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Review: Radiation Heat Transfer Through Fire Fighter Protective Clothing

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Abstract
A fire fighter garment is multilayer protective clothing with an outer shell, moisture barrier and thermal barrier, respectively. Fire fighters encounter different levels of radiant heat flux while performing their duties. This review study acknowledges the importance and performance of fire fighter protective clothing when subjected to a low level of radiation heat flux as well as the influence of air gaps and their respective position on the thermal insulation behaviour of multilayer protective clothing. Thermal insulation plays a vital role in the thermal comfort and protective performance of fire fighter protective clothing (FFPC). The main emphasis of this study was to analyse the performance of FFPC under different levels of radiant heat flux and how the exposure time of fire fighters can be enhanced before acquiring burn injuries. The preliminary portion of this study deals with the modes of heat transportation within textile fabrics, the mechanism of thermal equilibrium of the human body and the thermal protective performance of firefighter protective clothing. The middle portion is concerned with thermal insulation and prediction of the physiological load of FFPC. The last section deals with numerical models of heat transmission through firefighter protective clothing assemblies and possible utility of aerogels and Phase Change Materials (PCMs) for enhancing the thermal protective performance of FFPC.

Key words: *thermal insulation, low level of radiation heat flux, air gaps, multilayer protective clothing.*

Nomenclature

$\dot{Q}$	*Rate of heat flow*
λ	*Thermal conductivity*
ΔT	*Temperature difference*
h_c	*Coefficient of heat transmission*
ε	*Emissivity*
σ	*Stefan-Boltzman constant*
I_T	*Thermal insulation*
T_o	*Outside surface temperature*
T_i	*Inside surface temperature*
H_t	*Heat exhaust*
R_0	*Thermal radiation acquired by specimen*
R_1	*Incident heat flux*
T_h	*Exterior surface temperature of radiant flux sensor*
λ_a	*Thermal conductivity coefficient of air*
R_a	*Rayleigh number*
Q_t	*Total heat loss*
R_{cs}	*Average internal thermal resistance of sample*
R_{es}	*Average internal evaporative resistance*
R_{ct}	*Thermal resistance*
R_{et}	*Evaporative resistance*
ρ	*Density*
C_p	*Specific heat capacity*
γ	*Extinction coefficient*
q_{rad}	*Incident radiant heat flux*
t_{exp}	*Time of exposure*
τ	*Transmissivity*
l_{fab}	*Thickness of fabric*
ρ_b	*Mass per volume of blood*
c_b	*Specific heat of blood*
ω_b	*Blood perfusion rate*
T_b	*Arterial temperature of blood*
Q_m	*Origin of metabolic heat*
Ω	*Quantitative evaluation of burn injury*
A	*Area*
C	*Heat exhaust by natural convection*
E	*Energy of activation*
P	*Frequency factor*
R	*Universal gas constant*

Subscript

ASTM	*American standards for testing materials*
FFPC	*Fire fighter protective clothing*
ISO	*International organisation for standardisation*
TPP	*Thermal protective performance*
RPP	*Radiant protective performance*
FR	*Fire retardancy*
NFPA	*National fire protection agency*
THL	*Total heat loss*
NISTIR	*National institute of standards and technology*
PCMs	*Phase change materials*

Introduction

Clothing not only serves as a barrier to the exterior atmosphere but also acts as a heat transmission channel from the human body to the surrounding atmosphere [1]. The exchange of heat in clothing inculcates conduction via the air gap and fabric layer as well as convection of the air gap and radiation from the fabric layer to another fabric layer [2]. The transportation of heat means the rate of energy that is being transmitted from a medium of high temperature to one of low temperature, which continues until the two media reach the same temperature. The exchange of heat through conduction occurs due to the physical connection of two substrates. The greater the difference in temperature, the swifter the flow of heat between two substrates. The process of conduction inculcates the transportation of energy from high energy molecules to low energy molecules. When clothing is worn, the process of conduction takes place between two contact textile fabrics or between textile fabrics and human skin. The rate of energy being transmitted is dependent on the temperature gradient and the extent of resistance between the two media, termed as thermal conductivity, which can be illustrated by the following equation [3-4]:

$$\dot{Q} = \frac{\lambda A \Delta T}{x} \qquad (1)$$

In the above-mentioned equation is the rate of heat flow (W or J/sec), the area (m^2), the thermal conductivity (W/mK),

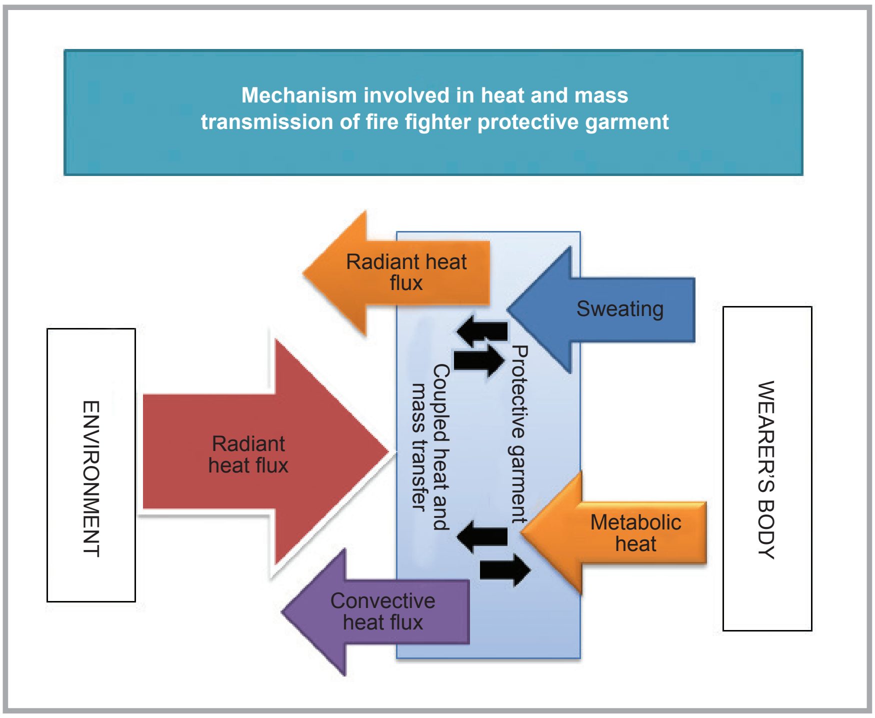

***Figure 1.** Processes involved in heat and mass transfer of fire fighter protective clothing [9].*

the temperature difference, and x is thickness of the material.

