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APPLICATION BIOHEAT EQUATION FOR HEAT TRANSFER MODEL OF FIREFIGHTER'S BURN INJURY

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Abstract

Firefighting is a life-threatening situation, they are exposed to extreme heat fire and explosion. Burn injury is the most common injury occur in firefighting. The firefighters are enforced to used personal protective clothing to protect them against fire. The purpose of the study is to assess the effectiveness of fire fighter's personal protective clothing by utilizing heat transfer model in finite element analysis. The model applied bioheat equation to solve heat transfer through living tissue at muscle area with consideration of metabolic heat generation and blood profusion. The validation of the heat transfer model was performed by comparing the predicted and measured skin temperatures with an acceptable error of less than 20%. The study found the skin temperature increases significantly with the heat flux intensities. The heat flux of 1200W/m^2 causes to skin temperature 38.3°C. Skin temperature will gradually rise at t = 0 second and approaches it's steady at t =198 seconds. The maximum air gap thickness reduces the heat stress effect. The reduction of 1 mm air gap thickness contributes to an increment of 0.2°C of the skin temperature.

Keywords: Fire fighter, heat stress, bioheat, heat transfer, heat stress.

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1. Introduction

Thermal protective clothing is primarily designed to provide protection from thermal hazards which include exposure to high temperature radiant sources, flame impingement, hot liquids and gasses. It is difficult to completely define the nature and characteristics of these thermal hazards, because of the many environmental and physical factors involved. Thermal hazards can be quantified through heat transfer analysis. Heat transfer from the thermal hazards can be transmitted by radiation, convection or conduction, or a combination of all. Heat flux transmitted by thermal hazards ranges from 20 – 160 kW/m^2 and can be encountered during large fires and explosions (He, Park, Li, & Kim, 2017). Severe thermal problems and life threatening injuries are associated with these conditions. For the existing protective clothing, the tolerance time for people that can sustain such heat flux intensities is in the range of 5 to 20 seconds (Barr, Gregson, & Reilly, 2010).

Approximately 100 firefighters suffer from fatal injuries in the USA annually and over 30,000 firefighters are subject to injuries while firefighting (Karter, 2012). From 2007 to 2012, firefighters who suffered from skin burn injuries received them most frequently in the head area (38%), the arm or hand (30%), the neck or shoulder area (16%), and the leg or foot (8%) (Karter, 2012). It is shown from the etiology of injuries to firefighters that scald burns were responsible for injury (65%) and flame burns caused injury to 20% of firefighters. However, other 15% patients received contact or compression burns (Kahn, Patel, Lentz, & Bell, 2012).

Quantifying the burn injury from firefighters during firefighting is impossible. Since there are many factors, influence the burn injuries such as heat flux, protective clothing material properties, metabolic rate and blood profusion rate. However, it could be achieved if the temperature of human skin was obtained. The temperature of the human skin can be determined through the Pennes bioheat equation (Pennes, 1948). Blood profusion, metabolic rates and skin tissue layers control the human skin temperature by heat transfer through the human skin's tissue.

Air gap thickness has strong influence to the skin burn. The air gaps that located between human skin and the inner surface of the personal protective clothing developed a buffer region resulting restricted heat transfer from the heat exposure to the human skin. When exposed to the heat, the air gap become an insulator protecting from burn injuries. It provides thermal insulation limits heat transfers to the human skin. A human body scanner was used to study the effect of air gap thickness with thermal manikin (Li, Zhang, & Wang, 2013; Psikuta, Frackiewicz-Kaczmarek, Frydrych, & Rossi, 2012). However, these experiments require complex equipment and exhaustive procedure.

