Heat Transfer Model for Steam Burn Injury among Fire Fighter

Zaina Norhallis Zainol, Masine Md Tap, Haslinda Mohamed Kamar, Nazri Kamsah

Abstract: Burn injury is the most common incident that could happen among firefighters. Firefighter use hose spray to spread water on flames and suppress fire. The personal protective clothing can becomes wet changing the material thermophysical properties increasing risk of burn injury. Burn injury will become severe in wet condition as moisture is absorbed in the personal protective clothing. This study is to develop heat transfer model using finite element method to predict steam burn injury among fire fighters. There are two conditions are studied dry and wet condition. The presence of moisture had transformed the personal protective clothing material properties. It has enhanced heat transfer from the heat flux through multilayers personal protective clothing to the skin. It can be found that the thermal conductivity, heat capacity and density are significantly increased with the presence of moisture. The evaporation process occurred as the temperature of the protective clothing layers is remained plateaued from the outer layer through the skin. Skin temperature is increased with 10°C increment than dry material. The predicted pain threshold of wet material at lower arm is 40s faster than dry material. It is found that wet material first degree burn sooner at t=9.5second than in dry material at t=25second. The highest predicted skin temperature value at lower arm for the dry condition is 46°C only which is less than the wet condition 56°C. It is observed that the presence of moisture had compromised thermal protection of firefighters personal protective clothing. Heat transfer from the heat flux is becomes greater leading to formation steam burn injury among fire fighters.

***Index Terms*: Keywords: Fire Fighters, Burn Injury, Steam Burn Injury, Heat Transfer.**

I. INTRODUCTION

In real life fire fighting situation, firefighters are subjected to various of fire intensity with various condition. There are working under low level radiation with prolonged period of time causing to skin burn injury and many heat related injuries. According to [1] skin burn injury occurs in low level thermal radiation ranging between 5 to 20kW/m^2. Approximately 100 firefighters suffer from fatal injuries in the USA annually and over 30,000 firefighters are subject to injuries while firefighting [2]. 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%) [2]. It is shown from the etiology of injuries to firefighters that skin burns were responsible for injury (65%) and flame burns caused injury to 20% of firefighters. However, other 15% patients received contact or compression burns [3].

Burn injury are usually classified on the depth of the skin dermal injury. The most common utilized the classification is the degree burn. The first degree burns are limited to the outmost layer of the skin, the epidermis. Second degree burn, the injury pass through the epidermis and the underlying dermis. The dermis consists of the hair follicles, sweat glands, capillaries and nerves. The third degree burn are those pass through all the way through epidermis and dermis entering the major third layer, the hypodermis composed of fat and the connective tissue [4], [5]. The protective clothing material consist of three layers the outer layer, moisture barrier and thermal liner. The outer layer is the first layer for thermal protection of the clothing. The material is designed to contact with fire and flame without burning and degradation. The most common material for the outer layer is Nomex made of aramid fiber. The moisture barrier is the inner layer of the outer shell fabric made of light web knitted structure either laminated or coated to the outer shell. The third layer is thermal liner which prevents from the heat from transmitting the skin layer [6].

The moisture absorbed and accumulated in personal protective clothing may come from the external or internal[7]. Internal is sweat profusion which normally the body reaction when exposed to heat and external moisture comes from hose spray and rainwater. The presence of moisture is significantly affecting the personal protective thermal protection. There will be heat transfer by evaporation, condensation, desorption and absorption. [7] found that the evaporation and condensation of moisture trapped inside the personal protective clothing can cause steam burn injury.

Accumulated water vapor influences the material thermophysical properties such as thermal conductivity, heat capacity and density. The amount of moisture absorbed in fabrics will evaporates and change phase from liquid to gas.[8] used experimental thermal testing at 6.3kW/m^2 to study the effect of the absorbed moisture on the personal protective clothing thermal performance. It can be found that with the presence of moisture will affect the predicted burn protection. [9]found that the relative humidity in the air gap was significant to skin temperature leading to steam

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burn injury. [7] investigated the evaporation process of the wet fabric with the heat flux 5kW/m^2. It is observerd that the temperature remained constant during the evaporation. The aim of this study is to predict steam burn injury for firefighter's personal protective clothing using finite element method.

