International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-9 Issue-2, December, 2019

The Effect of Air Gap and Moisture for the Skin Burn Injury of the Firefighter's Personal Protective Clothing (PPC)

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Abstract*: *Fire fighters are commonly exposed to intense heat and fire. They suppressed fire by spraying water to avoid flame from spreading. They are enforced to use the Personal Protective Clothing (PPC) made of the flame-retardant material to protect themselves from the skin burn injury. Skin burn injury is the most common injury occurs among them. Yet, the exposure to extreme heat and moisture absorption into the clothing layers caused severe burn injury formation. The purpose of this study is to investigate the effect of air gap combined with the moisture absorption in the fabrics using Finite Element Method (FEM) and the Bio heat Equation. From the simulation experiment it is discovered the air gap is a good insulator capable of preventing skin burn with a skin temperature of 48°C. However, the presence of moisture strongly affects skin temperature. It had elevated to 59.64°C forming a second-degree type burn injury. The presence of moisture had weakened thermal protection of the flame-retardant material and the air gap against the heat flux. It is found the moist material properties had enhanced heat transfer from the heat flux to the skin surface resulting severe skin burn despite they were encapsulated with the Personal Protective Clothing (PPC).

Index Terms*: *Bio Heat, Finite Element Method, Firefighter, Personal Protective Clothing

I.INTRODUCTION

Fire fighters encounter multiple hazards environment with extreme radiant temperature, surrounding temperature, hot gasses, hot liquid splashes, hot objects and extreme heat intensity from the flame [1-3]. In America, it is over 30,000 fire fighters suffer in injuries while fire fighting and emergency rescue cases. Some lose their lives on the job fighting fires, rescue people and responds to hazards incidents. Skin burn injuries are the most common during fire fighting [4]. Therefore, they are enforced to wear the Personal Protective Clothing (PPC) to prevent skin burn or any possible risk of accidents during fire fighting. The Personal Protective Clothing (PPC) imposes barrier against the hazardous environment. It consists of the three layers of flame-retardant material mainly consist of the outer shell, moisture barrier and thermal liner.

Revised Manuscript Received on December 30, 2019.
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The outer shell made of flame-resistant material against thermal radiation or direct flame contact with the primary purpose is to prevent burn injury. The Personal Protective Clothing (PPC) capable of absorbed moisture from human perspiration and surrounding [5]. They often used fire to contain the fire scene however it can cause moisture absorption in the clothing layers. The moisture is significantly affecting the thermal performance of the PPC by the level of heat intensity, radiation and the amount of the inner moisture content [6, 7] . The moisture absorbed in the fabric had enhanced the thermal conductivity of the PPC. It is significantly elevating the thermal conductivity and heat capacity of the flame-retardant material resulting increment amount of stored energy. At high temperature of the heat source, phase change of moisture occur due to the vaporization and condensation process formed steam burn injuries [6]. The study on the effect of moisture related to the heat and mass transfer the exposure of the heat flux and radiation had been studied extensively by many researchers [6, 8, 9]. The moisture had severely reduced thermal protection at 6.3kW/m^2 using the thermal testing platform [8]. The moisture had elevates the threshold of second degree burn with heat flux 21kw/m^2 and 42kw/m^2[10].Thermal manikin is used to investigate the influence of radiation and moisture on the heat transfer, he found that heat loss from the thermal manikin elevates with the sweat rate and decreased the intensity of the thermal radiation[11]. Hence significantly increased the skin temperature over time. Other researchers found the presence of moisture compromised the thermal protection of the PPC with the radiant heat intensity [12, 13].

Air gap has strong influence with the thermal protection of the PPC [14, 15]. Posture change and physical movement continually change the air gap size. Air gap holds low thermal conductivity and specific heat capacity can provide insulator against heat. The air possess good thermal insulator as it's material thermal conductivity is less than the fabrics [16]. The air gap can significantly improve as the air gap reached 6.4mm thickness between fabric and the sensor [17]. The air gap thickness that located between the fabric and skin layer the thickness varies at each of body location [15].