2. Problem Statement

The clothing evaluation for the material was done by using experimental and mathematical model. The experimental consist of three methods known as bench scale test (Song, Cao, & Gholamreza, 2011), thermal manikin test (Barr et al., 2010; Bröde et al., 2008; Fu, Yuan, & Weng, 2015; Havenith et al., 2006; Havenith et al., 2005) and test method for wet sample (Barker, Guerth-Schacher, Grimes, & Hamouda, 2006; Keiser & Rossi, 2008; Wakatsuki, Morii, Ogawa, & Tsuji, 2013; Zhu & Li, 2011; Zhu & Zhou, 2013). There were many types of sensors had been developed to simulate the human body specially to predict the amount of heat transferred through the human bodies during fire exposures. The thermal sensors

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available are TPP/RPP sensor, embedded sensor, skin simulant sensor, PyroCal sensor and water cooled sensor. These sensors commonly used for the thermal protective clothing evaluation (Barker et al., 2006; Sipe, 2004) sensors were embedded to record the amount heat transfer through clothing layer from the heat source. However, all type of sensors were conducted with fixed skin temperature. It is differed with real human skin temperature. During physical activities, core temperature is proportional to the metabolic rate and dependent of the wide range of environment conditions such as ambient temperature and humidity. The skin temperature is depends on skin blood profusion and the environment conditions (Fontana et al., 2017; Kenefick, Cheuvront, & Sawka, 2007). Strenuous physical activities such as running could cause fluctuations in skin temperature (Gan, Cheng, Ding, & Pan, 2010). The blood flow depends on fiber type and moisture level (Tanda, 2016). Therefore, there is a need to imitate the physiology human skin reaction to the environment.

3. Research Questions

How to predict firefighter's skin temperature with the variation of heat fluxes and the air gap thicknesses?

4. Purpose of The Study

This study is a new and practical approach to predict skin temperature by applying the (Pennes, 1948) bioheat equation and finite element analysis. It could lead more accurate model for the evaluation personal protective clothing evaluation. There are many researchers (Chitrphiromsri & Kuznetsov, 2005; Ghazy & Bergstrom, 2011; Onofrei et al., 2015) used bioheat as it is relevant for determination of the skin temperature. The equation takes into consideration the human metabolic rate, the skin material properties, the blood profusion rate. These variables are depending with the human physical activities that could lead to rise on the metabolic heat generation and the human skin temperature. The equation can avoid from using human subject in the climatic chamber which is dangerous and against the principal of humanity.

5. Research Methods

The analysis begins with solving the bioheat equation which is merely a steady conduction heat transfer of living tissue. 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.

5.1. Mathematical Model

Pennes (1948) introduced a modification of heat transfer in living tissue phenomena by adding metabolic heat generation and the heat exchange of thermal energy of flowing blood and the surrounding tissue. Both factors can be identified as the heat sources of heat in the heat transfer equation as the following:

$$\frac{d^2T}{dx^2} + \frac{\dot{q_m} + \dot{q_p}}{k} = 0 \quad (1)$$

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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.

$$\dot{q_p} = w\rho_b c_b (T_a - T) \quad (2)$$

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, Lm=34.2mm and a skin fat thickness, Lsf of 12.08mm (Ogaswara, 2012) as illustrated in the Figure 1. The surface area of the skin is estimated 1.8m² (Onofrei et al., 2015). 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/m3(Fiala, Havenith, Bröde, Kampmann, & Jendritzky, 2012). The radiation coefficient hr is 5.49 W/m2.K. The surrounding temp T_∞ is assumed 30°C. Table 1 shows the material properties of the human's muscle, skin and blood.