II. LITERATURE REVIEW

Previously numerical simulation had been conducted to predict heat and moisture transfer in fire fighter's personal protective clothing exposed to heat flux and radiation. [10] developed a numerical study with the effect of air gap. He found that the temperature distribution and moisture is significantly affect burn injury. He observed that the local temperature affects the moisture evaporation and condensation on the different layers of the fabric. [11]had established the numerical model of heat and moisture transfer and its behaviour of the fabric considering the fabric thermophysical properties and the also the drying process. They found that moisture increases the heat transmission and decreases the threshold time for burn injury. These numerical simulation did not consider absorption of thermal radiation by moisture as water has strong influence of thermal radiation [6].[12] constructed a numerical model heat and moisture transfer using finite difference method. His method was in 2 dimensional plane geometry. [13] developed a numerical model with consideration evaporation process and studied its relation with thermal radiation. [9] did an investigation of the effect different humidity level under air gap using the Thermal Protective Performance (TPP) tester and adjustable humidity in the microclimate chamber.

All of the previous numerical models only consider 2-dimensional plane geometry. The human body is very complexed geometry and many dimension variations. According to [14], the human limb basically consist of cylindrical geometry. Therefore 2-dimensional quarter geometry would be accurate and provide more reliable outcome. To improve this experiment is by using finite element method. Finite element method is used in this study as it can solve heat transfer problem with complex geometry.

III. METHODOLOGY

The analysis begins with determine the effective material properties of the wet material given by [12]. The equation consists of two components the solid phase and gas phase. The study followed with the design geometry, mesh, boundary condition specification using ANSYS software to solve heat transfer problem for the multilayers firefighter's personal protective clothing. The ANSYS software version 14 was used as a tool to perform the finite element method of the heat transfer analysis under transient conditions.

A. Mathematical Equations

The material model for moisture case consider as porous structure textile which consist of two components; the solid phase and gas phase. The solid phase are fibers and bound water and the gas phase are vapor and dry air. The model based on [12] assumed that any liquid build up on the skin surface will either drip off or wick into the fabric and then will absorb by the fabric fibers and become bound water. Free liquid on the skin surface and fabric layer does not exist. The two phase phase model consist of bound water and water vapour is developed with multi-layer protective clothing configuration subjected to heat flux. The effect of moisture is carefully analyse toward the skin burn injury. The skin model is employed for initial value of human skin temperature. The burn injury evaluation based on [15].

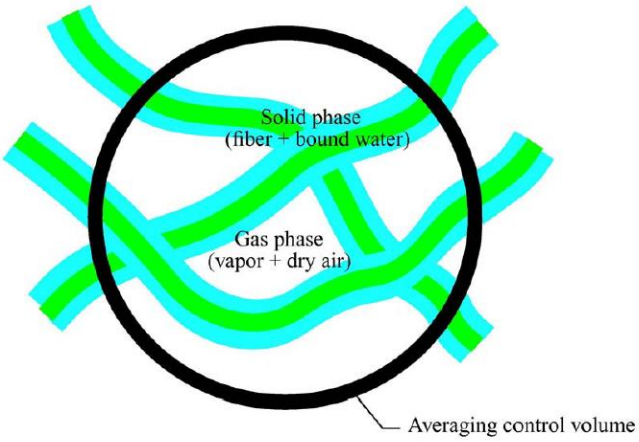

Fig. 1. Schematic diagram of two phase structure textile media in the averaging control volume adapted from [12]

The effective density ρ of the fabric can be calculated as [16]

$$\rho = \varepsilon_{bw}\rho_w + \varepsilon_{ds}\rho_{ds} + \varepsilon_\gamma(\rho_v + \rho_a) \qquad \text{Equation 1}$$

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 [16]

$$c_p = \frac{\varepsilon_{bw}\rho_w(c_p)_w + \varepsilon_{ds}\rho_{ds}(c_p)_{ds} + \varepsilon_\gamma[\rho_v(c_p)_v + \rho_a(c_p)_a]}{\rho} \qquad \text{Equation 2}$$