The Thermal Protective Performance (TPP) laboratory experiment is conducted to determine the thermal protection under conditions similar to the hazard at the fire scene [18]. the threshold of the second degree burn significantly affects by the air gap thickness under heat flux of 84k/Wm^2[19]. However [20] found the threshold decreased with the initial exposure and later improved the thermal protection. [21] Reported the PPC exposed to high radiant heat of 84kW/m^2 capable to provide thermal protection against skin burn injury as the air gap thickened.

The air gap thickness capable to lengthen the threshold time to second degree burn of low radiant heat [9, 22]. Furthermore, the influence of air gap thickness capable provide protection not only burn injury but also steam burn injury [23].

The air gap and moisture both criteria had positive and negative effect of the thermal protection. It is important to understand how these two combinations of air gap thickness and moisture affect the thermal protection of the PPC. The previous study, [24] did quantitative study the significant factors that affect thermal performance evaluation of the effect of the air gap thickness exposed under intense radiant heat source for both moist and dry fabric. [21] did bench scale experiment on the air gap size of the thermal insulation of the flame resistant fabrics with variation of moisture content. He found the moisture improved the thermal protection for the PPC if the air gap thickness less than 12mm. On contrary, [24] stated the moisture content had been weakened the thermal protection of the air gap and almost eliminated the effect as the insulator. He concluded the air gap in the fabrics can improve the thermal protection however it is complexes by the presence of moisture absorbed in the clothing layers. Furthermore the different amount moisture content of a different fabric of a multiple layer shows variation of tendency on the heat transfer through the skin surface [6]. [25] Suggested there is a need to improvised the moistening system and improve the current methods for evaluating the thermal performance of PPC material.

[26] had developed a heat transfer model to assess the thermal protection of the PPC using Finite Element Method (FEM) and the Bio heat equation. This model capable to predict skin burn under the influence of the air gap and moisture. This numerical method is new practical approach of predicting skin burn rather than conducting exhaustive experimentation.

This study is to investigate the effect of air gap combined with moisture absorption in the fabrics using new practical approach method the finite Element Analysis (FEM) and the Bio heat Equation. The objective of this investigation is to identify combination of the air gap and also moisture content towards the skin burn injury.

II. METHODOLOGY

The analysis begins with solving the bio heat equation which is merely a steady conduction heat transfer of living tissue. The equation also includes the heat generated by the metabolic and blood profusion rates. The equation solves heat transfer at muscle layer to determine the temperature between skin layers and muscle which in turn this temperature was used as a boundary condition in the finite element analysis. The ANSYS software version 14 was used as a tool to perform the finite element analysis under transient conditions.

A. Mathematical Model

Pennes [27] introduced a modification of heat transfer in living tissue phenomena by considering the human metabolic heat generation and the heat exchange of thermal energy of blood flow and the surrounding tissue.

$$\frac{d^2T}{dx^2} + \frac{\dot{q}_m + \dot{q}_p}{k} = 0 \qquad \textbf{(1)}$$

Where $\dot{q}_m$ and $\dot{q}_p$ is the metabolic and profusion heat rates. While the thermal conductivity k is assumes to be constant.

$$\dot{q}_p = w\rho_b c_b(T_a - T) \qquad \textbf{(2)}$$

Equation (2) represents the heat transfer rate of the blood flowing in the small capillaries. The inlet (arterial temperature) and exit temperatures of the blood are denoted as Ta and T, respectively. The rate at which the skin tissue layer gains the heat is the rate at which the blood loses the heat. The blood profusion rate is denoted as w (m^3/s of the volumetric blood flow) while ρ_b and c_b are the blood density and specific heat respectively.

Consider a human body that has a muscle thickness, L_m=34.2mm and a skin fat thickness, Lsf of 12.08mm [28] as illustrated in the Figure 1. The surface area of the skin is estimated 1.8m^2[29]. The core body temperature Tc and arterial temperature Ta are assumed to be 37ºC respectively. The metabolic heat generation rate of the person in a sedentary situation at the upper arm $\dot{q}_m$=684W/m^3[30].The radiation coefficient hr is 5.49 W/m2.K. The surrounding temp T_∞ is assumed 30ºC. Table 1 shows the material properties of the human's muscle, skin and blood.