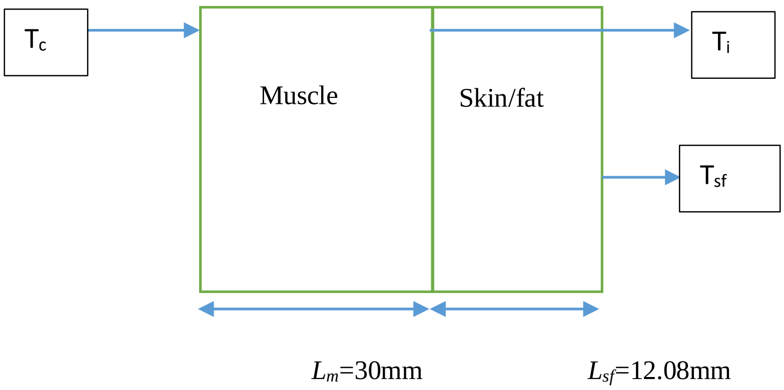

Figure 01. The Bioheat Model

Table 01. Properties of Human's Muscle, Skin and Blood

Properties	Value
Blood density (Onofrei et al., 2015)	1060 kg/m^3
Blood specific heat (Onofrei et al., 2015)	3770 K/kg.K
Blood profusion rate (Onofrei et al., 2015)	$1.25x10^{-3}s^{-1}$
Muscle thermal conductivity (Fiala et al., 2012)	0.42 W/mK
Muscle density (Fiala et al., 2012)	1085 kg/m^3
Muscle specific heat capacity (Fiala et al., 2012)	3768 J/kg.K
Skin fat thermal conductivity (Cooper & Trezek, 1971)	0.293 W/m.K
Skin fat emissivity (Cooper & Trezek, 1971)	0.95

The rate of heat transfer between the skin and the adjacent air can be described as:

$$\dot{q} = \frac{T_i - T_\infty}{R_{tot}} \quad (3)$$

Where the total resistance, R_{tot} is

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$$R_{tot} = \frac{L_{sf}}{k_{sf}A}\left(\frac{1}{1/_{h_r}A}\right)^{-1}$$
$$= \frac{1}{A}\left(\frac{L_{sf}}{k_{sf}} + \frac{1}{h_r}\right)$$

The radiation, h_r heat transfer coefficients of the air gap are 5.49 W/m^2.K.

The excess temperature at the boundary given by (Bergman, Incropera, DeWitt, & Lavine, 2011)are;

$$\theta(0) = T_c - T_a - \frac{\dot{q_m}}{w\,\rho_b c_b} = \theta_c \quad (4)$$

$$\theta(L_m) = T_i - T_a - \frac{\dot{q_m}}{w\,\rho_b c_b} = \theta_i \quad (5)$$

The prescribed temperature involving two boundary conditions given by (Bergman et al., 2011)is;

$$\frac{\theta}{\theta_c} = \frac{(\theta_i/\theta_c)\sinh \tilde{m}x + \sinh \tilde{m}\,(L_m - x)}{\sinh \tilde{m}\,L_m} \quad (6)$$

The heat leaving the muscle equal heat transfer through the skin/fat. The heat transfer rate at L_m is

$$q_{|x=Lm} = -k_m A\frac{dT}{dx}|_{x=Lm} = -k_m A\frac{d\theta}{dx}|_{x=Lm} = -k_m A\tilde{m}\theta_c \frac{\left(\theta_i/_{\theta_c}\right)\cosh \tilde{m}L_m - 1}{\sinh \tilde{m}L_m} \quad (7)$$

Combining the equation 3 and 7 will solve the surface temperature at muscle T_i

$$T_i = \frac{T_\infty sinh\tilde{m}L_m + k_m A\tilde{m}R_{tot}\left[\theta_c + \left(T_a + \frac{\dot{q_m}}{w\rho_b c_b}\right)\cosh \tilde{m}L_m\right]}{\sinh \tilde{m}L_m + k_m A\tilde{m}R_{tot}cosh\tilde{m}L_m} \quad (8)$$

