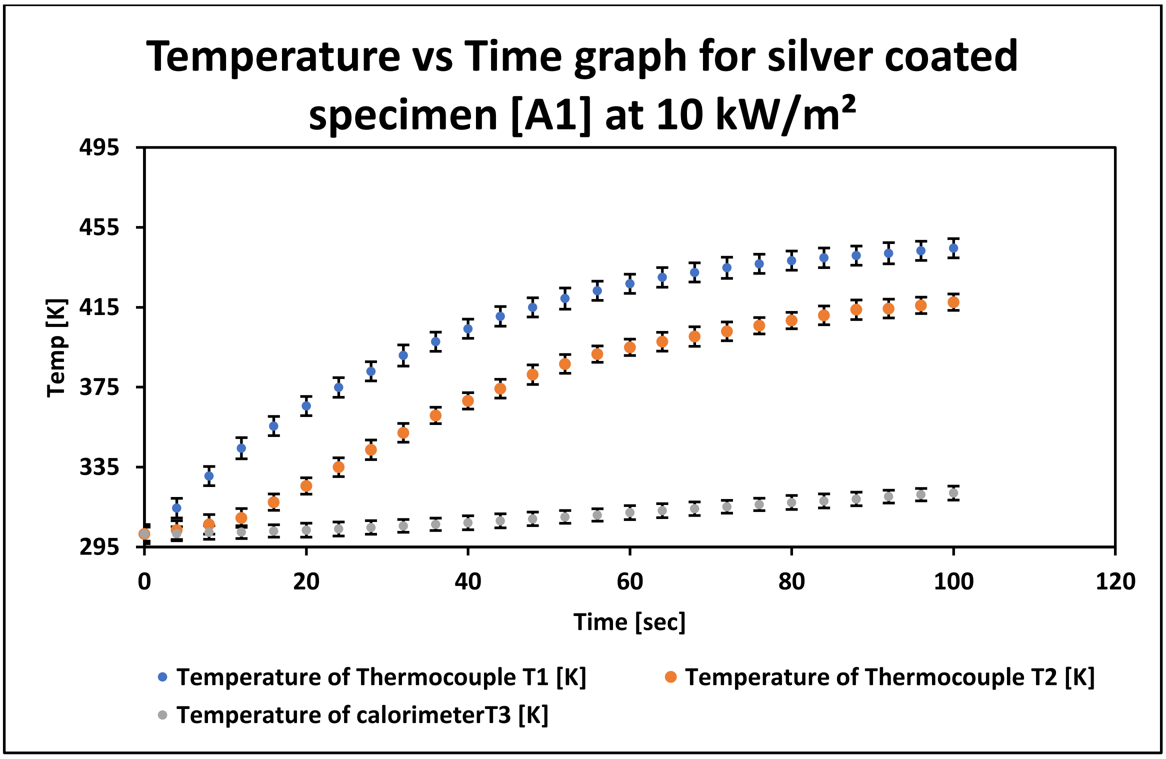


Figure 19: *Heat transmission at 10 kW/m² through silver coated specimen*

8.2 Transmission of heat from heating source to firefighter clothing assembly

As described earlier, uncoated and silver coated fabric assemblies are subjected to a heat flux of 10 kW/m^2 with the help of heating source. This process of heat transfer in firefighter clothing assembly due to heat flux incident by heating rods can be represented with the help of an energy equation as mentioned by Su et al [61][62]:

$$\rho_{fb} Cp_{fb} . \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{fb} \frac{\partial T}{\partial x}\right) + \frac{\partial q_{rad-abs}}{\partial x} \qquad [61][62] \qquad (8)$$

Where, ρ_{fb}, Cp_{fb}, and λ_{fb} are density, specific heat capacity and thermal conductivity of firefighter fabric respectively. $\partial q_{rad-abs}$ absorbed portion of radiant heat flux from heating source to outer shell. Equation 8 can also be written as:

$$C_{pfb}(x). \rho_{fb}(x) \frac{\partial T(x,t)}{\partial t} = \nabla\big(\lambda_{fb}(x). \nabla T(x,t)\big) + \frac{\partial Q_{rad-abs}(x,t)}{\partial x} \quad [64][65][66] \qquad (9)$$

Where $T(x,t)$ is temperature field under investigation and t is total time during which we investigate the temperature field. This equation is second order transient parabolic differential equation. It was assumed that textile material was homogeneous and isotropic. Therefore, values of λ_{fb}, C_{pfb} and ρ_{fb} are assumed constant. The ∇ designate the Vector Hamilton operator in Cartesian coordinate system. $Q_{rad-abs}(x,t)$ is the part of radiation absorbed by outer shell from radiant heat source. It was assumed that textile material was homogeneous and isotropic. Therefore values of λ_{fb}, C_{pfb} and ρ_{fb} are assumed constant [67][64][65][66].It is also possible to rewrite equation 9 in following way:

$$C_{pfb}(x). \rho_{fb}(x) \frac{\partial T(x,t)}{\partial t} = \lambda_{fb}. \Delta T(x,t) + \frac{\partial Q_{rad-abs}(x,t)}{\partial x} \quad [67][64][65][66] \qquad (10)$$

Where, the symbol Δ designates the Laplace operator. $\Delta T = \frac{\partial^2 T\,(x,t)}{\partial x_i^2}$. The thermal energy from heating source to the surface of cloth is transported due to thermal radiation and convection of air. In this scenario, the mode of radiation is the dominant as compared to convection. The radiant heat transmission between the heating source and outer shell is dependent on the differentiation of temperature and radiation view factor as shown in figure 20.

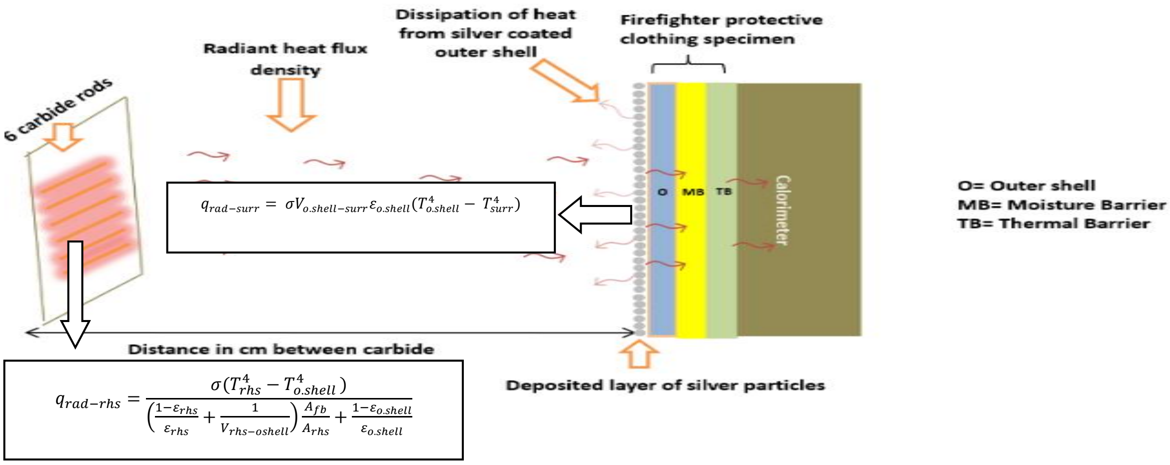


Figure 20: *Schematic diagram showing equations involved in transmission of heat from heat source towards outer shell*

8.3 Numerical solution

To solve equation 10, finite difference method was utilized. Implicit method was employed for discretization of second order parabolic differential equation. The values of temperature at discrete points (x_i and t_j) are indicated by T_i^j.