The convective heat transmission in clothing is the consequence of movement of air in the textile substrate, which is contingent on the openness of the fabric. When contact is made by air with the warm surface, heat is absorbed, due to which the air becomes less dense. The gradient of the density causes warm air to upsurge, and as a result natural convection takes place. However, wind can significantly influence convection and escalates heat transportation, causing forced convection. In the case of heat conduction, the flow of heat is dependent on the thickness of the textile substrate. By increasing the thickness of the textile substrate, a higher amount of air is confined in the fabric structure, due to which there is enhancement in thermal insulation. The rate of heat transmission due to convection can be calculated by Newton's law of cooling [3-4]:

$$Q = h_c A \Delta T \qquad (2)$$

In the above-mentioned equation, A is the heat transmitted surface area and is the coefficient of heat transmission from the surface to the fluid, known as the "convective heat transfer coefficient". This equation is true for the situation where the surface is heated due to fluid having a higher temperature than the surface. Heat transmission through radiation does not require any material medium ot textile substrates, and it can be significant in low density textile substrates. The transfer of heat via radiation takes place in the form of electromagnetic waves. Furthermore, radiation is not affected by the thickness of the textile substrate. The transfer of heat by radiation from the body at temperature T is given by the following relation [3-5]:

$$Q = A\, \varepsilon \sigma T^4 \qquad (3)$$

Where is the emissivity of the surface, the Stefan-Boltzman constant, whose value is 5.67 x 10^{-8} W/m^2K^4 , and T is the temperature of the body.

***Table 1.** Different conditions with respect to heat flux and temperature [7, 8].*

Conditions	Heat flux, kW/m^2	Air Temperature, °C
Routine conditions	0.42 to 1.26	10-60
Hazardous conditions	1.26 to 8.37	60-300
Emergency conditions	8.37 to 125.6	300-1000

Protective clothing in a hot environment

Fire fighter protective clothing (FFPC) in an elevated temperature climate guards fire fighters from the threats of radiant heat and delivers thermal equilibrium to the human body [6]. The body of fire fighters actuates the sweat glands (evaporative cooling process) in response to a heat source. The protective clothing not only shields firefighters from the surrounding heat and moisture but at the same time averts their flow away from the body to the surrounding climate i.e. in the opposing path [6]. However, there will be an upsurge in the threat of heat stress and steam burn damage [9]. The transportation of heat and moisture characteristics of protective clothing has a dominant influence on the working and protection of firefighters in a high temperature atmosphere. Improvement in these two above-mentioned properties from the skin to clothing can upgrade the comfort and efficiency of the person wearing these clothes. The protective garment should be sufficiently effectual to decrease heat stress while shielding the human body [7]. Makinen [8] mentioned that most of the previous studies were performed under conditions of acute heat fluxes, however emergency situations are not common and firefighters are most commonly subjected to routine and hazardous situations [7]. ***Table 1*** shows the range of heat fluxes and temperature linked to various firefighting situations.

Various procedures involved in heat and moisture transmission of a fire fighter protective garment are shown in ***Figure 1***.

Thermal insulation of protective clothing

Quantitative evaluation of heat transfer through several layers of a clothing assembly is depicted by the thermal insulation of the clothing arrangement [10]. Hence thermal insulation is one the most important factors related to the thermophysiological comfort and shielding property of clothing. The thermal insulation of clothing is primarily evaluated by the bench scale test like heat guard plate??? [10-13] or full-scale test like thermal manikin [14-18] utilized in a normal, warmer and colder atmosphere. The evaluation of thermal insulation of a garment through a heat guard plate is explained by several standards like ASTM 1868, ISO 11092 [19-20].

Firefighters and other workers performing their duties in the steel and construction industry are mostly subjected to the elevated temperature of the surrounding atmosphere or low level radiant heat. Therefore the thermal insulation of clothing is pertinent to ensure thermal safeguard against combustion and other hazards [21, 6]. The functionality of protective clothing facing several thermal exposures is determined by the Thermal Protective Performance (TPP) [22] test and Radiant Protective Performance (RPP) test [23], which is evaluated under conditions of elevated or moderate radiant heat of 84 kW/m^2 and 21 kW/m^2, correspondingly. Furthermore the thermal insulation of protective clothing, evaluated by a bench scale or full scale test in normal surroundings is utilised in norms like the Predicted Heat Strain Model for predicting an agreeable encounter time period in elevated-temperature surroundings [24]. The agreeable encounter duration in an elevated temperature climate may not be determined with high accuracy when employing the thermal insulation experienced in normal environmental conditions [25]. Hence the results of thermal insulation when measured in normal environmental conditions may differ in their actual outcomes in high-temperature environments, bearing in mind the several phenomena of heat transfer between the human body and surrounding climate via the multilayer fabric arrangement [25].