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} [16]

$$k_{eff} = k_\gamma \left\{ \frac{1 + (\varepsilon_{bw} + \varepsilon_{ds})k_\sigma + \varepsilon_\gamma k_\gamma}{\varepsilon_\gamma k_\sigma + [1 + (\varepsilon_{bw} + \varepsilon_{ds})]k_\gamma} \right\} \qquad \text{Equation 3}$$

Where
k_σ is the thermal conductivity of the solid phase
k_γ is the thermal

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conductivity of the gas phase

The thermal conductivity of the gas phase k_γ [16]

$$k_\gamma = \left(\frac{k_v \rho_v + k_a \rho_a}{\rho_v + \rho_a}\right) \quad \text{Equation 4}$$

Where
k_v is the thermal conductivity of the saturated water vapour
k_a is the thermal conductivity of the dry air

The thermal conductivity of the solid phase k_σ [16]

$$k_\sigma = \left(\frac{k_w \rho_w \varepsilon_{bw} + k_{ds} \rho_{ds} \varepsilon_{ds}}{\rho_w \varepsilon_{bw} + \rho_{ds} \varepsilon_{ds}}\right) \quad \text{Equation 5}$$

Where
k_w is the thermal conductivity of the liquid water
k_{ds} is the thermal conductivity of the dry solid

B. Design Geometry

A simplified quarter geometry model of multi-layer clothing materials was developed using ANSYS transient thermal finite element software version 14. The model also includes a human skin and air gap layers. Fig. 2 shows the clothing materials consist of three layers, namely the outer shell, thermal liner and moisture barrier. The air gap is placed between the clothing and skin layers.

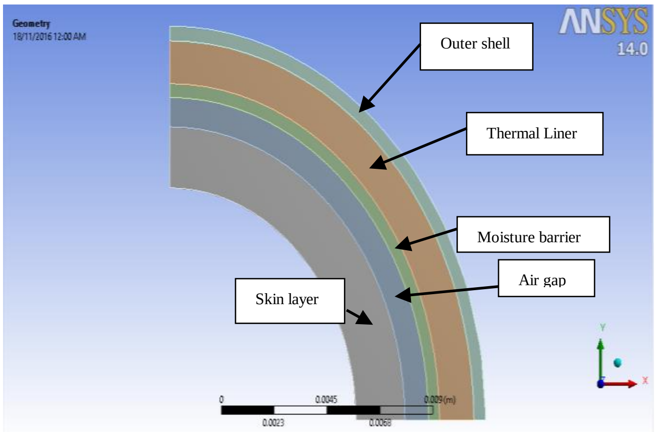

Fig. 2 The design of the model

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 excluded the moisture effect in the clothing materials. Table I shows the thickness of each layer. Table I shows the model dimension at each layer.

Table I. The model dimension

Layers	Thickness (mm)
Skin	2.08
Air gap	1.00
Moisture barrier	0.47
Thermal barrier	1.46
Outer Shell	0.50

C. 3.2 Mesh

Fig. 3 shows the type of element used for meshing the model. The type of element used is quadrilateral uniform. 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 layers 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.

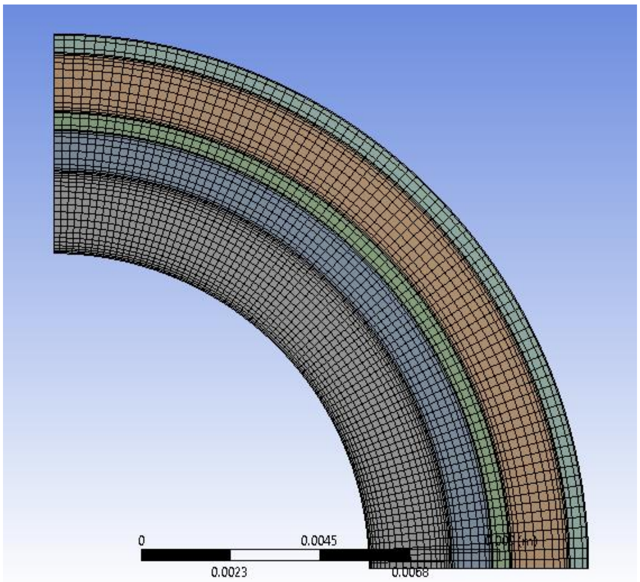

Fig. 3. Meshing pattern

D. Material Properties

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 material properties for the protective clothing are given in Table II.