Due to scattering and absorption of radiation, Beer's law was utilized to explain extinction of incident thermal radiation (Q_{rad}) in multilayer fabric system [69][62]. Mostly Beer's law is used for liquid solutions, however it can also be utilized for porous medium like textiles.

$$\frac{\partial Q_{rad-abs}(x,t)}{\partial x} = [Q_{rad}](e^{-\gamma_{fb} i \Delta x})\gamma_{fb} \qquad [61][62] \tag{11}$$

$$\frac{\partial Q_{rad-abs}(x,t)}{\partial x} = [q_{rad-rhs} - q_{rad-surr}](e^{-\gamma_{fb} i \Delta x})\gamma_{fb} \qquad [61][62] \tag{12}$$

$$\frac{\partial Q_{rad-abs}(x,t)}{\partial x} = \qquad [62]$$

$$\left[\frac{\sigma(T_{rhs}^4 - T_i^{j\,4})}{\left(\frac{1-\varepsilon_{rhs}}{\varepsilon_{rhs}} + \frac{1}{V_{rhs-o.shell}}\right)\frac{A_{fb}}{A_{rhs}} + \frac{1-\varepsilon_{o.shell}}{\varepsilon_{o.shell}}} - \sigma V_{o.shell-surr} . \varepsilon_{o.shell}\left(T_{i.}^{j\,4} - T_{surr}^4\right)\right](e^{-\gamma_{fb} i \Delta x})\gamma_{fb} \tag{13}$$

σ is Stefan boltzman (5.678×10^{-8}) W/m^{2}K^4

T_{rhs} is temperature of radiant heat source in K

T_{surr} is temperature of surrounding atmosphere in K

A_{fb} is area of firefighter fabric in m^2

A_{rhs} is the area of radiant heat source in m^2

ε_{rhs} is emissivity of radiant heat source

$\varepsilon_{o.shell}$ is emissivity of outer shell

$V_{rhs-o.shell}$ is view factor from radiant heat source towards outer shell [61][62]

$V_{o.shell-surr}$ view factor from outer shell towards surrounding atmosphere

$$V_{o.shell-rhs} . A_{fb} = V_{rhs-o.shell} . A_{rhs} \qquad [62] \tag{14}$$

$$V_{o.shell-surr} + V_{o.shell-rhs} = 1 \qquad [62] \tag{15}$$

View factor is fraction of radiation leaving one surface which is interpreted by another surface. It was assumed, that heating source and exterior shell are considered as disk to parallel coaxial disk of unequal radius [62][69].

$$V_{rhs-o.shell} = \frac{1}{2}[S - \{s^2 - 4\left(\frac{r_{o.shell}}{r_{rhs}}\right)^2\}^{1/2}] \qquad [68] \tag{16}$$

$$S = 1 + \frac{1+R^2_{o.shell}}{R^2_{rhs}} \qquad [68] \tag{16a}$$

$$R_{rhs} = \frac{r_{rhs}}{L} \qquad [68] \tag{16b}$$

$$R_{o.shell} = \frac{r_{o.shell}}{L} \qquad [68] \tag{16c}$$

L is the distance between heating rods and multilayer clothing assembly in meters and $r_{o.shell}$ is the radius of outer shell and r_{rhs} is radius of heating source.

γ_{fb} is the extinction coefficient of outer shell which is illustrated by:

$$\gamma_{fb} = \frac{-\ln(\tau)}{h_{o.shell}} \qquad [62] \tag{17}$$

Where τ is transmissivity of outer shell. h_{shell} is thickness of outer shell [67]. Some important values are mentioned in following table 14:

Table 12: *Values used in equations*

Symbols	Values
$\varepsilon_{o.shell}$ (uncoated)	0.86
$\varepsilon_{o.shell}$ (silver coated)	0.52
$\varepsilon_{rh.s}$	0.98 [70]
A_{fb}	0.002826 m^2
A_{rhs}	0.0397 m^2
$V_{rhs-o.shell}$	0.0065
$V_{o.shell-hs}$	0.091
$V_{o.shell-surr}$	0.909
τ (uncoated shell)	0.01
τ (silver shell)	0.007
C_p [uncoated fabric]	1241.5 j/kg.K
C_p [silver coated]	1221.5 j/Kg.K
ρ of fabric [Uncoated]	195.3 kg/m^3
ρ of fabric [silver coated]	198.1 Kg/m^3
λ of fabric [Uncoated]	0.036 W/[m.K]
λ of fabric [silver coated]	0.039 W/[m.K]

Equation 10 can also be written as:

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda_{fb}}{C_{p.fb}(x).\rho_{fb}(x)} \cdot \frac{\partial^2 T}{\partial x^2} + \frac{Q_{rad}((e^{-\gamma_{fb} i\Delta x})\gamma_{fb}}{C_{p.fb}(x).\rho_{fb}(x)} \tag{18}$$

Partial derivatives in equation 18 were substituted by implicit finite divided scheme generating a discrete description related to position x_i and time t_j :

$$\frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{\lambda_{fb}}{C_{p.fb}.\rho_{fb}} \cdot \left[\frac{T_{i+1}^{j+1} - 2T_i^{j+1} + T_{i-1}^{j+1}}{\Delta x^2}\right] + \frac{Q_{rad}((e^{-\gamma_{fb} i\Delta x})\gamma_{fb}}{C_{p.fb}.\rho_{fb}} \tag{19}$$

$$\frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{\lambda_{fb}}{C_{p.fb}.\rho_{fb}} \cdot \left[\frac{T_{i+1}^{j+1} - 2T_i^{j+1} + T_{i-1}^{j+1}}{\Delta x^2}\right] + \frac{Q_{rad}((e^{-\gamma_{fb} i\Delta x})\gamma_{fb}}{C_{p.fb}.\rho_{fb}} \tag{19a}$$

$$T_i^{j+1} - T_i^j = \frac{\lambda_{fb}}{\Delta x^2. C_{p.fb}.\rho_{fb}}. \Delta t\left[T_{i+1}^{j+1} - 2T_i^{j+1} + T_{i-1}^{j+1}\right] + \frac{Q_{rad}\left((e^{-\gamma_{fb} i\Delta x})\right)\gamma_{fb}.\Delta t}{C_{p.fb}.\rho_{fb}} \tag{19b}$$

$$T_i^j = -kT_{i-1}^{j+1} + (1+2k)T_i^{j+1} - kT_{i+1}^{j+1} - \frac{Q_{rad}\left((e^{-\gamma_{fb} i\Delta x})\right)\gamma_{fb}.\Delta t}{C_{p.fb}.\rho_{fb}} \tag{19c}$$

$$T_i^j + \frac{Q_{rad}\left((e^{-\gamma_{fb} i\Delta x})\right)\gamma_{fb}.\Delta t}{C_{p.fb}.\rho_{fb}} = -kT_{i-1}^{j+1} + (1+2k)T_i^{j+1} - kT_{i+1}^{j+1} \tag{19d}$$

For further solution, Thomas Algorithm method was employed to solve above mentioned equation. Where:

$$k = \frac{\lambda_{fb}.\Delta t}{\Delta x^2. C_{p.fb}.\rho_{fb}} \tag{19e}$$

$$Interval\ of\ node\ \Delta x = \frac{Thickness\ of\ fabric}{Number\ of\ nodes}$$

The fabric assembly is divided into 5 nodes.

Number of time steps $= \frac{Time_{final} - Time_{initial}}{\Delta t}$

$$= \frac{100sec - 0sec}{1} = 100$$

Interval of time Δt = 1 sec

T_i^j corresponds to temperature at node i, that is

$x = i.\Delta x$ and $t = j.\Delta t$

8.3.1 Boundary conditions

$$\lambda_{o.shell}.\frac{\partial T(x,t)}{\partial x} = -\alpha(T_{o.shell} - T_{surr}) + q_{rad-abs} \quad (20)$$

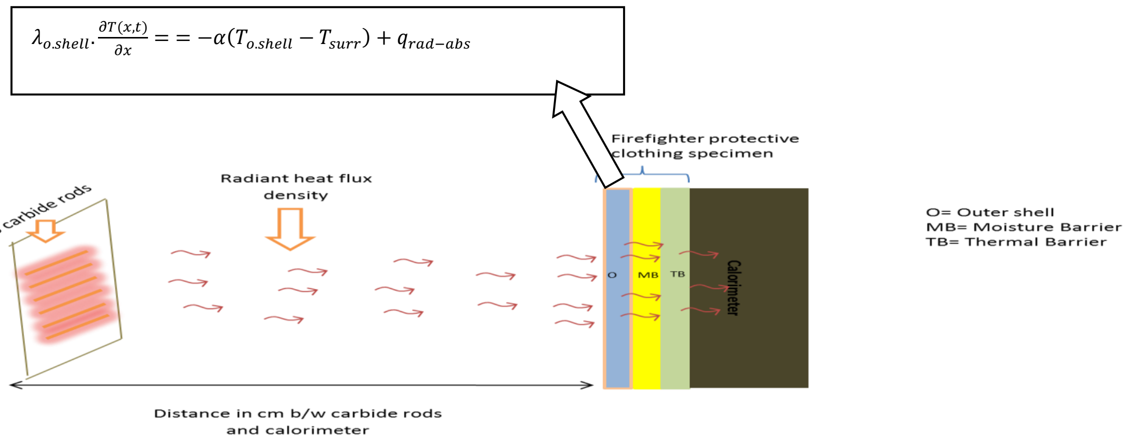


Figure 21: *Schematic diagram showing boundary condition of outer shell*

$$\lambda_{T.B}.\frac{\partial T(x,t)}{\partial x} = Q_{calorimeter} - \lambda_{air}.\frac{\partial T}{\partial x} \qquad [61][62] \quad (21)$$