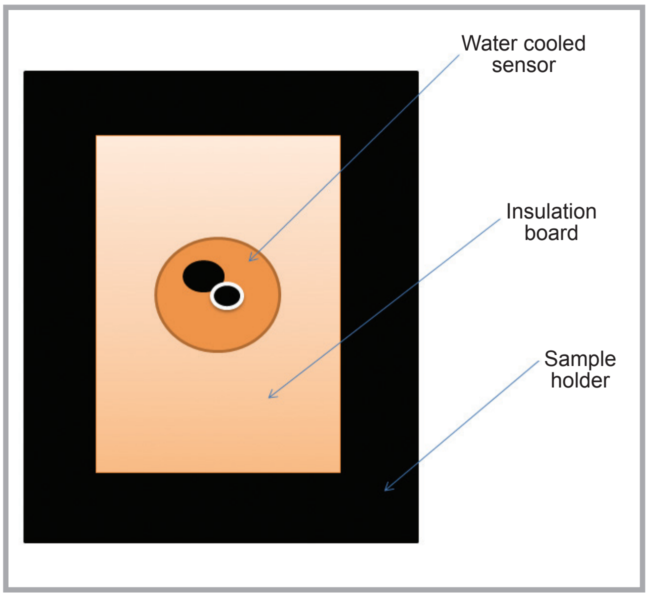

Figure 2. *Sample holder and water cooled sensor utilsed in the equipment [7].*

In a research performed by Fu et al [25], the thermal insulation of protective clothing under exterior thermal radiation is evaluated by means of bench scale equipment (self-developed). Nine altered arrangements of a protective clothing assembly with different sizes and placements of air gaps were examined. The outer shell was made of 93% meta aramids, 5% para aramids and 2% P140; the moisture barrier was 50% meta aramids and 50% par aramids; the thermal barrier was made up of 100% meta aramid, and the inner layer was 50% meta aramids and 50% FR viscose. A cone shaped radiant electrical heater, as stated by ISO 5660-1 [26], was utilised to deliver the requisite flux of thermal radiation [27]. The overall thermal insulations (I_T, °Cm^{2}W^{-1}) of the multilayer clothing in elevated temperature environments were measured from the heat exhaust in the multilayer fabric arrangements and the temperature gradient between the exterior surface of the external shell and internal surface of the interior layer is given by ***Equation (4)*** [25]:

$$I_T = \frac{T_o - T_i}{H_t} \tag{4}$$

In this equation and are the outside surface temperature of the exterior shell and inside surface temperature of the interior layer (°C), correspondingly [30]. is the heat exhaust in (W/m^2) in the multilayer fabric arrangement (W/m^2), evaluated by ***Equation (5)***:

$$H_t = R_0 - R_1 - C \tag{5}$$

is the thermal radiation from the cone heater in (W/m^2) acquired by the surface of the specimen being tested. is the incident heat flux acquired by the radiant flux sensor (W/m^2). C is the exhaustion of heat by natural convection within the air gap between the interior layer and flux sensor (W/m^2), evaluated by ***Equation (6)***:

$$C = h_c(T_i - T_h) \tag{6}$$

is the exterior surface temperature of the radiant flux sensor (°C). is the convective heat exchange coefficient in (W/m^{-2}/°C^{-1}) and is determined by ***Equation (7)***, obtained from Incropera et al in [28]:

$$h_c = \begin{cases} 0.59\lambda_a \dfrac{Ra^{1/4}, Ra \leq 10^9}{L} \\ 0.1\lambda_a \dfrac{Ra^{1/3}, Ra > 10^9}{L} \end{cases} \tag{7}$$

is the thermal conductivity coefficient of air (Wm^{-1}/°C^{-1}), L the the breadth of the clothing assembly, and is the Rayleigh number, discussed in detail by Incropera et al. [28].

The outcomes of the experiments conducted by Fu et al [25] reveal that the overall thermal insulation of multilayer protective clothing in a regular climate exceeds the elevated temperature climate and declines with the incrementing external radiant flux. The results in the investigation also raise awareness of the impact of the local thermal resistance of each fabric layer and air gap on the overall thermal insulation, demonstrating that gaps of air contribute to improve overall thermal insulation and, hence, deliver increased heat protection against heat exchange from exterior thermal radiation to several layers of the clothing assembly [25].

Barker, Shalev and Lee [29] speak comprehensively on the usage of TPP (NFPA 1971) test methodology to determine the thermal behaviour of individual layered fabrics in elevated temperature encounters. The radiant protective performance of single layer fabrics was evaluated using a RPP tester by Sun [30]. The outcomes revealed that the thermal resistance of textile substrates was primarily associated with the chemical and physical morphology of the textile substrates [31]. Firefighters can acquire burns in thermal encounters which are substantially more minor than flashover conditions. These burns are acquired due to prolonged exposure to thermal climates designated as routine or hazardous situations [32]. The two main characteristics of the clothing which influence thermal equilibrium between the human body and the climate are the thermal resistance (R_{ct}) and the resistance due to evaporation (R_{et}) [7].