Table II. Material Properties of Clothing Materials

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

The simulation was performed under a transient condition in a duration of 1000 seconds. The initial ambient temperature was specified at 26°C as prescribed the International Organization for Standardization [17].Table III shows the material properties of the porous fabric according to [12]. The material properties are in dry condition without

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considering any gas vapour or free liquid.

Table III. The material properties of the porous fabric according to [12]

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-1K-1)	1420	1325	1200
Thermal conductivity of the dry solid k_{ds} (Wm-1K-1)	0.179	0.144	0.130

Table IV shows the material properties of water vapour at gas phase. These values depending with the temperature. The temperature changed with time to heat exposure. By referring to [14] thermophysical properties, the water vapour starts to develop when the temperature reaches 263K. Thus the properties of water vapour from the beginning until 60second of heat exposure is neglected.

Table IV. The material properties of water vapour at gas phase the value obtain from Incorpera, Dewitt & Bergman (2007)

Time (s)	**0**	**10**	**20**	**40**	**60**
Temperature (°C)	33	38	75.5	92	263
Density ρ_v (kgm-3)	-	-	-	-	0.4117
Specific heat $(c_p)_v$ (Jkg-1K-1)	-	-	-	-	1994
Thermal conductivity k_v (Wm-1K-1)	-	-	-	-	36780

According to [12] the evaporation process start to develop at 60 second after subjected to heat. Thus the material properties for water vapour prior to that is neglected. Table V shows the material properties of the dry air. The material properties is keep changing with air temperature. The air temperature will continue to rise with time as the heat flux is subjected to the outer surface of the personal protective clothing.

Table V. The material properties of dry air the value obtained from [14]

Time (s)	**0**	**10**	**20**	**30**	**40**
Temperature (°C)	33	38	75.5	92	263
Density ρ_a (kgm^{-3})	1.1414	1.1249	0.9950	0.9628	0.6507
Specific heat $(c_p)_a$ (Jkg^{-1}K^{-1})	1007	1007	1009	1010	1037
Thermal conductivity k_a (Wm^{-1}K^{-1})	26744	27114	30000	30990	43000

Table VI shows the volume fraction water which is the content of water absorbed and bounded at the textile fibre. These values given by [12]. According to [12], the amount of bound water reducing with time as water may be dripped or vaporize. Vaporization reduces values of volume fraction bound water at the outer shell, thermal liner and the moisture barrier.

Table VI. The volume fraction of bound water ε_{bw} based on [12]

	Volume fraction of bound water ε_{bw}		
Time (s)	**Outer shell**	**Thermal liner**	**Moisture Barrier**
10	0.074	0.034	0.039
20	0.070	0.030	0.034
40	0.065	0.0258	0.026
60	0.062	0.024	0.024

Table VII, VIII and IX shows the effective material properties of each layers for the personal protective clothing which is the outer shell layer, moisture barrier and thermal liner. The amount of volume fraction bound water, gas vapour and the temperature are not remained fixed. It changed with time as heating from the heat flux increases, it induces temperature from the vaporization process. Thus bound water change into gaseous. These tables VII, VIII and IX are the solutions of the effective material properties had been determine from equation 7, equation 8 and equation 9 respectively.

Table VII. The effective material properties with moisture at outer shell.

Time (s)	**0**	**10**	**20**	**40**	**60**
Temperature (°C)	33.0	38.0	75.5	92.0	263.0
Density ρ_{eff} (kgm^{-3})	540.93	536.92	532.85	527.83	524.90
Specific heat $(c_p)_{eff}$ (Jkg^{-1}K^{-1})	1822.46	1802.82	1784.79	1762.01	1749.55
Effective Thermal conductivity k_{eff} (Wm^{-1}K^{-1})	2.427	2.451	2.475	2.506	2.525

Table VIII. The effective material properties at moisture barrier. These values obtained from equation