$\boxed{T_{TB}}$ $\boxed{Q_{calorimeter} = \frac{\sigma(T_{T.B}^4 - T_{cal}^4)}{\left[\left(\frac{1}{\varepsilon_{T.B}}\right)+\left(\frac{1}{\varepsilon_{cal}}\right)\right]-1}}$

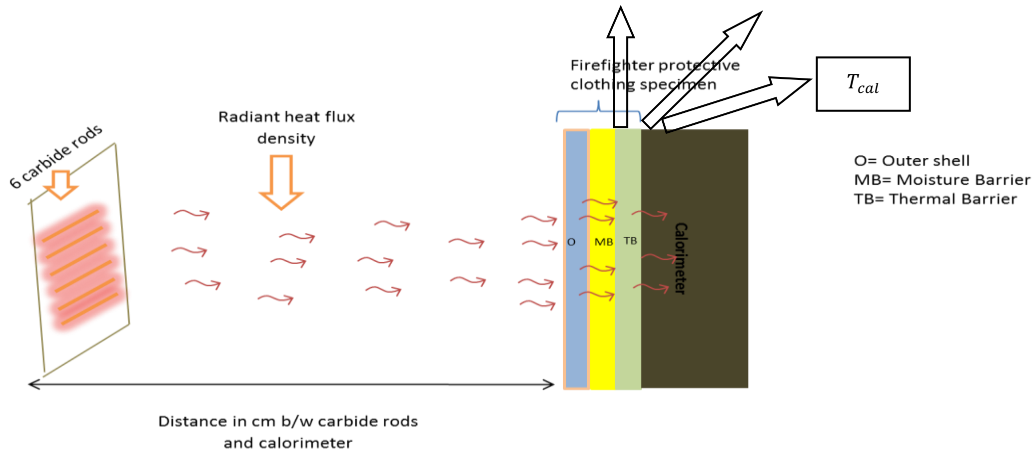


Figure 22: *Schematic diagram showing equation for boundary condition of thermal barrier*

$$q_{calorimeter} = \frac{\sigma(T_{T.B}^4 - T_{cal}^4)}{\left[\left(\frac{1}{\varepsilon_{T.B}}\right)+\left(\frac{1}{\varepsilon_{cal}}\right)\right]-1} \tag{22}$$

$\varepsilon_{T.B}$ is emissivity of thermal barrier and ε_{cal} is emissivity of calorimeter[61]. $T_{T.B}$ is temperature of thermal barrier and T_{cal} is temperature of calorimeter.

The distribution of temperature at different nodes in different interval of time for uncoated and silver coated specimen was depicted in figure 23 and figure 24 respectively.

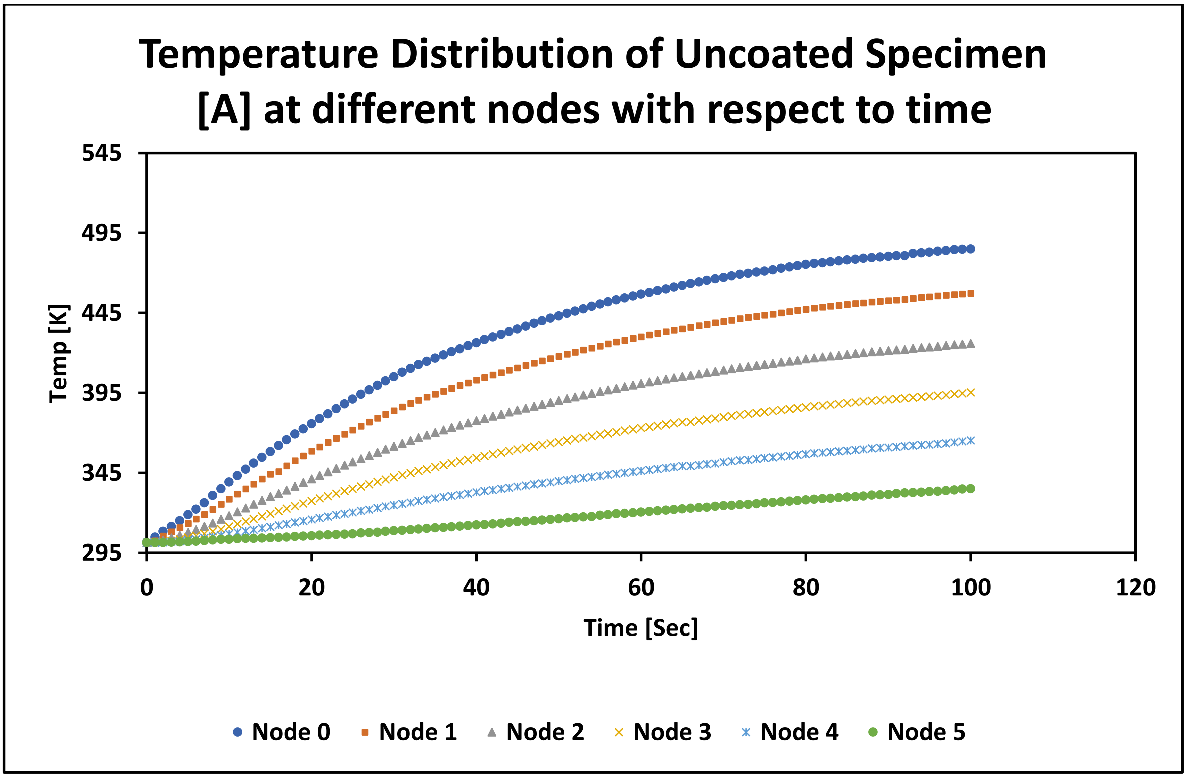


Figure 23: *Temperature distribution in uncoated specimen with respect to time*

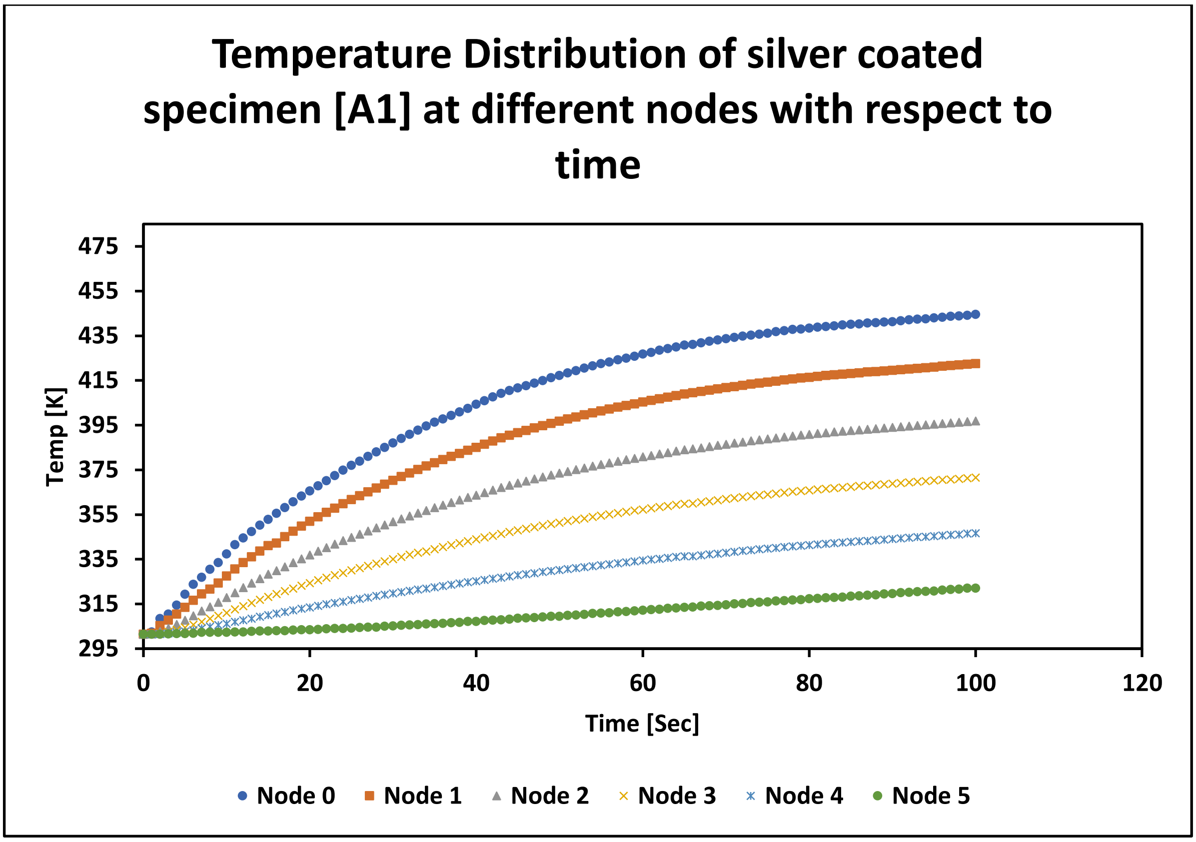


Figure 24: *Temperature distribution in silver coated specimen with respect to time*