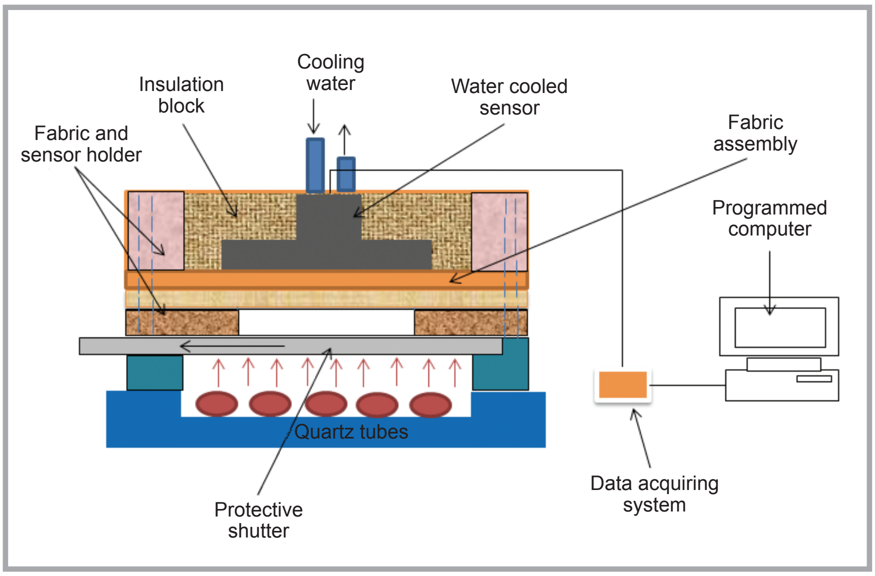

Figure 3. *Schematic diagram of apparatus utilised to evaluate thermal protective performance* [7].

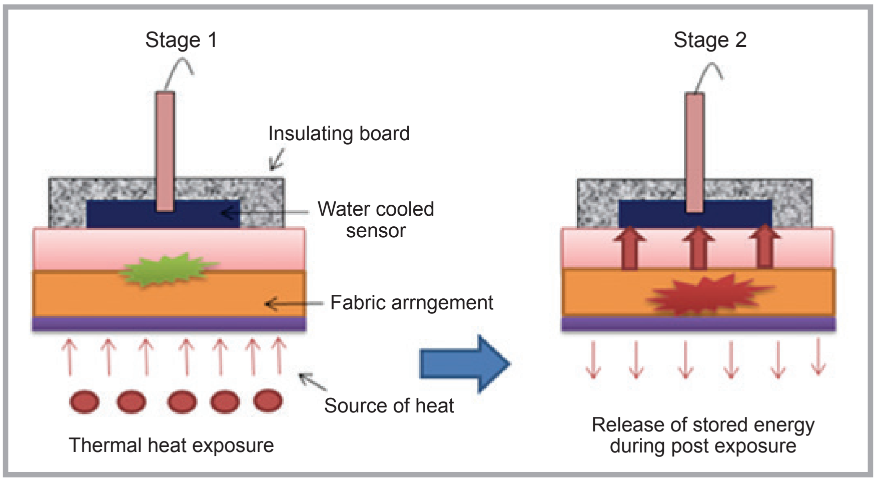

Figure 4. *Stored-energy test schematic methodology for acquisition of data [7].*

Song et al [7] conducted a study to investigate the thermal protective behaviour of a clothing assembly in low level radiant heat within the limits of 6.3-8.3 kW/m^2 by employing two different methodologies. The fabric schemes were developed as individual layer and two layer combinations as well as multilayer composite systems. The extrinsic layer was made up of 100% meta aramid (woven); the thermal barrier was also made up of 100% meta aramid (nonwoven), and 100% wool was utilised in the intrinsic layer. Quartz tubes were employed as the origin of radiation heat as per standard ASTM F 1939 for evaluating radiant heat resistance. The specimen holder and water cooled sensor used in the apparatus are demonstrated in ***Figure 2*** [7].

Two methodologies employed in the study conducted by Song et al [7] for evaluating the thermal protective performance of clothing assemblies are TPP/RPP methodology and stored-energy methodology: TPP/RPP methodology acknowledges energy transmitted through the fabric assembly when subjected to a source of radiation, whereas stored-energy methodology indicates that thermal energy is retained in exposed the test sample after encountering a radiation heat source [7]. The test equipment, with radiant heat source, sample holder, water cooled sensor, data collection system and programmed skin burn prediction software, is presented in ***Figure 3***.

In TPP/RPP methodology, the overall energy supplied to sensors is acquired from that transported during confrontation with thermal heat and aggregates to a degree that might create a skin burn wound [7]. Stored energy methodology is a two stage procedure: the thermal heat confrontation stage and cooling stage. In this methodology, the entire energy creating skin burn damage comprises energy transferred during confrontation and that released in the duration of cooling. A smaller confrontation time is essential to generate predicted burn damage in stored-energy methodology [7].

Prediction of physiological load of multilayer protecting clothing

Song et al [7] determined the thermal resistance R_{ct} and evaporative heat resistance (R_{et}) of a fabric assembly in accordance with ASTM F 1868. This method is a standard test approach for evaluating the thermal and evaporative resistance of fabric substrates by utilising a sweating hot plate. The total heat loss (THL) was measured from ***Equation (8)*** given below [7]:

$$Q_t = \frac{10^oC}{0.04K.m^2.W^{-1} + R_{cs}} + \\ + \frac{3.57\ kPa}{0.0035kPa.m^2.W^{-1} + R_{es}} \quad (8)$$

In the above-mentioned equation, is the total heat loss, the average internal thermal resistance of the sample, and is the average internal evaporative resistance of the specimen [7]. It was concluded that for low level radiant heat flux i.e. from 6.3 to 8.3 kW/m^2, a three layer thermal protective clothing assembly is mandatory to protect skin from burn wounds. The protection time for these clothing assemblies is expected to be from 60 to 300 seconds utilizing TPP/RPP methodology, which does not consider the release of thermal energy retained in the clothing assembly. Nonetheless there was a decline in the protection time for the fabric assemblies chosen, from 30 to 180 seconds in the case of stored-energy methodology [7]. The thermal energy retained in the fabric assembly might be released after encountering radiant heat, resulting in skin burn wounds. Consequently the stored thermal energy is expected to have a lower exposure time period as compared to the TPP/RPP approach due to amalgamation of transferred and stored energy after exposure to a radiant heat source [7]. It was also revealed that the influence of moisture on thermal protective behavior when faced with a low level of radiation heat is a complicated phenomenon because it is dependent on the quantity of retained moisture, transmission of moisture in the fabric layer assembly and magnitude of exposure etc. [7]. Several test methodologies like bench-scale investigations [30,33] and a full-scale instrumented human manikin [34] are applicable for determining the thermal protective behaviour of a protective garment in emergency situations [35].