Time (s)	**0**	**10**	**20**	**40**	**60**
Temperature (°C)	33.0	38.0	75.5	92.0	263.0
Density ρ_{eff} (kgm^{-3})	278.76	273.749	271.65	267.62	265.71

Specific heat $(c_p)_{eff}$ **(Jkg^{-1}K^{-1})**	1707.86	1662.55	1643.75	1605.67	1583.78
Effective Thermal conductivity k_{eff} **(Wm^{-1}K^{-1})**	4.483	4.587	4.629	4.716	4.762

Table IX. The effective material properties at thermal liner

Time (s)	**0**	**10**	**20**	**40**	**60**
Temperature (ºC)	33.0	38.0	75.5	92.0	263.0
Density ρ_{eff} **(kgm^{-3})**	202.66	198.65	191.55	185.52	183.61
Specific heat $(c_p)_{eff}$ **(Jkg^{-1}K^{-1})**	1838.32	1791.00	1703.23	1622.86	1599.48
Effective Thermal conductivity k_{eff} **(Wm^{-1}K^{-1})**	6.328	6.492	6.802	7.091	7.193

E. Boundary Condition

The Fig. 5 shows the boundary conditions specified in this model. The boundary condition comparable with [12] finite difference model. The skin temperature value is fixed 38.8ºC located at the E layer. Heat flux is applied at D layer which the value is constant 7000W/m^2. The radiation is specified at A layer, B layer and C layer with the emissivity value are 0.9, 0.96 and 0.94 respectively. The ambient temperature is 34ºC prescribed in this model referring to [12]experiment. The solution is at the skin layer which is at the inner layer to observe the variation against time. The simulation is simulated for 60 second.

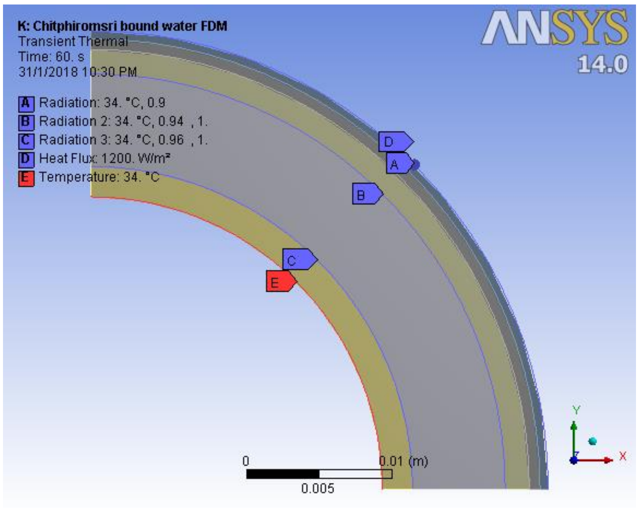

Fig. 5 Boundary condition for two phase model

IV. VALIDATION

The model developed by [12] used finite difference method in 2 dimensional plane geometry. The goal of the study to assess the effectiveness of the personal protective clothing with the presence of moisture. He applied two phase and three phase effective material properties for wet firefighter's personal protective clothing. He also conducted Thermal Protective Performance (TPP) to predict skin temperature using wet sample.

Table X shows error value of the comparison the research model with [12] numerical finite different method. It is observed that, initially the error value was less than 1%. The error values continue to rise with prolonged exposure. At 60 second is the highest error value recorded 12.34%, however it is consider as acceptable according to American Society of Heating, Refrigerating and Air-Conditioning Engineers [18]. This shows that the model is reliable in predicting human skin temperature during firefighting.

Table X Comparison the research model with Chitphiromsri numerical simulation FDM

Time (s)	**Skin Temperature (ºC)**		**Error (%)**
	Chitprhromsri 2004	**The research model**	
0	34.00	34.17	0.51
1	34.13	34.32	0.55
2	34.08	34.73	1.89
5	34.26	35.88	4.71
10	35.43	35.88	1.26
20	37.50	36.34	3.09
30	37.60	37.09	1.37
40	37.91	37.22	1.82
50	41.20	37.25	9.58
60	42.50	37.26	12.34

Table XI shows comparison with the Thermal Protective Performance (TPP) experiment. The TPP experiment is compare with the research model to confirm the validity for assessment the firefighter's personal protective clothing. It can be found that the error is less than 5% during first 5 seconds after heat exposure. During 10 seconds heat exposure error is increased to 11.33%. Prolonged heat exposure up to 45second percentage error continue to rise from 16.98% to 17.89%. However this values are less than 20% is consider acceptable to American Society of Heating, Refrigerating and Air-Conditioning Engineers [18].Thus the research model is reliable to assess the effectiveness personal protective clothing.