It can be witnessed from figure 23 and figure 24, that there was sequential increment in rise of temperature for different curves with increase in time. However, this increment was not in linear form. It was also noticed that as the number of nodes increases, there was decline in values of temperature for same time period. This indicates decline in temperature values with increase in thickness of firefighter clothing assembly for both uncoated specimen *A* and silver coated specimen *A1*.

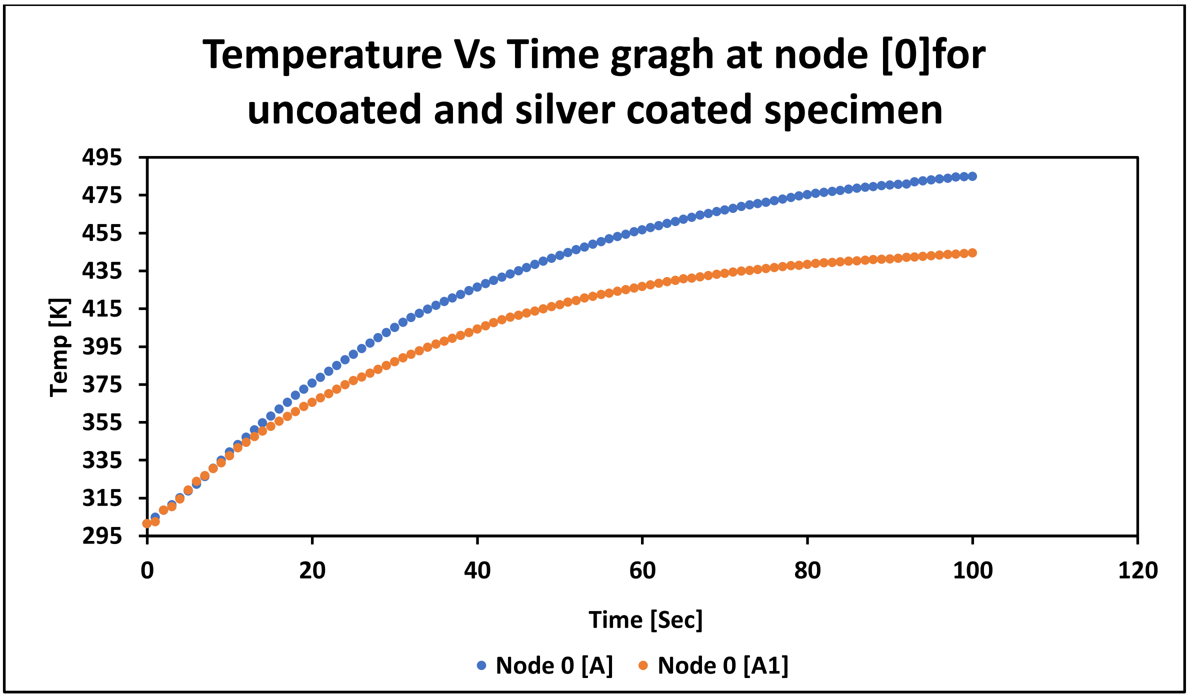


Figure 25: *Comparison of temperature distribution of uncoated and silver coated specimen at node [0]*

It can be noticed from figure 25 that till first sixteen seconds the curve of uncoated specimen *A* and silver coated specimen *A1* overlapped with each other. Afterwards, a gap appears between curve of silver coated and uncoated specimen. This gap went on increasing with the increase in time.

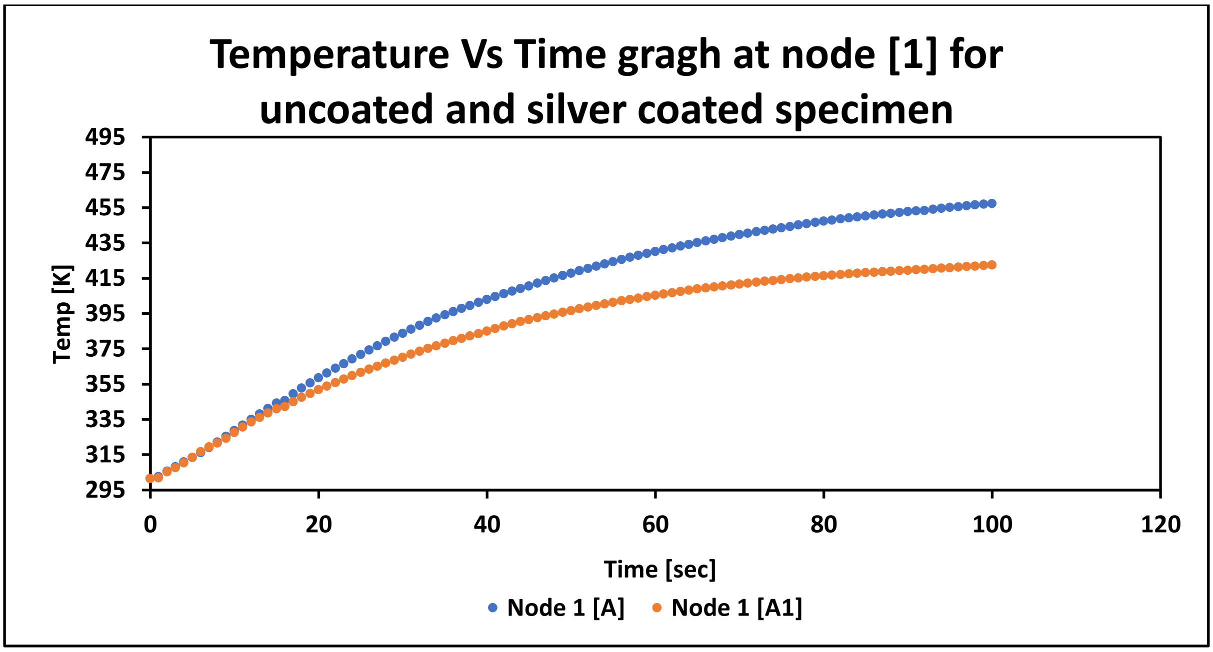


Figure 26: *Comparison of temperature distribution of uncoated and silver coated specimen at node [1]*