Torvi et al. [36] employed bench-top testing, numerical modelling and flow visualisation experimentations with and without an air gap between the fabric specimen and sensors to investigate the influence of the air gap dimension. The outcomes revealed that there is an occurrence of free convection in air gaps of 6-7 mm size. Ghazy et al. [37] formulated a heat transfer model with both conduction and radiation in the air gap between the human skin and textile substrate, in order to examine the transmission of heat in a protective garment during a flash fire of 83 kW/m^2 for a duration of 10 seconds, succeeded by 90 seconds of a cooling span . The thermal behaviour of a protective garment is largely influenced by the dimension placement of the air gap [36-38] [25] and the air volume fraction [38].

Fu et al [39] investigated the thermal performance of firefighter protective clothing entangling several air gaps and subjected to low level heat fluxes by utilising bench-scale test equipment. To analyse the effect of air, a conical radiant electrical heater, indicated in ISO 5660-1:2002 [40, 41], was selected to distribute the requisite amount of thermal radiation and was extensively employed to replicate heat flux equivalent to small or medium fire situations [27]. The heat flux from conical heater was attached to sample surface was set at 2, 5 and 10 kW/m^2 [39].

In the middle of the specimen holder, a radiant flux sensor was fixed to resemble the incident heat flux density acquired by human skin [42]. In a research conducted by Torvi et al [36], the air gap between individual fabric layers was investigated by allocating a size range of 2-10 mm.

While Fu et al [39] performed a study in which the placement of air gaps was at 0, 2 and 5 mm. Thermocouples were utilised to evaluate the dissemination of temperature all the way through the clothing arrangements, according to NISTIR 7467 [43] and studies of Keiser et al [44].

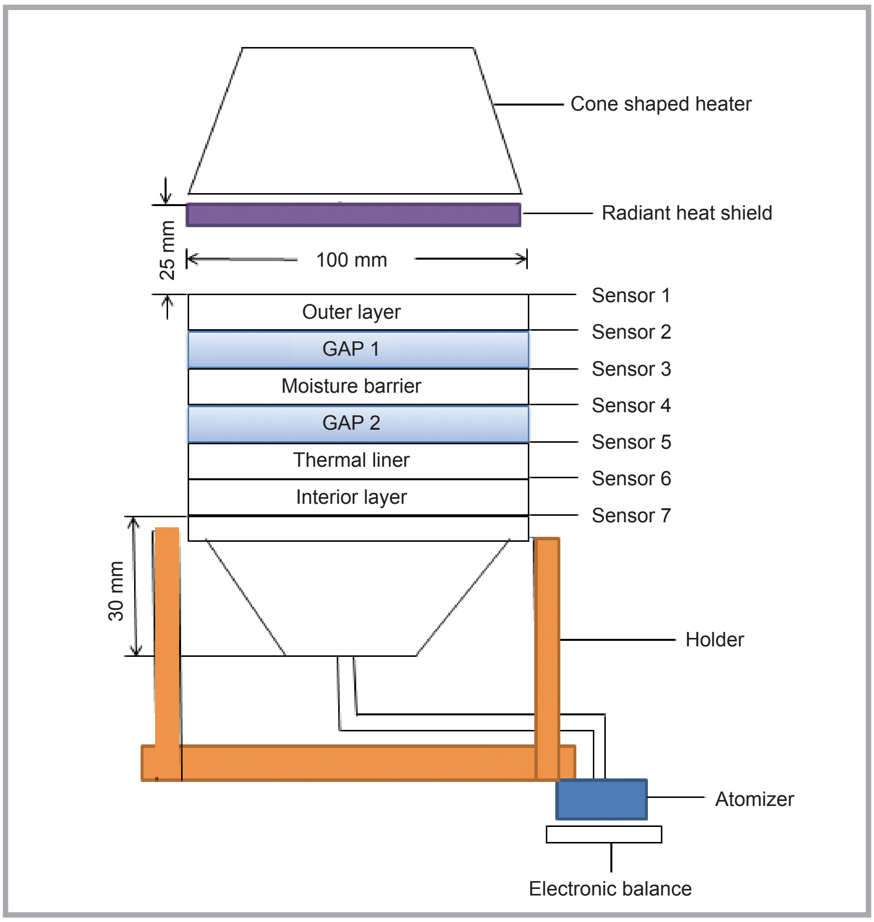

***Figure 5.** Schematic diagram of bench-scale test equipment [48].*

Influence of air gaps on protective behaviour of multilayer fire fighter clothing

Fu et al [39] found that the temperature at the back of the interior layer and incident heat flux acquired by the skin escalates with incrementing exterior heat flux, and there is decrease in the thermal protective behaviour of the multilayer clothing assembly on facing a reduced level of radiation heat flux, with or without the air gap. It was also deduced that the duration for skin injury when having a straight connection with interior layer increments with an expanding size of the air gap is owing to enhancement in the entire thermal resistance of the clothing assembly [39]. Furthermore it was noted that the air gap enhances the thermal behaviour of the clothing assembly against low level thermal heat flux over a lengthy period of time [39]. Several scientists have examined the thermal performance of protective clothing when facing a low level of radiant flux in moisture conditions [45-47]. The dissemination of temperature in clothing layers were examined by Keiser and Rossi [44] to investigate the evaporation phenomena at 5kW/m^2 for a duration of 10 minutes, and the outcomes revealed that moisture had a strong influence on the behaviour of thermal protection. Nevertheless, in earlier wetting methodologies, samples being tested were submerged in distilled water and surplus water was evacuated by squeezing the fabric samples [44-47]. There is no agreement of this wetting procedure with real human sweat transmitted from the layer of skin to the fabric assembly. Furthermore these past researches focused on the qualitative investigations of the influence of the air gap in wet conditions [44-47].