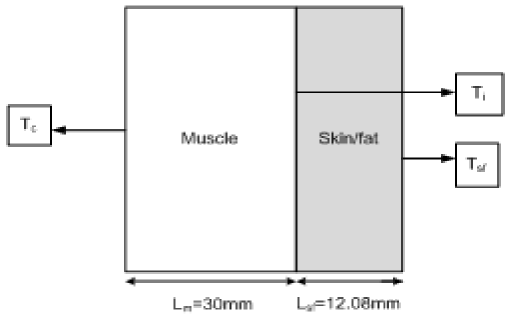

Fig. 1 The bio heat model

Table. 1 Properties of human's muscle, skin and blood [26]

Properties	Value
Blood density [31]	1060 kg/m^3
Blood specific heat [29].	3770 K/kg.K
Blood profusion rate [29].	1.25x$10^{-3}s^{-1}$
Muscle thermal conductivity [30]	0.42 W/mK
Muscle density [30]	1085 kg/m^3
Muscle specific heat capacity [30]	3768 J/kg.K
Skin fat thermal conductivity [32]	0.293 W/m.K
Skin fat emissivity [32]	0.95

The surface temperature at muscle T_i[26]

Retrieval Number: B4943129219/2019©BEIESP
DOI: 10.35940/ijeat.B4943.129219
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

$$T_i = \frac{T_\infty sinh\tilde{m}L_m + k_m A\tilde{m}R_{tot}\left[\frac{\theta_c + \left(T_a + \frac{\dot{q_m}}{w\rho_b c_b}\right)}{cosh(L_m}\right]}{sinh\,\tilde{m}L_m + k_m A\tilde{m}R_{tot}cosh\tilde{m}L_m} \quad (3)$$

Where

$$\tilde{m} = \sqrt{\frac{w\rho_b c_b}{k_m}} \quad (4)$$

the skin temperature is [26]

$$T_{sf} = \frac{q_{cond|x=Lsf} + h_r T_\infty}{h_r} \quad (5)$$

B. Finite Element Model

A simplified one-dimensional multi-layer of the clothing materials was developed using ANSYS transient thermal finite element software as shown in Figure 2. The model in quarter cylindrical geometry represents the human arm this geometry similar to [33-35] .The clothing materials consist of three layers, namely, outer shell, thermal liner and moisture barrier. The air gap was located between the fabrics and skin layers. The effects of the air gap thickness on the skin temperature, Ti was evaluated based on six different thicknesses, specifically 1 mm, 2 mm, 3 mm, 4 mm,5 mm and 6 mm. The analysis included moisture absorbed in the porous materials. Table 2 shows the thickness of each layer.

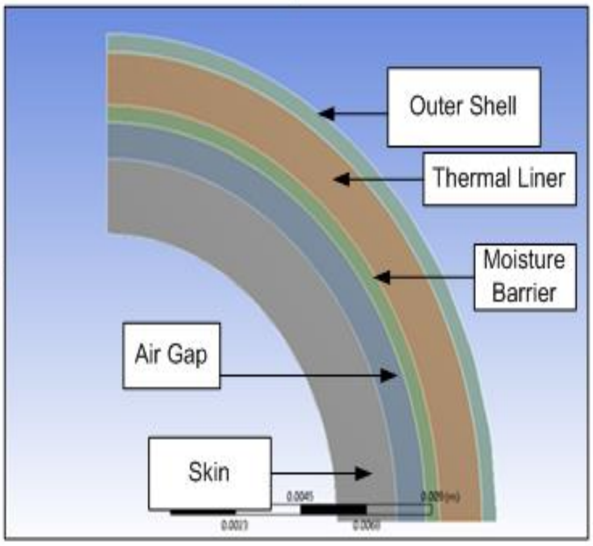

Fig. 2 The model Structure

Table 2. Dimension

Layers	Thickness (mm)
Skin	12.08
Air gap	1.00
Moisture barrier	0.47
Thermal barrier	1.46
Outer Shell	0.50

C. Material Properties

The type of material was defined as aramid since it has a high insulator thermal protective performance fabric commonly used during fire suppression. Table 3 shows the material properties of clothing material. The outer shell is made of polyurethane coated with 100% aramid, while the thermal barrier and moisture barrier are made of 100% aramid. The material properties for the protective clothing were given in Table 3.