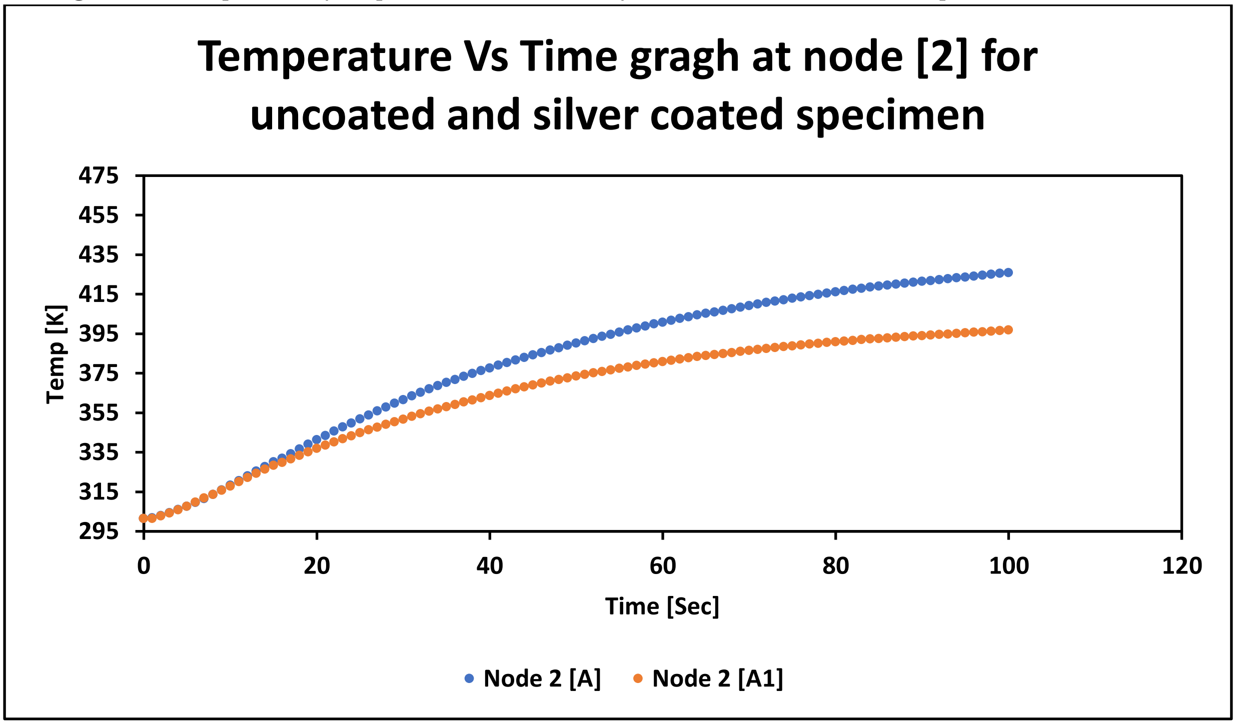


Figure 27: *Comparison of temperature distribution of uncoated and silver coated specimen at node [2]*

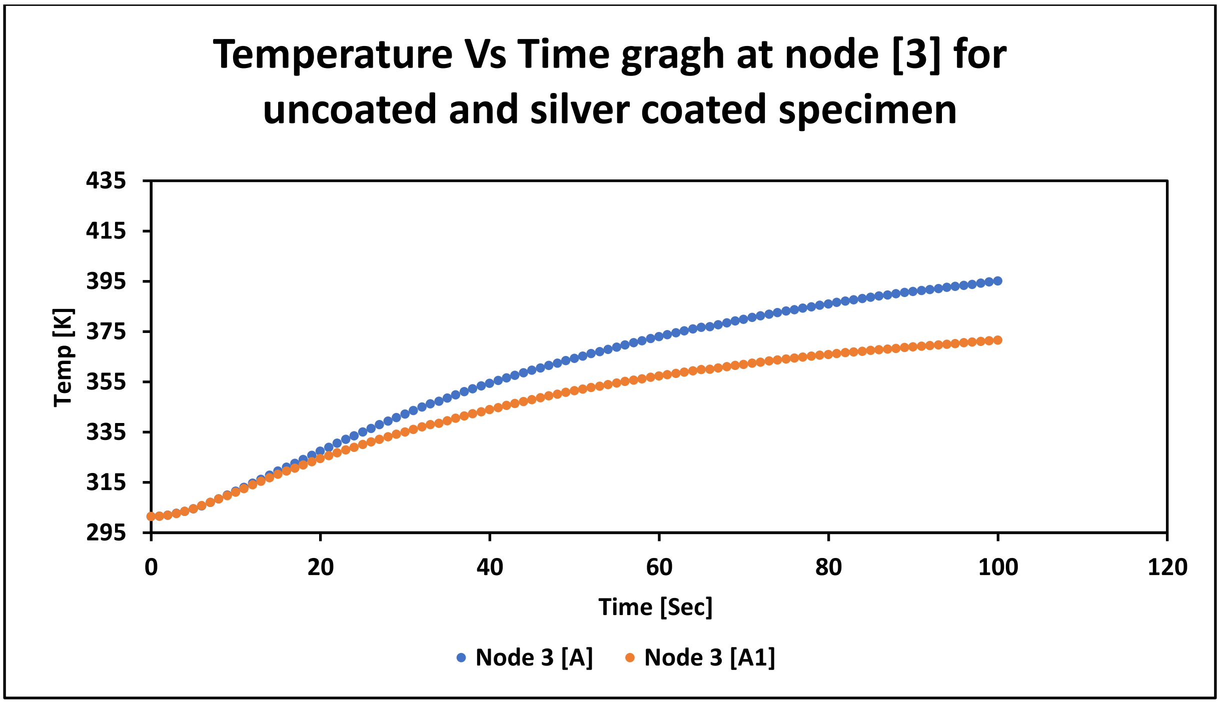


Figure 28: *Comparison of temperature distribution of uncoated and silver coated specimen at node [3]*

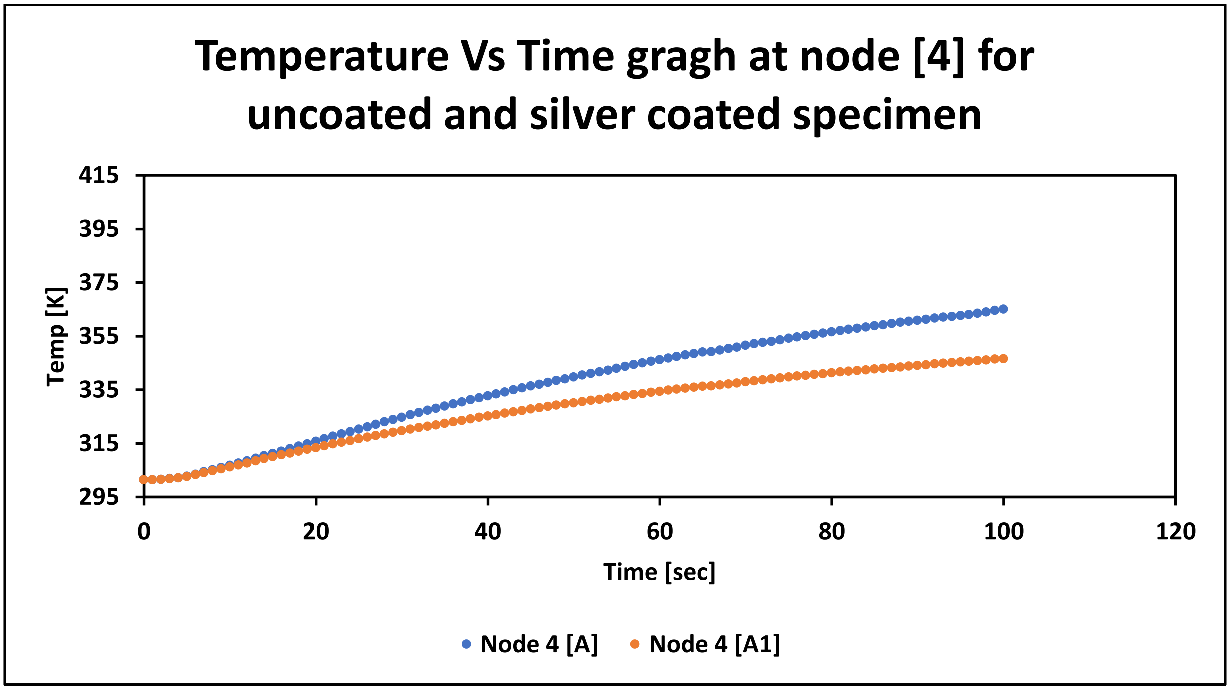


Figure 29: *Comparison of temperature distribution of uncoated and silver coated specimen at node [4]*

It can be witnessed from figure 26 to figure 29 that till first 15 seconds; both curves of uncoated and silver coated specimen were superimposing each other. Later on the curve of uncoated specimen started to get steeper as compared to curves silver coated specimen. It was also observed that as the number of nodes increases, the curve of both uncoated and silver coated specimen became flatter as compared to previous nodes. The slackness in the curve indicates that rate of rise of temperature takes place slowly. As a consequence better will be thermal protective performance because less amount of heat is transmitted towards fabric assembly.