Fu et al [48] conducted experimental studies to examine the influence of multiple air gaps ensnared in a multilayer fabric arrangement at a reduced-radiation level (2-10 kW/m^2) in moisture conditions. Bench scale equipment generating human sweat was developed to generate drops of liquid and replicate human sweat transmitted through multilayer clothing [48]. Thermal resistance analysis methodology established by Fu et al [39] was employed to differentiate the influence of air gaps entrapped in different positions within clothing. Linear regression was utilised to investigate the impact of radiation on the thermal resistance of the clothing assembly [48]. The test equipment included a heat source, an atomiser with heater, metal frames and sample holders. A cone-shaped radiant electrical heater was employed as source of heat [26] for delivering low and moderate radiant heat flux [49-50]. An atomiser coupled with the cone shape heater was utilised to create drops of liquid for examining the wet test, as shown in figure 5 [48]. The fabric specimen comprised 4 layers and was positioned vertically downwards 25 mm from the cone heater, with the irradiance of the subjected sample surface being uniform within the central 5×5 cm area. A detachable radiant shield was utilised to guard against exposure before the exposure test.

Liquid drops generated by the atomiser were maintained at a constant temperature of 35 °C by the heater, measured by a K thermocouple and regulated by a proportional integral derivative system. All drops generated by the atomiser have a diameter smaller than the fibres, yarns and fabrics utilised for creating the test specimen [48]. For examining the influence of the air gap, metallic frames with varying thicknesses (shown in ***Figure 5***) were utilised to develop different air gap sizes between the exterior shell and moisture barrier (Gap 1) and/or the moisture barrier and thermal liner (Gap 2) [48]. There was no gap between the thermal liner and interior layer. The metal frames were made of stainless steel with dimensions of 12×12 cm. The size of the air gaps were 0, 2 and 5 mm.

When subjected to low level radiant heat for 5 minutes, a quasi-stable state (15-30 minutes) was achieved for temperature dissemination of every substrate layer [51]. Consequently the average temperature of each specimen layer was utilized during a quasi-stable state when examining the thermal resistance of the clothing assembly [39]. It is evident from figure 5 that Gap 1 occurs before Gap 2 for acquiring the exterior heat flux, and the temperature gradient can be decreased through the heat radiation transferred. Furthermore the interior moisture from sweating liquid can decrease the temperature of the interior layers of the protective clothing assembly [48]. The drops of liquid generated from the atomiser are transmitted from the interior layer to the thermal liner. When there is an existence of an air gap (Gap 2) between the moisture barrier and thermal liner, the liquid being absorbed may vaporise and retain a huge quantity of heat from the thermal and interior layer. The thermal liner and interior layer can be cooled by this mechanism [48]. Nonetheless the liquid retained might not be transported through the moisture barrier and there might be condensation of surplus water vapours which are not transmitted out of the moisture barrier, thus dispelling heat to the moisture barrier and exterior shell [7]. Fu et al [48] acknowledged that the total thermal resistance of a multilayer fabric assembly and local thermal resistances of Gaps 1 and 2 decline linearly with the heat flux. It was inferred that the impact of the air gap was not influenced by the dimension of another air gap and that the positive influence of Gap 1 is superior to that of Gap 2, enhancing the thermal behaviour of the fabric arrangement subjected to radiation [48].

Onofrei et al [9] designed a mathematical model of heat transmission in protective clothing facing routine fire situations (low radiant heat flux) for developing a systematic foundation for textile substrates and clothing for optimising the thermal protective performance and comfort. In the past decade, several researches have been performed with respect to the design and mathematical modeling of different features of the physical performance of protective clothing [34, 52, 53]. Two types of mathematical models were formulated [52]:

- One that considers only transmission of heat
- One that consider the transportation of heat and moisture [54-58]

Data acquired in previous years reveal that most burn wounds acquired by firefighters ensued at a low-radiation level (specified as routine or hazardous situations) were due to elongated encounter. Only heat transmission was taken into account by Onofrei et al [9], while the impact of moisture was not investigated. Thermal characteristics of a fabric specimen were evaluated with a Hot Disk TPS 2500 S instrument in accordance with Standard ISO 22007-2:2008 [58], and textile substrates were assumed homogeneous. The research conducted by Onofrei et al [9] was divided into two stages, in first stage a heat transfer model was formulated for forecasting temperature and heat flux in a firefighter protective garment using a COMSOL Metaphysics package based on the finite element method (FEM), and in the second stage, for predicting first and second degree burns, a model of heat transportation through a multilayer protective system was combined with a heat transfer model for the skin [9]. Predictions of the temperature by the model were in good agreement with the experimental temperature. It was also inferred that with an increase in the air gap, there was an increase in time for a first degree burn and second degree burn i.e. by incrementing the size of the air gap, there was a decline in the extent of insulation as there was a decrease in the transmission of heat to the skin [9].