Where $\tilde{m} = \sqrt{\frac{w\rho_b c_b}{k_m}}$

The skin/fat temperature T_{sf} is obtained by equating the heat transfer by conduction at skin/fat layer to heat by radiation q_{rad} at the air layer. Which the heat transfer through muscle layer, $q_{|x=Lm}$ is equal to heat transfer through skin/fat, $q_{cond|x=Lsf}$. Thus;

$$q_{cond|x=Lsf} = q_{rad}$$
$$q_{cond|x=Lsf} = h_r(T_{sf} - T_\infty)$$

Therefore the skin temperature is

$$T_{sf} = \frac{q_{cond|x=Lsf} + h_r T_\infty}{h_r} \quad (9)$$

5.2. Finite Element Model

A simplified two-dimensional model of multi-layer clothing materials was developed using ANSYS transient thermal finite element software as shown in Figure 2. The model also includes a human skin and air gap layers. The clothing materials consist of three layers, namely, outer shell, thermal liner and moisture barrier. The air gap was placed between the clothing and skin layers. The effects of the air gap thickness on the skin temperature, T_i was evaluated based on six different thicknesses, specifically 1 mm, 2 mm, 3 mm, 4 mm,5 mm and 6 mm. The analysis excluded the moisture effect in the clothing materials.

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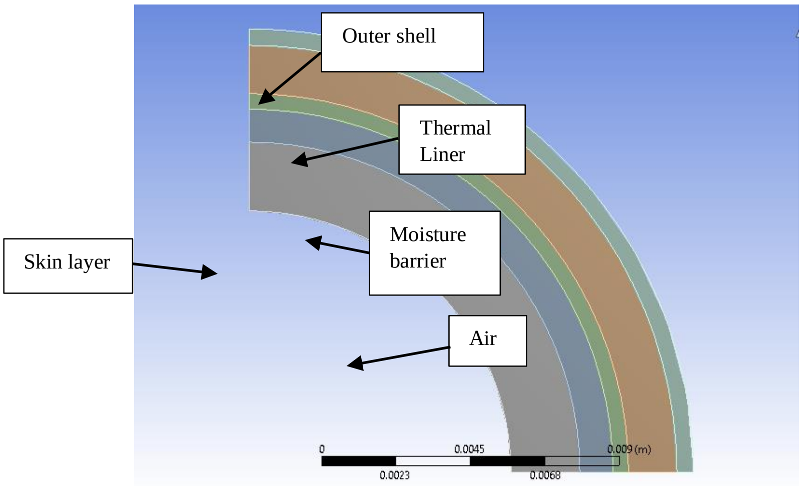

Figure 02. The design of the model

Figure 3 shows the boundary condition prescribed on the model. Bioheat equation was used to obtain 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 prescribed at the outermost layer for describing the real flame, specifically at the D-layer. The effects of heat flux on the skin temperature were evaluated based on five different intensities, they were 1200 W/m^2,1000 W/m^2, 800 W/m^2, 600 W/m^2 and 400 W/m^2. 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 type of material was prescribed as aramid since it has a high insulator thermal protective performance fabric commonly used during fire suppression. The outer shell is made of polyurethane coated with 100% aramid, while the thermal barrier and moisture barrier are made of 100% aramid.. The simulation was performed under a transient condition in a duration of 1000 seconds. The initial ambient temperature was specified at 22°C as prescribed by the (ISO, 2002)