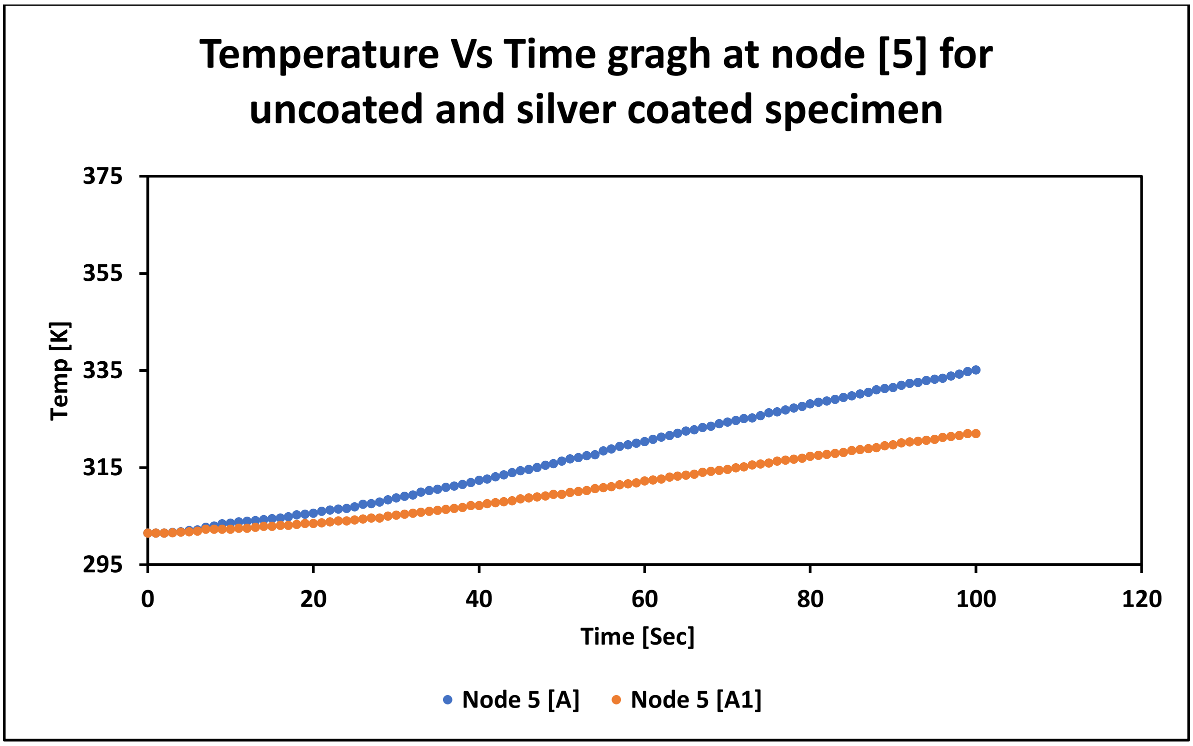


Figure 30: *Comparison of temperature distribution of uncoated and silver coated specimen at node [5]*

It was evident from figure 30, the pattern of curve for uncoated and silver coated specimen was almost same after initial 5 seconds. Later on, the curve of uncoated specimen starts to raise by creating gap between the curves of uncoated *A* and silver coated specimen *A1*. The wideness of this gap increases between two curves increases till end of 100 seconds. This indicates better thermal protective performance of silver coated specimen *A1*.

It can be inferred that numerical model solution predicts temperature distribution at different nodes for uncoated specimen *A* and silver coated specimen *A1* at different interval of time. This model also shows the silver coated specimen *A1* incurs less steep curve of temperature values as compared to uncoated specimen *A* at different nodes. This flatness of curve was also witnessed in case of silver coated specimen *A1* for experimental work. With the help of numerical model it was possible to estimate temperature distribution at different places along thickness of fabric which was not possible in experimental work.

9. Conclusion

1. It can be inferred that thermal protective performance is one of the most important feature of firefighter protective clothing. Thermal protective performance determines capability of the firefighter protective clothing to protect the body of firefighter against second degree burns. The greater the thermal protective performance, the better will be thermal protective ability of firefighter clothing.
2. In this research some of the alternate methodologies have been employed to increases thermal protective performance. One approach was to employ aerogel layer as a substitute to thermal barrier. Four specimen assemblies were made. *Specimen A* and *specimen B* used thermal barrier. *Specimen C* and *specimen D* employs aerogel blanket as substitute to thermal barrier. When aerogel blanket was used as an alternate layer to thermal barrier:

i. The specimens having aerogel blankets have greater thermal resistance value as compared to specimen in which thermal barrier was used. This might be due to nano-porous structure of aerogel due to which gaseous molecules become immobile and this might block conductive heat transmission. Convective heat transfer is also obstructed due to no circulation of air. Furthermore, thermal conductivity of aerogel [0.015 W/m.K] which was also less than still air [0.026 W/m.K].

ii. Specimens having aerogel blanket as substitute to thermal barrier have higher water vapor resistance values as compared to other specimens. This high water vapour resistance values might be due to hydrophobic character and closed porous configuration of aerogel structure.

iii. When specimens were exposed to different levels of radiant heat flux density levels [kW/m^2] in radiant heat transmission machine. Those specimens in which aerogel blanket was used have lower values of transmitted heat flux densities Q_c [kW/m^2] and high values of *RHTI 24*. The high value of *RHTI 24* indicates that time for rise of 24 ºC was more in case of specimen using aerogel as an alternate layer due to which transmission of heat is delayed. This might be due to fact that aerogel layer is able to absorb infra red radiation. When specimens were subjected to 10 kW/m^2, *specimen C* has improved *RHTI 24* values as compared to *specimen A* by **61.7 percent**. Whereas, *specimen D* has better *RHTI 24* values by **51.5 percent** as compared to *specimen B*. When specimens were exposed to 20 kW/m^2, RHTI 24 value in *specimen C* was enhanced by **24 percent** as compared to *specimen A*. Similarly, *Specimen D* has better value of *RHTI 24* as compared to *specimen B* by **36.5 percent.** When subjected to 30 kW/m^2, *RHTI 24* value of *specimen C* was enhanced by **51 percent** in comparison with *specimen A* and there was **56.74 percent** improvement in *RHTI 24* value of *specimen D* as compared to *specimen B*. When specimens were facing 40 kW/m^2, *specimen C* has increased value of *RHTI 24* by **82.4 percent** as compared to *specimen A*. However, *specimen D* has improved value of *RHTI 24* by **80.6 percent** in comparison with *specimen B*.

3. Another way to improve thermal protective performance was to coat exterior side of outer shell by silver particles through magnetron sputtering (new approach) at 1 μm, 2 μm and 3 μm thickness level. Previously this method of coating was used to coat metallic particles on thin films. As a result, four different combinations of specimens are formed. *specimen A* (uncoated), *specimen A1* (1 μm coating), *specimen A2* (2 μm coating) and *specimen A3* (3 μm coating).

i. It was also witnessed that when silver coated and uncoated specimens were exposed to various levels of radiant heat flux density, silver coated specimen have low values of transmitted heat flux density Q_c and high values of *RHTI 24*. This indicates improvement in thermal protective performance. As the thickness level of silver metallic particles increases there was further reduction in transmitted heat flux density values and increase in *RHTI 24* values. On exposure to 10 kW/m^2, *specimen A1* has improved thermal protective performance in terms of *RHTI 24* by **43 percent** as compared to *specimen A*. When specimens are exposed to 20 kW/m^2, *specimen A1* has improved *RHTI 24* values by **30.35 percent** as compared to *specimen A*. When specimens are subjected to 30 kW/m^2, *RHTI 24* value of *specimen A1* enhanced by **17**

percent in comparison with uncoated *specimen A*. On facing radiant heat flux density of 40 kW/m^2, *specimen A1* has increased value of *RHTI 24* as compared to *specimen A* by **28 percent**. There was minor difference between values of water vapour resistance for silver coated and un-coated specimens indicating that breathability of silver coated specimen was not compromised. There was also no significant differentiation in values of air permeability indicating that porous configuration of silver coated specimen was not completely blocked. A slight increase in bending moment values of silver coated specimen was witnessed.

ii. The emissivity value of silver coated specimen was 0.52 which was very low as compared to emissivity value of uncoated specimen 0.86. The lower value of emissivity indicates better reflectivity which indicates that incident radiant flux density is dissipated towards the surrounding atmosphere and transmitting less heat towards calorimeter. The reflectivity value of 1 μm silver coated specimen was 0.47 which was greater than reflectivity value of uncoated specimen having value of 0.09.

iii. The durability of 1 μm silver coated specimen was investigated after 5 washing cycles as per standard NFPA 1851 and there was minor decline in values of transmitted heat flux density Qc [kW/m^2] after 5 washing cycles when exposed to 40 kW/m^2. This indicates stability and durability of silver particles coating on surface of outer shell.

