Study on Thermal Protective Clothing for High Temperature Working Environment

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ABSTRACT: In parallel with the development of the iron and steel industry and craft villages in Vietnam, many workers always have to work in high temperature environments. In order to improve the safety and production efficiency of workers working at high temperature, in this paper, we proposed the thermal protective clothing design model for industrial working at high temperature. Firstly, for the system of three-layer fabric materials (composed of an outer shell, a moisture barrier and a thermal liner), body skin and the air gap between the clothing and the skin, an improved heat transfer model together with boundary/initial conditions was presented in high temperature environments. Secondly, the presented model was applied to calculate the temperature on the fixed contact surface changing with time, and the numerical results were compared with the existing model under the same condition to verify the credibility of the model. Finally, the developed model was also used to predict the critical time to first-/second-/third-degree burn injury and to analyze the influence of air gap and textile thickness on the performance of thermal protective clothing.

Keywords: Thermal protective clothing; Design model; Heat transfer model and optimal thickness.

INTRODUCTION: The thermal protective ability[1-5] and various heat transfer models[6-10] of thermal protective garments have been well investigated over the past decades. Two skin burn prediction methods are widely applied in experimental measurements and numerical assessment. One is the Stoll criterion, proposed by Stoll in the 1960s, in which surface temperature over a thermal manikin is utilized to determine the potential skin burn. Temperature rise of the fabric is compared with the toll curve, and the intersection point of the two curves is defined as the tolerance time of the fabric samples. The other method is Henrique's' burn empirical integral method.[11] Based on these two methods, many investigations have been carried out into the thermal protective garment, air gap and human body microsystem. For instance, Torvi et al.[12 & 13] established a heat transfer model of a one-layer fabric subjected to the high heat fluxes used in bench top tests, and Stoll curves were employed to confirm the accuracy of the model. Zhu et al.[14 & 15] developed a cylindrical geometry testing apparatus incorporating a novel skin bioheat transfer model and pyrolysis kinetics to test flame resistant fabrics used in firefighting, and the Henrique's' equation acted as the rule to determine second degree of skin burn. Henriques' equation was also useful in a more reasonable model considering the accurate condition in the air gap proposed by Ghazy.[16]

All the above works focused their attention on the performance of thermal protective garments during fire exposure. And the two popular criteria can only represent the thermal protective ability of thermal garments at high temperature. However, once the heat source is removed from the thermal protective garment, heat absorption of the garment is not shut off immediately; resultant heat continues to transfer to human skin via the air gap resulting in temperature rise and burn injury to human skin. Therefore, the transient post-fire exposure period is an important period influencing the thermal response and skin burn injury in the thermal protective garment, air gap and human skin microsystem, and this period has not been highlighted and investigated in any literature.

As we all know that the degree of skin burn is treated as the key parameter to evaluate thermal protective performance of thermal garment. But, the influence of ambient condition, fabric texture and air-gap on the degree of skin burn was not numerically investigated, and such work is important to predict the ability of thermal protective clothing. Therefore, in this paper, we investigate the heat transfer of air-gap considering conduction and radiation heat transfer to deal with the transient heat transfer of microsystem, the degree of skin burn is determined. Furthermore, some key parameters are investigated and compared.

MATERIALS AND METHODS:

Mathematical model:

Heat transfer in thermal protective clothing: When working in a high temperature environment, people need to wear special clothing to avoid burns. Special clothing is usually composed of three layers of fabric material, which are recorded as layers I, II, and III. The layer I is in contact with the external environment, the between the layer III and the skin is a gap and it is recorded as the IV layer. The schematic diagram of the microsystem consisting of thermal protective clothing, an air gap and multilayer human skin is shown in Fig.1. During the fire exposure period (t < t_{exp}), once the microsystem is exposed to the heat source, the heat released from the heat source can rapidly transfer to the thermal protective clothing via heat radiation (F_{rad}) and heat convection (F_{cnv}). And then, the heat transfer in the garment is via heat conduction and radiation resulting in temperature rise and the residual heat transferring into its air gap along with some loss of heat energy into the atmosphere (F'_{rad}). Next to the air gap, the residual heat transfers to the multilayer human skin. In our model, human skin has three layers: epidermis, dermis and subcutaneous, which provides for an accurate representation of human skin.