Numerical model of heat transfer

A one dimensional model was assumed because of the length scales of the clothing thickness compared to its surface [9]. For one dimensional heat transmission, the energy equilibrium in the infinitesimal element of the fabric can be illustrated as below:

$$-\frac{\partial}{\partial x}\cdot\left(-\lambda\frac{\partial T}{\partial x}\right)+\gamma q_{rad}e^{-\gamma x}=$$
$$=\rho C_p\frac{\partial T}{\partial t}\quad \text{for } 0<t\leq t_{exp} \qquad (9)$$

$$-\frac{\partial}{\partial x}\cdot\left(-\lambda\frac{\partial T}{\partial x}\right)=$$
$$=\rho C_p\frac{\partial T}{\partial t}\quad \text{for } t>t_{exp} \qquad (10)$$

is the thermal conductivity (W/m K), the density (kg/m^3), C_p the specific heat capacity (J/kg K), the extinction coefficient of the textile substrate (1/m), q_{rad} the incident radiation heat flux (W/m^2), t_{exp} the time of exposure, and x is the linear horizontal coordinate [9]. The extinction coefficient depicting the decline in thermal radiation as it pierces through the textile substrate is expressed by ***Equation (11)***:

$$\gamma=\frac{-\ln(\tau)}{l_{fab}} \qquad (11)$$

Here is the transmissivity of the fabric and is the thickness of the fabric. In the second step of the experimental research conducted by Onofrei et al [9], a model of theheat exchange through multilayer protective garments combined with a heat transfer model of the skin was created, as shown in ***Figure 6***. It was assumed that temperature is dependent only on time and position, T (t, x). Heat conduction and radiation penetrating through the solid medium are contemplated for heat exchange within the textile fabric.

It was presumed that radiation enters through the outer layer of the fabric only. The conduction and radiation transmission process are considered through the air gap. The width of the air gap between the skin and fabric was assumed as 1 mm.

No external air flow nor evaporative heat was considered in this model. The temperature of the epidermis and subcutaneous surface was 33 °C and 37 °C, respectively. The ambient temperature was 20 °C and the metabolic heat considered was 4343 W/ m^3.

Bioheat exchange model

The Pennes model has been utilised by several researchers for modeling heat exchange in living tissue [34, 43, 59, 60]. The skin is separated in three different layers, as mentioned by this model: epidermis, dermis, and subcutaneous, and the overall heat exchange by the flow of blood is proportionate to its rate of volumetric flow and the temperature gradient between the blood and human body tissue [9]. Pennes [34, 43, 59] suggested an equation for highlighting the exchange of heat in human tissue. For one dimensional heat transfer, ***Equation (12)*** is as below [9]:

$$\frac{\partial}{\partial x}\cdot\left(-\lambda\frac{\partial T}{\partial x}\right)+\rho c_p\frac{\partial T}{\partial t}= \\ = Q_m+\rho_b c_b \omega_b (T_b-T) \quad (12)$$

Where is the thermal conductivity (W/m K), the density(kg/m^3), c_p the heat capacity (J/kg K), _________????? the thermal characteristics of t human tissue, ρ_b (kg/m^3) the mass per volume of blood, termed blood density, c_b (J/kg K) the quantity of thermal energy essential for generating a unit temperature variation in the unit mass of blood, labeled as the specific heat of blood, ω_b (1/s) the blood perfusion rate, explaining the volume of blood per second that flows through a unit volume of tissue, T_b is the arterial temperature of blood in kelvin, which is the temperature at which blood escapes the arterial blood veins and arrives in the capillaries, T the temperature of the tissue, measured in kelvin, and Q_m (W/m^3) is the origin of metabolic heat, illustrating the production of heat from the process of metabolisation [42].

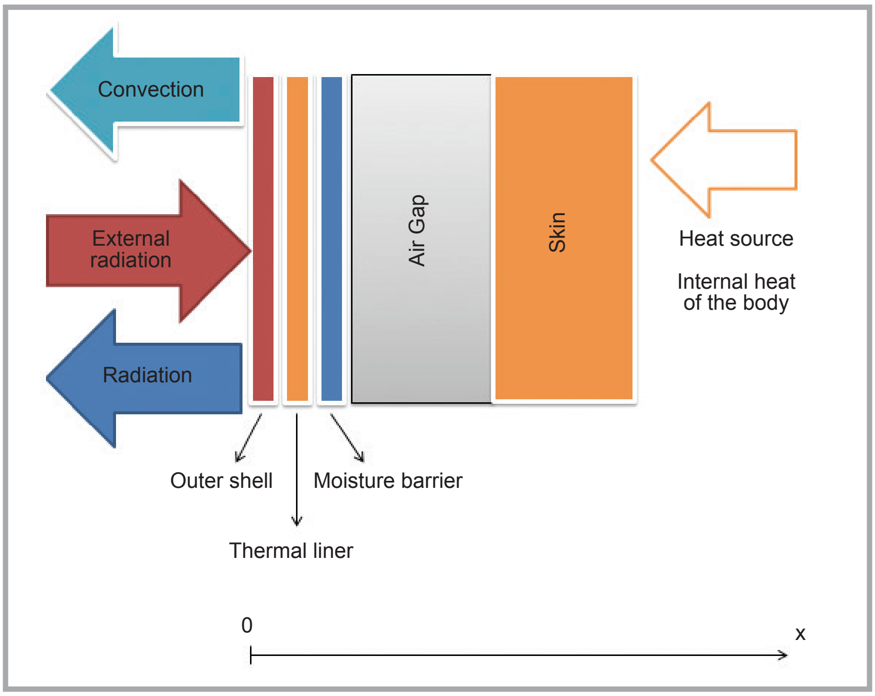

Figure 6. *Schematic cross section of one dimensional heat transfer models [9].*

Model for burning of skin

Henriques and Moritz [43, 78, 86] were pioneers in developing a skin burn injury model, utilising a first-order Arrhenius rate ***Equation (13)*** for evaluating the rate of tissue injury, shown below:

$$\frac{d\Omega}{dt}=P\ exp\left(\frac{-\Delta E}{RT}\right) \quad (13)$$

means quantitative evaluation of burn injury at the basal, the frequency factor (s^{-1}), the energy of activation for the skin (J/mol), the universal gas constant (J/k mol K), T the absolute temperature in kelvin at the basal layer, and t is the overall time for which T is above 317.15 K. By integrating, equation 14 becomes [9]:

$$\Omega=\int_0^t Pexp\left(\frac{-\Delta E}{RT}\right)dt \quad (14)$$

Integration is carried out for a time when the temperature of the basal layer (the interface between the epidermis and dermis in human skin), T, surpasses or equals