4. Lastly the Numerical model and its solution were established using the appropriate equations for transmission of heat. The distribution of temperature through multilayer sandwich structure was determined with the help of Numerical model and its solution. Previously no attempt was made to predict the distribution of temperature for fighter clothing coated with low emissivity silver coated particles. The distribution of temperature through multilayer firefighter clothing assembly was deeply studied in this technique. The results can be useful for the researcher and the industrial partner to predict the thermal protection of firefighter clothing with low emissivity coating.

10. Future Work

1. For future studies, different coating techniques can be employed to impregnate metallic coating on outer shell via different metallic particles of aluminium, copper and titanium.
2. Evaluation of moisture management (mass transfer properties) between different layers of firefighter can provide lot of help in future research.
3. Numerical solution with the help of computer simulation using python/MATLAB software.

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12. List of papers published by the author

Publications in journals

[1a] **Naeem J**, Mazari A, Havelka A. REVIEW: RADIATION HEAT TRANSFER THROUGH FIRE FIGHTER PROTECTIVE CLOTHING, Fibers and Textiles in Eastern Europe, 25(4), 2017, page: 65-74, ISSN # 12303666.

[2a] **Naeem J**, Mazari A, Akcagun E, Kus, Z: REVIEW: SIO_2 AEROGELS AND ITS APPLICATION IN FIREFIGHTER PROTECTIVE CLOTHING, Journal of Industria Textila, 69 (1), 2018, page 50-54, ISSN # 12225347

[3a] **Naeem J,** Mazari A, Akcagun E, Kus Z, Havelka A; ANALYSIS OF THERMAL PROPERTIES, WATER VAPOR RESISTANCE AND RADIANT HEAT TRANSMISSION THROUGH DIFFERENT COMBINATIONS OF FIREFIGHTER PROTECTIVE CLOTHING, Accepted, Journal of Industria Textila, vol 69(6), 2018, page: 458-465. ISSN # 12225347

[4a] **Naeem J,** Mazari FB, Mazari Areport: INSTRUMENTS USED FOR TESTING MOISTURE PERMEABILITY, Vlakna a Textil, 23 (1), 2016, page 42-48, ISSN # 13350617

[5a] Mazari F B, Chotebor M, **Naeem J,** Mazari A, Havelka A; PERFORATED POLYURETHANE FOAM ON MOISTURE PERMEABILITY OF CAR SEAT COMFORT, Fibers and Textiles in Eastern Europe, 24 (6), 2016, pages 165-169, ISSN # 12303666

[6a] **Naeem J,** Mazari A: COMPARATIVE STUDY OF RADIANT HEAT FLUX DENSITY TRANSMISSION THROUGH FIREFIGHTER PROTECTIVE CLOTHING, Vlakna Textile,25(2),2018, ,pages:79-86 ISSN # 13350617

[7a] **Naeem J,** Mazari A, Volskey L: EFFECT OF NANO SILVER COATING ON THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING, Journal of Textile Institute, vol 10(6), 2019, page: 847-858. ISSN # 0040-5000

[8a] **Naeem J**, Mazari A, Kus Z: COMPARISON OF THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING AT DIFFERENT LEVEL OF RADIANT HEAT FLUX DENSITY, Journal of Tekstilec, vol 61(3), 2018 pages: 179-191. ISSN # 2350-3696.

Conferences and Workshops

1. **Naeem J**, Mazari A, Volskey L, ENHANCEMENT OF THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING, Autex Conference 2018, ISBN 978-961-6900-17-1.
2. **Naeem J,** Mazari A, Krejcik M, Impact of Metallic Coating on Thermal Protective Behavior of Multilayer Protective Clothing, NART Conference 2019**.**
3. **Naeem J** : INVESTIGATION OF THERMAL RESISTANCE AND WATER VAPOR RESISTANCE OF MULTILAYER PROTECTIVE CLOTHING BY USING AEROGEL BLANKET, Billa Voda Workshop, 2016, ISBN # 978-80-7494-293-8
4. **Naeem J**, Mazari A, Krejcik, M, INFLUENCE OF METALLIC COATING ON THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING, PhD Work shop, Technical University of Liberec, 2019.

Curriculum Vitae

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Research/work experience

• Department of Clothing Technologies, Faculty of Textile Engineering, Technical University of Liberec, Liberec, Czech Republic.	PhD Scholar	2014 – present
• Garment Manufacturing Department, National Textile University, Faisalabad, Pakistan	Lecturer	2013 – present (on study leave)
• Industrial Engineering Department, Crescent, Ltd. Faisalabad, Pakistan	Assistant Manager	2012

Academic profile

• University of Boras, Boras, Sweden.	The Swedish School of Textiles	M.Sc.	2012
• National Textile University, Faisalabad, Pakistan	Garment Manufacturing Department	B.Sc. Textile Engineering	2008

Impact factor journal publications

1. **Naeem J**, Mazari A, Havelka A. Review: Radiation heat transfer through fire fighter protective clothing, Fibers and Textiles in Eastern Europe, 25(4), 2017, page: 65-74, ISSN # 12303666.
2. **Naeem J**, Mazari A, Akcagun E, Kus, Z: Review: Sio_2 aerogels and its application in firefighter protective clothing, Journal of Industria Textila, 69 (1), 2018, page 50-54, ISSN # 12225347
3. **Naeem J,** Mazari A, Akcagun E, Kus Z, Havelka A; Analysis of thermal properties, water vapor resistance and radiant heat transmission through different combinations of firefighter protective clothing, Accepted, Journal of Industria Textila, vol 69(6), 2018, page: 458-465. ISSN # 12225347
4. **Naeem J,** Mazari FB, Mazari Areport: Instruments used for testing moisture permeability, Vlakna a Textil, 23 (1), 2016, page 42-48, ISSN # 13350617
5. Mazari F B, Chotebor M, **Naeem J,** Mazari A, Havelka A; Perforated polyurethane foam on moisture permeability of car seat comfort, Fibers and Textiles in Eastern Europe, 24 (6), 2016, pages 165-169, ISSN # 12303666

6. **Naeem J,** Mazari A: Comparative study of radiant heat flux density transmission through firefighter protective clothing, Vlakna a Textil,25(2), 2018, pages:79-86 ISSN # 13350617
7. **Naeem J,** Mazari A, Volskey L: Effect of nano silver coating on thermal protective performance of firefighter protective clothing, Journal of Textile Institute, vol 10(6), 2019, page: 847-858. ISSN # 0040-5000
8. **Naeem J**, Mazari A, Kus Z: Comparison of thermal protective performance of firefighter protective clothing at different level of radiant heat flux density, Journal of Tekstilec, vol 61(3), 2018 pages: 179-191. ISSN # 2350-3696.

Conference publications

1. **Naeem J**, Mazari A, Volskey L, Enhancement of thermal protective performance of firefighter protective clothing, Autex Conference 2018, ISBN 978-961-6900-17-1.
2. **Naeem J,** Mazari A, Krejcik M, Impact of Metallic Coating on Thermal Protective Behavior of Multilayer Protective Clothing, NART Conference 2019**.**
3. **Naeem J** : Investigation of thermal resistance and water vapor resistance of multilayer protective clothing by using aerogel blanket, Billa Voda Workshop, 2016, ISBN # 978-80-7494-293-8
4. **Naeem J,** Mazari A, Krejcik, M, Influence of metallic coating on thermal protective performance of firefighter protective clothing, PhD Work shop, Technical University of Liberec, 2019.

Research projects

1. Member of the student grant completion (SGS) project 2017 (project no.21200), Faculty of Textile Engineering, Technical University of Liberec, Czech Republic.
2. Member of the student grant completion (SGS) project 2018 (project no.21246), Faculty of Textile Engineering, Technical University of Liberec, Czech Republic.
3. Member of the student grant completion (SGS) project 2019 (project no.21309), Faculty of Textile Engineering, Technical University of Liberec, Czech Republic.

Other professional activities

1. Three-month Erasmus+ traineeship from 5 May 2017 to 10 August 2017 at University of Minho, Guimares, Portugal
2. Member of National Textile University Alumni Association. Pakistan.