Table. 3 Material properties of the PPC

Layers	Moisture Barrier	Thermal Barrier	Outer Shell	Air
Density (kg/m^3)	489	67	418	1.184
Emissivity	-	-	0.9	-
Thermal conductivity (W/mK)	0.1154	0.0633	0.09	0.02551
Specific heat capacity (J/kg.K)	951	2113	1011	1007

The determination of the material properties in wet condition is by using [35] prediction steam burn injury model equation. It applies [36] method of determining the material properties of the porous material. For this case the moisture absorbs in the porous material, as the material are exposed to continuous heat exposure phase change of moisture occur from liquid to solid within the porous material. This is due to the vaporization and evaporation process. The two phase phase model consists of bound water and water vapor is developed with multi-layer PPC configuration subjected to constant heat flux. The effect of moisture is carefully analyzed toward the skin burn injury. The skin model is employed for initial value of human skin temperature. The burn injury evaluation based on [37]. Hence the material properties of the flame-retardant fabric directly change with the heat exposure time.

The effective density ρ of the fabric can be calculated as [38]

$$\rho = \varepsilon_{bw}\rho_w + \varepsilon_{ds}\rho_{ds} + \varepsilon_\gamma(\rho_v + \rho_a) \quad (6)$$

Where

ε_{bw} is the volume fraction of water absorbed in solid phase
ε_{ds} is the volume fraction of the dry solid fiber (constant)
ε_γ is the volume fraction in the gas phase
ρ_w is the water density
ρ_{ds} is the density of dry solid
ρ_v is the density of water vapour
ρ_a is the density of dry air

The effective specific heat c_p of the fabric [38]

$$c_p = \frac{\varepsilon_{bw}\rho_w(c_p)_w + \varepsilon_{ds}\rho_{ds}(c_p)_{ds} + \varepsilon_\gamma[\rho_v(c_p)_v + \rho_a(c_p)_a]}{\rho} \quad (7)$$

Where

$(c_p)_w$ is the specific heat of liquid water

$(c_p)_{ds}$ is the specific heat of dry solid

$(c_p)_v$ is the specific heat of water vapor

$(c_p)_a$ is the specific heat of dry air

The effective thermal conductivity of the fabric k_{eff}[38]

$$k_{eff} = k_\gamma \left\{ \frac{1 + (\varepsilon_{bw} + \varepsilon_{ds})k_\sigma + \varepsilon_\gamma k_\gamma}{\varepsilon_\gamma k_\sigma + [1 + (\varepsilon_{bw} + \varepsilon_{ds})]k_\gamma} \right\} \quad (8)$$

Where

k_σ is the thermal conductivity of the solid phase

k_γ is the thermal conductivity of the gas phase

The thermal conductivity of the gas phase k_γ[38]

$$k_\gamma = \left(\frac{k_v\rho_v + k_a\rho_a}{\rho_v + \rho_a} \right) \quad (9)$$

Where

k_v is the thermal conductivity of the saturated water vapor

k_a is the thermal conductivity of the dry air

The thermal conductivity of the solid phase k_σ[38]

Where

k_w is the thermal conductivity of the liquid water

k_{ds} is the thermal conductivity of the dry solid

Table. 4 The material properties of the porous fabric [39]

Property	Outer Shell: Kombat 7.5 oz/yd^2	Moisture Barrier: Comfort Zone	Thermal Liner: Aralite
Density of dry solid ρ_{ds} (kgm-3)	1384	1295	1380
Specific heat of dry solid $(c_p)_{ds}$ (Jkg^{-1}K^{-1})	1420	1325	1200
Thermal conductivity of the dry solid k_{ds} (Wm^{-1}K^{-1})	0.179	0.144	0.130

D. Boundary Conditions

Figure 3 shows the boundary condition defined for the model is by referring to [33]. Bio heat equation was used to determine the initial value of the inner surface skin temperature precisely, at the E-layer. The initial inner surface temperature was fixed at 38.8ºC. Heat flux was defined at the outermost layer for describing the real flame, specifically at the D-layer. The analysis considered the effect of radiation heat transfer by specifying emissivity values on each A-layer, B-layer and C-layer, respectively as shown in Figure 4. The simulation was performed under a transient condition in a duration of 60 seconds. The initial ambient temperature was specified at 22°C as prescribed by the [40].