Table XI. Comparison TPP experiment with the research model

Time (s)	**Skin Temperature (ºC)**		**Error (%)**
	Chitphiromsri TPP 2004	**The Research model**	
0	27.60	27.18	1.53
5	27.70	28.82	4.03
10	28.00	30.00	7.13
15	29.50	39.73	34.67
20	32.00	41.03	28.22
25	35.80	42.03	17.40
30	39.20	42.03	7.21

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35	43.00	42.03	2.26
40	47.70	42.87	10.13
45	51.40	43.47	15.43
50	53.90	43.91	18.53
55	55.30	44.51	19.51
60	55.80	44.68	19.93

V. RESULT

During fire duty, fire fighters are subjected to a variety of fire conditions with different levels of radiant heat flux. Long working hours and continuous exposure to heat resulting to skin burn injuries. Skin burn injury would become severe with the presence of moisture known as steam burn injury. Moisture accumulation in fire fighter protective clothing comes from both internal and external moisture [7]. The internal moisture is from sweating by firefighters. External moisture sources normally consist of the dousing water from hose spray and water dews from rains [19]. According to [7] the moisture transfer of the wetted protective clothing strongly affects the heat transfer by evaporation, condensation, desorption and absorption. These moisture that trapped within the protective clothing can cause steam burns ([7], [13]

The Fig. 6 shows comparison for the skin temperature for wet and dry condition at lower arm in stationary position. The initial skin temperature is 38.8°C. The both material layers are exposed to heat flux 7000W/m^2 and it held constant for 60second. The plot shows that at t=0second the skin temperature in wet condition start to rise sharply and it stabilized at t=56second. Meanwhile the skin temperature for dry condition is remained constant and increases at approximately t=17second. The temperature gradient for the wet condition is higher than dry condition.

[15] stated that the skin temperature can reach various significant thresholds. The pain threshold begins at 44°C, the predicted first degree burn at 48°C and second degree burn start to form at 55°C. It can be found that the pain threshold for wet condition is 7second and 43second for the dry condition. It is predicted that the subject experience pain sooner in wet material than dry. From the Fig. 6, first degree burn for the wet condition occur at t=9.5second and second degree burn occurred at t=25second. The highest skin temperature value for the dry condition is 46°C which is less than the wet condition 56°C. It is observed that first and second degree burn do not occur in dry condition. The dry material can enhance safety and prevent burn injury for the firefighters. This shows that, wet personal protective clothing material had compromised thermal protection as it is alters material thermo physical properties. The wet material's density, heat capacity and conductivity of the protective clothing are greater with moisture absorbed in the porous clothing material. The heat resistance of the multilayers personal protective clothing material is reduced. Hence heat transmission comes from the external heat flux is enhanced resulting elevation human skin temperature.