Table 2. *Skin and blood properties used in the three-layer skin model.*

	Property	Value
Epidermis	Thickness	8 × 10^{-5} m
	Specific heat	3598 J/Kg K
	Density	1200 Kg/m^3
	Thermal conductivity	0.255 W/m K
Dermis	Thickness	2 × 10^{-3} m
	Specific heat	3222 J/ Kg K
	Density	1200 Kg /m^3
	Thermal conductivity	0.523 W/m K
Subcutaneous	Thickness	1 × 10^{-2} m
	Specific heat	2760 J/Kg K
	Density	1000 Kg/ m^3
	Thermal conductivity	0.167 W/m K
Blood	Blood perfusion rate	1.25 × 10^{-3} m
	Specific heat	3770 J/Kg K
	Density	1060 Kg/m^3

Table 3. *Occurrence of first and second degree burns as concluded by Henriques [43, 74, 78].*

Henriques concluded	If is less than 0.5	No skin damage at basal layer
	If is between 0.5-1.0	First degree burn
	If is greater than 1.0	Second degree burn occurs

44 °C, because harm to the skin starts when the temperature of the basal layer surges above 44 °C. The conclusions of Henriques are mentioned in ***Table 3***.

There is possible applicability for the criteria of P tissue burn damage, if suitable values of and ΔE are known. Weaver and Stoll [69] submitted values for the basal layer: If T is less than 50 °C, then $P = 2.184 \times 10^{124}$ s^{-1} and $\Delta E = 93534.9$ K. If T is greater than 50 °C, then $P = 1.823 \times 10^{51}$ s^{-1} and $\Delta E = 39109.8$ K.

Effect of moisture on the performance of firefighter protective clothing

The influence of interior moisture on heat and mass exchange through a multilayer garment when subjected to thermal radiation has been investigated by several scientists [51, 56, 79, 80, 81, 82, 83, 84]. Barker et al [81] examined the influence of absorbed moisture on the thermal protective behaviour at a low moisture level by employing a thermal testing platform at 6.3 kW/m^2 and it was noted that there was a serious decline in the protective behaviour at a low level of moisture. Zhu and Li [84] determined that moisture enhanced the time period for acquiring a second degree skin burn at a radiant heat flux of 21 kW/m^2. However, there was an enhancement of heat exchange through clothing under a heat flux of 42 kW/m^2. The influence of moisture on thermal insulation is also dependent on thermal radiation [79].

Fu et al [85] carried out another study to examine the coupled influence of moisture and thermal radiation on the thermal protective behaviour of garments subjected to a low level of radiant heat. Fu et al [85] utilised a sweating manikin with 20 independent zones. For all the zones of the manikin, a uniform sweating rate was applied and three different sweating rates (100, 200 and 300 g/m^{2}h) were chosen for research. The manikin was maintained at a constant surface temperature of 35 °C for each zone, as mentioned by ASTM F 1291 [86]. It was concluded that the combined effects of moisture and radiation influences heat loss and wet skin with two noticeably different trends. Heat loss from the manikin increases with the rate of sweating and declines with the intensity of thermal radiation. However, deviations in the wet skin surface temperature with the intensity of radiation and sweating rate reveals an opposite trend [86].

Use of Phase change materials and aerogels for improving protective performance

For almost a decade, many scientists been trying their level best to improve the thermal protective performance of fire fighter protective clothing through the incorporation of phase change materials and silica based aerogels. Zhu et al [66] stated that phase change materials (PCMs) can be utilised to decrease heat stress and enhance the thermal protective performance of firefighter protective clothing under a higher level of heat flux. Shape stabilised PCMs were utilized in firefighter protective clothing and it was noted that fabrics with PCMs yield a higher heat protection time in comparison to parent fabrics. However, this thermal protection is temporary, which is a kind of drawback of PCMs. Shahid et al [67] and Jin et al [68] applied aerogel particles to nonwoven fabrics and utilized them as a thermal liner, discovering aerogel can enhance the thermal protective performance of firefighter protective clothing.

Conslusions

It can be summarised that firefighter protective clothing must have at least three layers i.e. an outer shell, moisture barrier and thermal barrier, even when exposed to a low level of radiant heat flux. The thermal insulation property can be measured through tests like the bench scale test, heat guard plate test or full-scale test. Like with a thermal manikin. For TPP/RPP methodology energy is exchanged through the fabric arrangement when exposed to a source of radiation. In the case of stored energy methodology, heat energy is reserved in the specimen after being exposed to a radiant heat source. It was also deduced that the impact of the air gap and entire thermal resistance of multilayer protective clothing declines linearly with an increasing heat flux. When studying the combined influence of thermal radiation and moisture on firefighter protective clothing in confronting a low level of heat, it was noticed that heat discharged from the sweating manikin increases with the rate of sweating and declines with the intensity of thermal radiation. However, a reverse trend was witnessed in the case of a wet skin surface. When the Pennes model was employed for simulation of the transfer of heat in living tissue, the skin is separated in three separate layers i.e. the epidermis, dermis and subcutaneous layers. The period of exposure during which FFPC shields the firefighter from acquiring first and second degree burns can be predicted by employing the Henriques equation. Thermal protective performance can be improved by inculcating silica based aerogel particles or phase change materials. The more the improvement in the thermal protective capability of firefighter protective clothing, the more time can be used by firefighters to perform their duties when exposed to radiant heat flux.

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