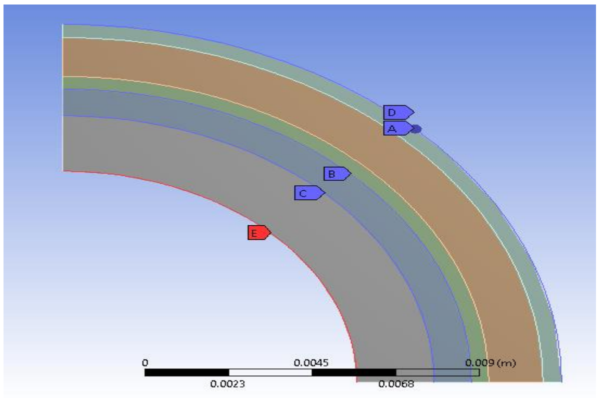

Fig. 3 Boundary Condition

E. Mesh

Figure 4 shows the type of element used for meshing the model follows. The type of element used is quadrilateral uniform.

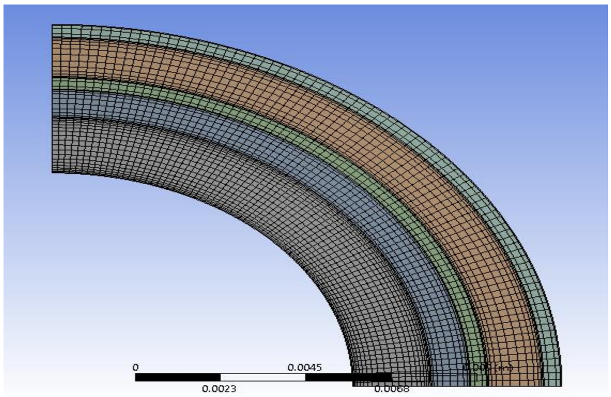

Fig. 4 Mesh structure

The nodes at each interface were kept unbroken to promote a continuous physical interaction between heat flux and material properties to produce a realistic interface temperature.

The number of element at each layer from the outer layer to the inner layer is kept constant in order to ensure the nodes is unbroken. The aspect ratio for each element was fixed as 1:1. However, the aspect ratio decreases with the thickness of the layers.

III.RESULTS AND DISCUSSION

Figure 5 shows the plot of skin temperature against time with the variation of air gap. The figure shows the air gap thickness directly affects the skin temperature. It is observed the reduction of air gap increases skin temperature. However, the skin temperature intensifies without air gap structure. It is noticed the skin temperature reduced to 10°C with air gap thickness of 1mm. The skin temperature reduced further as the air gap thickened.

This is due to the air gap material properties holds low thermal conductivity and specific heat capacity capable to provide insulator against heat. The air is good thermal insulator as the thermal conductivity lower than the flame-retardant fabrics[16]. However, without air gap structure the buffer regions seem had removed from causing enhancement of the heat transmission from the heat flux throughout the multi layers of the protective clothing. Air gap thickness has strong influence with the thermal protection of the PPC [14, 15]. Posture change and physical movement continually change the air gap size.

It is predicted the first degree burn formed without air gap structure with the threshold time of 10s of the heat exposure. This indicates the firefighters experience pain and irritations at the skin surface if the air gap thickness of 1mm. Yet, it does not achieve skin burn injury as the thicknesses increased. The air gap thickness fluctuates depending with the garment fabric material stiffness and affects material drapability [15]. The human posture is another factor affecting the air gap thickness. He predicted the skin burns injury occurred at the smallest air gap location.