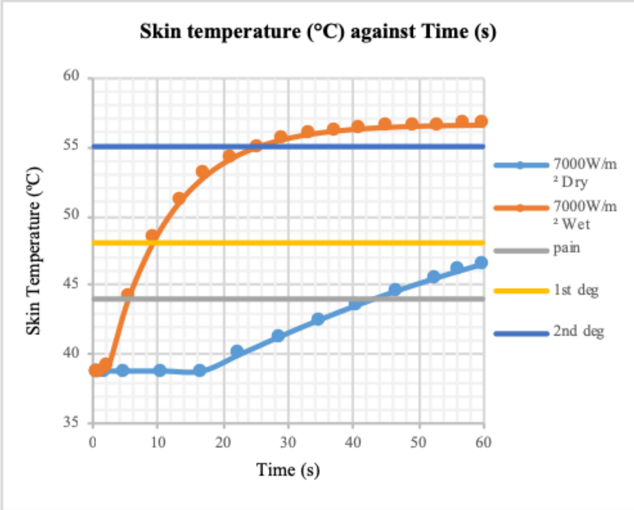

Fig. 6. Comparison skin temperature wet and dry condition at upper arm

Fig. 7 shows the plot of the temperature variation at each layer of the personal protective clothing material with exposure of 7000W/m^2 heat flux is held constant for 60seconds. The firefighter's personal protective clothing consists of outer shell, moisture barrier, thermal liner, air gap and skin. From the Fig. 7, it can be found that the temperature reduces significantly at the air gap between the heat source. The outer shell experiences the highest temperature of 138.85°C since it is located closest to the heat source. For the dry condition, the temperature start to reduce at every layer significantly until it reached the skin surface with skin temperature 47.813°C. The multilayered structure consists of various materials creating good thermal resistance to hinders heat transfer resulting significant reduction of skin temperature. Placing these materials together minimizes the radiation heat transfer due to increment thermal resistance. It is observed that dry material is good insulator as it holds low thermal conductivity, heat capacity and density. It provides thermal protection for the fire fighter preventing from burn injury.

From the Fig. 7, wet condition the temperature is plateau through at every material layer from the incident heat flux to the skin. [7] explained that the temperature remained constant as moisture starts to evaporate. Evaporation process is liquid change its phase to gas. Thermal radiation from the heat flux is significantly creating incident energy for evaporation process. The incident energy is absorbed for evaporation causing temperature to plateau during the process. It is observed that the skin temperature for the dry condition is 47.813°C which is less than wet condition that is 59.642°C. It is predicted that the subject may suffer second degree burn in wet condition. According to [15] steam burn injury can be achieved when the absorbed liquid changes to gases as well as the skin temperature reaches second degree burn at 55°C. The burn injury will become severe with wet material leading to formation second degree burn also known as steam burn. The presence of moisture will increase the material properties such as thermal conductivity, heat capacity and density. It enhances the heat transfer from the heat flux through the

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multilayers material and elevates the skin temperature. It is considered that with the presence of moisture has compromised the thermal protection reducing the material thermal resistance and increases risk of burn injury.

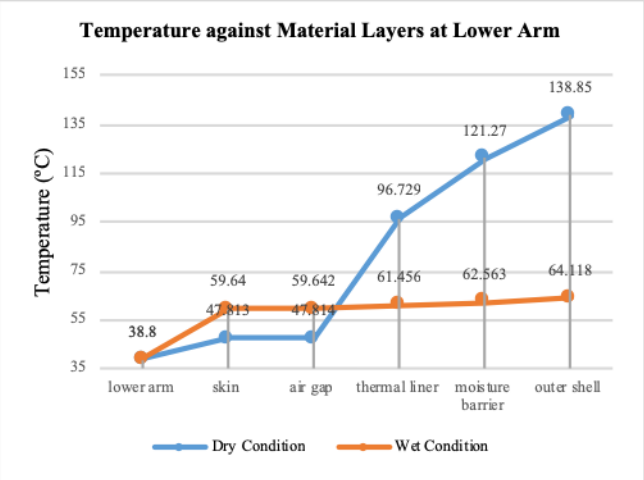

Fig. 7. Temperature variation at each layer for the clothing in wet and dry condition

VI. CONCLUSION

Prediction steam burn injury in real firefighting situation of the human attire geometry and simulate fire scene environmental conditions are very complex to study. The aim of the study is to predict steam burn injury of the firefighter's personal protective clothing. This model used finite element method in 2-dimensional quarter geometry to solve heat transfer problem. From the study it can be found that using finite element method and two phase effective material properties, the model capable to predict occurrence steam burn injury among firefighters. The presence of moisture is the responsible factor of steam burn injury as thermal protection of the personal protective clothing was compromise. The moisture enhanced heat transfer from the heat flux to the skin surface. It increased the material properties such as thermal conductivity, heat capacity and density. Moisture had degraded the material's thermal resistance against heat flux. Therefore the firefighters must avoid from prolonged exposure themselves to the heat if the personal protective clothing is wet. This could lead to development steam burn injury more severe than the dry burn.

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