13. Recommendation of the supervisor

Recommendation of the supervisor

Supervisor's opinion on PhD thesis of Mr.Jawad Naeem M.Sc.

Thesis tittle: THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING

Mr. Jawad Naeem B.Sc. is an PhD student in Department of Clothing Technology, Faculty of textile, Technical University of Liberec. He is an excellent hard working and efficient student who is very dedicated and attentive to detail. He was able to learn the experimental procedures and was also able to solve technical problems. His approach is always systematic and precise.He has successfully passed all the course examinations and also passed his internship exam. Later on, he successfully passed State doctoral exam.

Up to now he has published seven articles as main author in different scientific journals like Journal of Textile Institute, Fibers and Textiles in Eastern Europe, journals Industria Textila, Vlakna a textil and Tekstilec. Out of these seven articles, five articles were published in impact factor journals. He has also published his scientific work in two conferences of Autex and NART respectively.

His PhD thesis titled "THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING" is quite comprehensive and fulfils the planned objectives. The work is very interesting and is related to thermal protective performance of firefighter protective clothing. He was able to analyze thermal protective behaviour of different firefighter combinations. Moreover, improvement in thermal protective performance was also analyzed with the help of aerogel blankets and coating of silver particles. Furthermore, numerical model was implemented to understand temperature distribution in multilayer clothing assembly.

I therefore strongly recommend him for defence of his doctoral work.

Prof.Dr.Ing. Zdeněk Kůs

Supervisor

Liberec 31st July 2020

14. Opponent's reviews

Title of dissertation: **Thermal protective performance of firefighter protective clothing**

Author: Jawad Naeem, M.Sc

Examined by: Prof. Ing. Karel Adámek, CSc.

The presented work contains 93 pages, divided in several parts, as Introduction (3 p.), Scope and research objectives (3 p.), Literature review (20 p.), Materials and equipment (13 p.), Research methodologies (7 p.), Results and discussion (31 p.), Numerical model for prediction of temperature distribution (14 p.) and Conclusion (4 p.). At the end author presents 135 references mentioned in the work and adequate number of 13 own publications focused on the topic of the work.

At the beginning they are defined parameters of the thermal protective performance, important for firefighting clothing. Many features are tested and discussed, also after wearing and washing of real clothing.

Methods used by author are complex, detailed, transparent and understandable – discussion of references, own theoretical and experimental procedures and comparison of their results.
The main topic of the dissertation is completed by observing of next thermal parameters influencing the comfort of clothing, as for instance permeabilities of water, vapor, air.

For testing of heat resistance of clothing with respect to time several temperatures were measured in different depths of the different kinds of clothing (from the outer radiated surface). Results are logical and present resistivity of individual samples in time.

Interesting is the description of numerical model for prediction of temperature distribution (in the clothing thickness). Both experimental and simulated results are in a good coincidence.
In general, I recommend to use for numerical simulation any commercial code, describing complex heat and mass flow in complex volume of clothing. Suitable and verified code is disponible at TUL (Fac. of machinery and Fac. of mechatronics) and also in VÚTS (dept. of simulations). It is possible to gain many results relatively quickly for various combinations (also for those that really do not exist), the most interesting of them can be consequently tested and – in the case of positive results – prepared for practical use.

Values of theoretical and laboratory heat stability of tested clothing were verified also after wearing and washing of real clothing. As the result of such procedures is the recommendation of suitable kind of clothing.

The defined goal – thermal protective performance of firefighter protective clothing - is achieved, together with necessary focusing on many other parameters, influencing the comfort of clothing. In tested clothing they are important permeabilities of air, water (sweat) and water vapor. It should be to remark, that different units of permeability have the same basis as volume flow (m^3/s) through the sample area (m^2), also (m/s). For higher differences of pressure or temperature it should be used mass flow, independent on state quantities. Of course, the resistance (s/m) is the reciprocal value of permeability.

At the conclusion of my review I would state that presented dissertation fulfils all formal requirements of relevant internal rules of TUL and I recommend the dissertation submitted by Mr. Jawad Naeem for next procedure at the Faculty of textile engineering of the TUL.

In the case of the positive result of the defense of the dissertation I recommend to award the title of Ph.D.

Liberec, 25.8.2020
Karel Adámek

Review of Doctoral Thesis

Assoc. Prof. Ing. Michal Petrů, Ph.D.

Technical University of Liberec
Studentska 2
461 17 Liberec

Title of Ph.D. thesis: Thermal protective performance of firefighter protective clothing

Author: Jawad Naeem, M.Sc.

Supervisor: Prof. Dr. Ing. Zdeněk Kůs, Department of Clothing technologies

The doctoral thesis is entitled "Thermal protective performance of firefighter protective clothing" has all necessary parts required for an appropriate thesis. The thesis mostly contains smooth data instead of worthless concise result. A PhD thesis should be a few concise and compact. The quality of thesis is good but sometimes disputable and therefore candidate must answer all my questions and try to convince the board about the quality of this work.

Brief overview of doctoral thesis:

The topic of the presented dissertation is undoubtedly up-to-date and it respects current innovative trends towards the development, manufacturing and use of alternative environmental materials which could be applied in industrial applications and fire/thermal safety protection. The research objectives are stated in Chapter 2. Concentrating on firefighter protective clothing specimens as their measured thermal insulation and thermal protective properties, I find reasonable, since it made the thesis compact and allowed for achieving all the goals stated. This is evident from Chapter 8 summarizing the principal outcomes of a very broad and diverse experimental program. Their choice is also supported by a detailed state of the art section and literature survey presented in Chapter 3, which shows a good orientation of the candidate in this field. Core results supported by your developed experimental measurements should be given more to finalize this very good work, I believe. In general conclusion section is good and satisfactory. The present work clearly describes and clarifies several approaches to the enhancement of thermal protective performance of firefighter clothing. The author is aware of the limits and limitations of their application. After studying the work as a whole, it can be stated that the defined goals of the work and PhD student's intentions were fulfilled.

Organization of the work and overall comprehensiveness:

The thesis is written in good English with only few grammatical errors. If leaving out too brief description of individual experimental measurements, the thesis are easy to follow and the results are clearly explained. However, in my opinion it might be beneficial to present some of the results of both composites within the same tables or graphs. Also, some of the general conclusions are not always fully supported by the presented results, e.g. the mentioned increase of hardness of CMF based composites with increasing amount of particles over of the whole range of temperature, see Table 8. The results for 800 DC of BMF composites in Table 7 are missing.

Treatment of the topic - methodical and conceptual approach
The methodical and conceptual approach is described in Chapter 5 outlining the experimental program carried out in the course of this thesis. While the program is rather broad, its theoretical description is fairly concise mainly for a reader not recognizable with the subject. Standard test methods, procedures and measuring devices (thermal insulation properties, air permeability, thermal protective performance, water vapor resistance, transmission of radiant heat flux, water vapor permeability, analysis of surface morphology, stiffness/bending test, emissivity, SEM, Alambeta, Permetest, reflectance and transmissivity test, etc.) were used to characterize the properties of students created uncoated and coated firefighter clothing.

Overall comments:
The PhD student has used the adequately available equipment and methods in the dissertation to meet the stated objectives, so it can be stated that the chosen methodology was chosen in accordance with the stated objectives of the work. All the stated objectives has been fulfilled. The doctoral thesis fulfils the conditions of independent creative scientific work and contains the original results published by the author in several foreign excellent scientific journals (e.g. Journal of the Textile Institute, Fibers and Polymers) with the appropriate citation response. He has H-index = 3. The formal and graphic layout of the doctoral thesis is good but the quality of several figures is poor and most of the indexed figures look like copy paste from internet without providing source. The research work presented by author in this doctoral thesis show original aspects but it has also a few mistakes.

Questions to be answered:

1. Why did not you add chemical structures of all fibers in material selection?
2. Why did not you mention standard of water vapor permeability? (see page 35)
3. Please explain what the difference between I_a and I_T in Eq. (14) is.
4. From table 14: Why there is not such a significant drop in RHTI 24 for A1 samples with increase in number of washing cycle?

Final statement:

Based on the quality of presented doctoral thesis and results published in scientific journals I recommend this doctoral thesis for defence and in case of successful defence I recommend awarding Jawad Naeem, M.Sc. with the academic title **“doctor of philosophy”** resp. **Ph.D.**

TUL, Liberec, 15.9. 2020

Assoc. Prof. Ing. Michal Petrů, Ph.D., v.r.