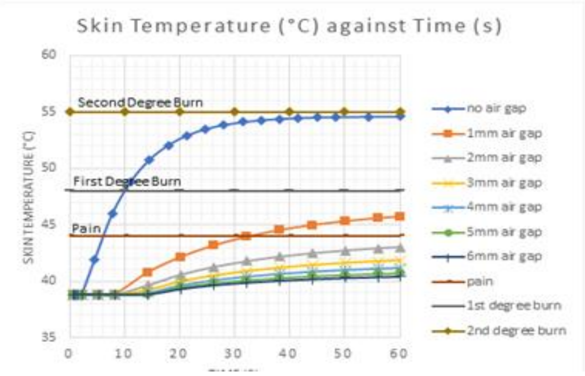

Fig. 5 Skin temperature against time in dry condition

Figure 6 shows the skin temperature against time with the variation of air gap in wet condition. The heat flux is 4000W/m^2 and remained constant for 60second of the simulation. It predicted that the firefighter feel pain with air gap value of 1mm and 2mm. Compare with the dry material the predicted pain only occurs at 1mm air gap.

However, the skin temperature is further reduced with 4°C with the increment of air gap thickness 2mm. From the plot, the presence of air gap significantly upgraded the thermal protection with the air gap thickness of more than 2mm. Air gap is an insulator which holds low thermal conductivity that capable to limits heat transfer from the heat source to the skin surface.

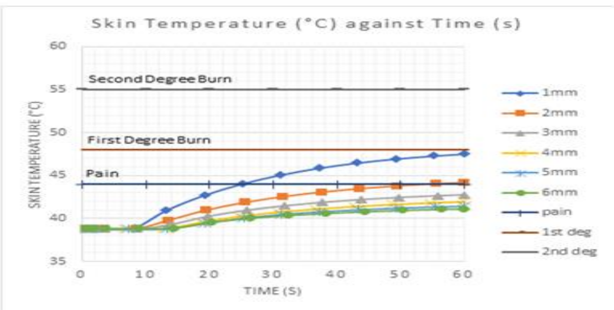

Fig. 6 skin temperature against time in wet condition

However, it is observed the air gap effect is weakened with the presence of moisture absorbed in the flame-retardant material. It is noticed that there is small difference of the skin temperature less than 1°C for 4mm to 6 mm thickness. The findings is consistent with [24] work. The moisture is significantly affecting the thermal performance of the PPC by the level of heat intensity, radiation and the amount of the inner moisture content [6, 7] . Hence presence of moisture had compromised the insulation of the air gap as the material properties of the fabric had been altered. The material properties with moisture content capable to enhanced heat transfer. As it possess high value of thermal conductivity that compromised the thermal protection provide by PPC in dry condition.

IV.CONCLUSION

From the experiment it is concluded that the air gap thickness capable to prevent skin burn injury in dry condition. However the presence of moisture absorbed in the multi layers PPC had weakened the air gap insulation and compromised thermal protection that provided by the flame retardant fabric. This is due the alteration of the effective material properties of the porous PPC with the moisture content.

ACKNOWLEDGEMENT

This research work is funded by Geran Universiti Penyelidikan (GUP) QJ130000.2524.18H79 provided by Universiti Teknologi Malaysia (UTM).

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Masine Md. Tap is an Associate Professor at School of Mechanical Engineering Faculty of Engineering at Universiti Teknologi Malaysia (UTM).She received Bachelor of Engineering of Mechanical Industrial Engineering (UTM) and Master's of Philosophy at Heriot Watt University. Her PhD in Manufacturing at Dundee University. Her research areas in ergonomics and safety, work design, industrial engineering, metrology, engineering economy, project management, operation research, CAD/CAM, human factor engineering, advanced engineering economy and finance. She received 3 university funded grants and 3 national grants. She has published3 books, 11 indexed publications, 4 non indexed publication and 9 other publications. She is an editor of Jurnal Teknology UTM and also reviewer of Jurnal Teknologi, FKM, UTM. In 2004 she received award of excellent service UTM and award of excellent service (teaching) FKM UTM. She has 2 patents and 2 copyright materials.

Haslinda Mohamed Kamar is an Associate Professor at School of Mechanical Engineering Faculty of Engineering at Universiti Teknologi Malaysia (UTM). She graduated from Mechanical Engineering of University of Glasgow. Her research areas in automotive air conditioning, thermal comfort and Indoor Air Quality (IAQ), Computional Fluid Dynamic (CFD) and Finite Element Analysis (FEA). She received 5 university funded grants and 2 national grants. She has published 28 indexed publications, 10 non indexed publications and 35 others publications. Currently supervised 10 PhD students and 4 Master students.

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