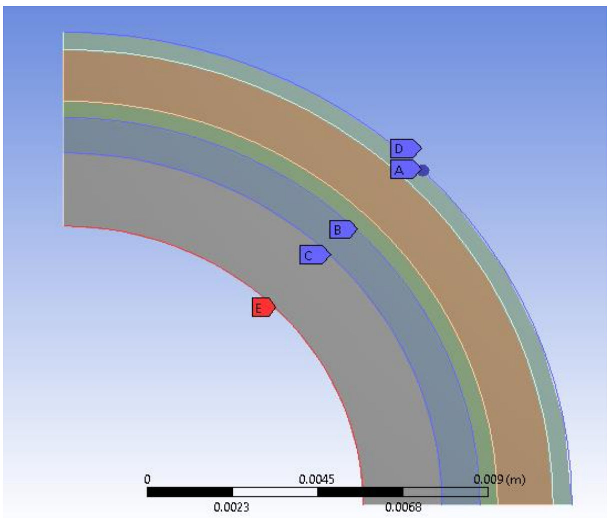

Figure 03. Boundary Conditions

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6. Findings

The model developed by (Onofrei et al., 2015) was based on numerical analysis for solving a heat transfer model of the protective clothing exposed to heat. The goal of the study is to evaluate the thermal performance of multi-layer materials when they are exposed to the heat hazard. She modelled the multi-layer materials system as a rectangle geometry which employed a two-dimensional quarter circle geometry. When compared to the (Onofrei et al., 2015) model, the model presented in this paper used finite element analysis to solve the heat transfer problem through the protective clothing layers on the hand and leg sections of human body. The model in this study are in two-dimensional cylindrical geometry. However, both studies used the bioheat equation of the living tissue to solve the heat transfer problem. Table 2 shows the results of skin temperature for various heat flux for the model validation purposes. The finite element model was validated by comparing the predicted skin temperature with the results obtained by (Onofrei et al., 2015). From the table, it is found that the percentage error of the skin temperature increases as the heat flux on the outer of the clothing increases. The (Onofrei et al., 2015) model reached a second-degree burn when the heat flux was fixed at 1000 W/m^2. However, based on the present model predicted skin temperature does not reach the burn injury temperature of 44°C.

Table 02. Validation with the previous experiment (Heat Flux)

	Previous Research	**The Research Model**	
Heat flux (W/m^2)	**Skin Temperature ($^\circ$c)**	**Skin Temperature ($^\circ$c)**	**Error (%)**
1200	47.00	38.34	17.55
1000	44.80	38.06	15.00
800	43.00	37.77	10.03
600	41.00	37.47	8.62
400	39.00	37.15	4.70

Table 3 shows the results of the skin temperature for various air gap thickness. The percentage error of the skin temperature increases as the air gap thickness increases. The (Onofrei et al., 2015) model shows that when the air gap thickness was specified at 3-mm and the heat flux of 1200 W/m^2, the skin reaches the second-degree burn temperature of 44°C. However, that is not the case for the current study, the highest skin temperature was obtained below the second-degree burn temperature. According to (ASHRAE, 2001) a percentage error of less than 20% can be considered as fair and the model can be used for subsequent analysis.

Table 03. Validation with the previous experiment (Air gap thickness)

	The Previous Research	**The Research Model**	
Air Gap Thickness (mm)	**Skin Temperature ($^\circ$C)**	**Skin Temperature ($^\circ$C)**	**Error (%)**
1	43.50	38.34	11.86
2	43.50	38.54	11.40
3	44.00	38.30	12.9
4	44.80	38.13	14.9
5	45.50	37.80	16.9
6	46.50	37.99	18.3

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Figure 4 shows the temperature contour inside the multi-layer materials. It is found that the temperature decreases significantly when the gap between the heat source at the outer layer and skin layer increases. The outer shell layer experiences the highest temperature of 88.18ºC since it is closest to the heat source. Figure 6 it can also be seen that the temperature changes gradually with the variation of layer materials. The multi-layered structure consists of various material layers causing the thermal resistance to grow which leads to a significant reduction of the skin temperature to around 38ºC when compared to the outer layer temperature. Furthermore, placing additional shields between layers minimizes the radiation heat transfer due to an increase of radiation thermal resistance. The aramid material plays a primary role in reducing the skin temperature since the material possesses a low thermal conductivity, heat capacity and density. The material is considered as a good insulator that is capable of preventing burn injuries.

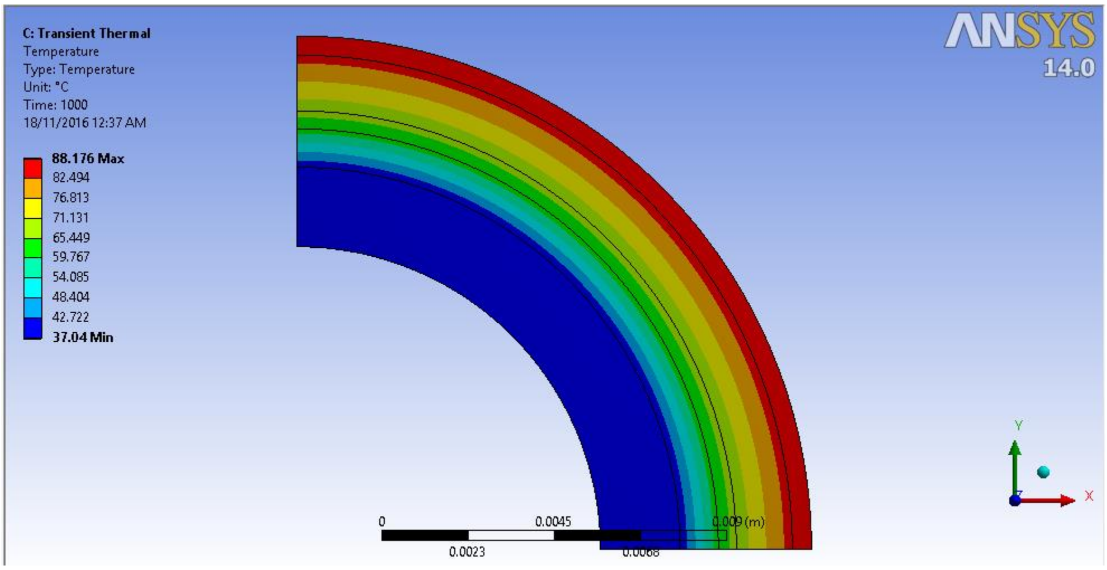

Figure 04. Temperature distribution across the protective clothing layers

Figure 5 shows the plots of skin temperature variation against time for various heat flux intensities. It can be observed from the figure 5, the skin temperature increases as the heat flux increases. The skin temperature rises gradually as the protective clothing material exposed uniformly to the heat flux at t = 0 second and reaches a steady condition when t = 198 seconds. The skin temperature remains unchanged in the following sequence although the heat flux is held constant throughout the simulation. According to (Weaver & Stoll, 1967) a second-degree burn is achieved when the skin temperature reaches 44°C. However, it can be observed from the figure 7 that, the highest predicted skin temperature is around 38.3°C when the heat flux is held constant at 1200W/m^2. From the findings, it can be presumed that, a human skin may suffer second-degree burn if the heat flux on the outer layer of the protective clothing material is above 1200 W/m^2.

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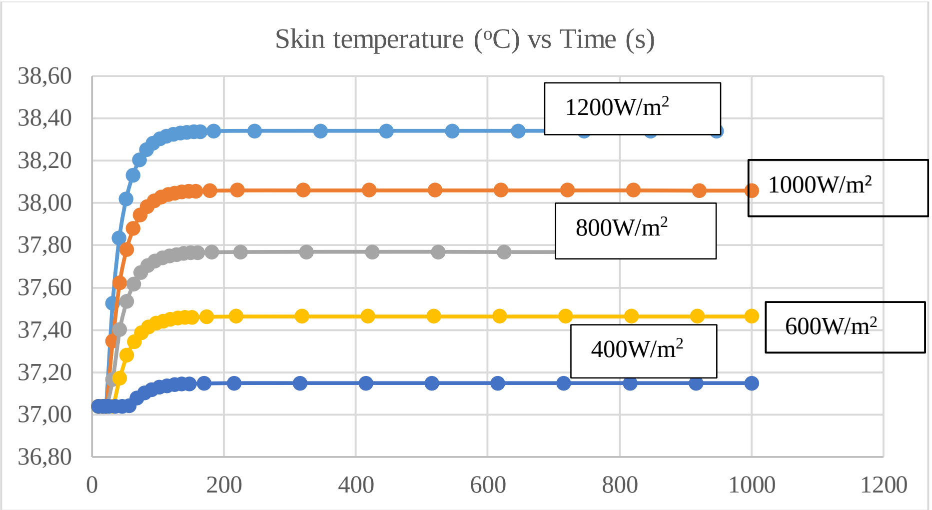

Figure 05. Skin temperature against time (Heat flux)

Figure 6 shows the plots of skin temperature variation against time for various air gap thickness. The heat flux exerted at 1200W/m^2. It can be observed that the skin temperature increases as the air gap thickness decreases. The heat flux intensity comes from heat exposure affects the skin temperature distribution. The finding shows that the air gap thickness capable of regulating the skin temperature effectively since it could enhance the conduction and radiation thermal resistances of the multi-layer materials system. The effects of the air gap thickness on the skin temperature are based on the human body parts. (Song et al., 2004) reported that the optimum air gap thickness of a human leg is in a range of 15 to 22 mm while the shoulder section is around 1.6 mm. Air has a low thermal conductivity and specific heat, thus, it reduces the heat transfer rate and becomes buffers as it restricts thermal transfer from the external environment to the skin. The air gap can be considered as an insulator to the heat. Less burn severity occurs when the thickness increases. The factors contributing to microclimate thickness are the drapability, rigidity and weight of the protective clothing. Good draping and less rigid garments have smaller microclimate thicknesses (Li et al., 2013). For a garment that possesses excellent drape, the closer the fabrics are to the skin the most likely the skin will suffer a higher skin temperature if the outer layer of the garment is continuously exposed to the heat.

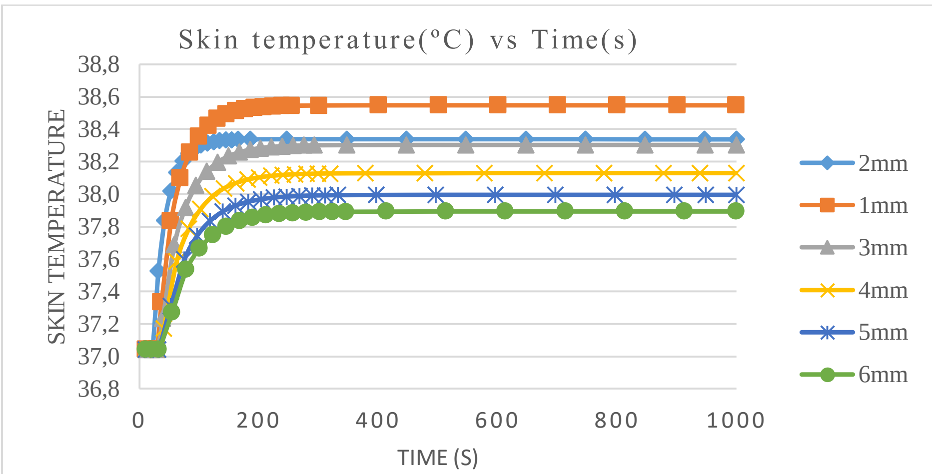

Figure 06. Skin temperature against time (air gap thickness)

7. Conclusion

Quantifying heat intensity in the real firefighting condition to protective clothing for firefighters is complex. Life-threatening environment during actual firefighting condition test and the size of the attire are the contributory factors of the complexity. The goal of this study is to evaluate the effects of heat intensity and air gap of a multi-layer material on the skin burn temperature. The finite element analysis is used for solving the heat transfer problem through the clothing layer. It is found that the skin temperature increases significantly with the heat flux intensities. The heat flux of 1200 W/m^2 causes the skin temperature to reach 38.3ºC. The reduction of 1 mm air gap thickness contributes to an increment of 0.2ºC of the skin temperature. As the air gap thickens, less heat is transmitted to the skin surface. It is also noticed that the material properties of firefighters protective clothing are a causative factor for minimizing burn injury to the skin. Especially to the material that holds low thermal conductivity and heat capacity.

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