The heat transfer in the microsystem is assumed as one-dimensional, the thermal protective clothing is treated as a grey body, and moisture transfer is neglected. The convection portion of the heat source could reach to the fabric surface while the radiation heat flux could penetrate to a certain depth or pass completely through the fabric, depending on the fabric structure and the incident radiation wavelength distribution. Infrared radiation is considered here while the ultraviolet radiation from flames is neglected owing to it margin effect.
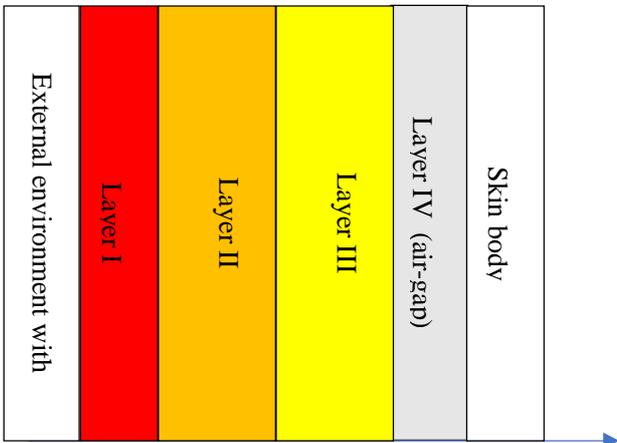
Figure 1: The thermal protective clothing air-gap human skin system.

Based on the above assumptions, the heat transfer model of the three-layer thermal protective clothing[17]:

$$C_{shl}^A \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{shl} \frac{\partial T}{\partial x}) + \frac{\partial F_{rad}}{\partial x} - \frac{\partial F_{conv}}{\partial x} \quad (1)$$
$$(x,t) \in \theta_1 \times (0, t_{exp})$$

$$C_{msr}^A \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{msr} \frac{\partial T}{\partial x}), \ (x,t) \in |\theta_2 \times (0, t_{exp}) \quad (2)$$

$$C_{lin}^A \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{lin} \frac{\partial T}{\partial x}), \ (x,t) \in \theta_3 \times (0, t_{exp}) \quad (3)$$

Where C_{shl}^A, C_{msr}^A, C_{lin}^A is apparent heat capacity (J.m^{-3}.K^{-1}) of layer I, II, III; T is temperature (K); t is time (s); x is position (m); k_{shl}, k_{msr}, k_{lin} is thermal conductivity of layer I, II, III (W.m.K^{-1}); F_{rad}, F_{conv} is heat radiation and heat convection (W); t_{exp} is exposure time (s); θ_i (i=1,2,3,4,5) is thickness of layer (m), θ_1 =(0, L_{shl}), θ_2 = (L_{shl}, $L_{shl}+L_{msr}$), θ_3 = ($L_{shl}+L_{msr}$, L_{fab}), $L_{fab}= L_{shl}+L_{msr}+:L_{lin}$ respectively.

Based on[17] we can identify the heat radiation and heat convection as:

$$\frac{\partial F_{rad}}{\partial x} = \beta F_{rad} - \beta \sigma T^4, (x,t) \in \theta_1 \times (0, t_{exp}) \quad (4)$$

$$\frac{\partial F_{conv}}{\partial x} = \beta F_{conv} + \beta \sigma T^4, (x,t) \in \theta_1 \times (0, t_{exp}) \quad (5)$$

In that β is radiation absorption constant (K^{-1}), σ is Stephen Boltzmann constant and σ =5.670 .10-8 W/(m2.K4).

The initial condition of the fabric layer:
$$T(x,0) = T_1(x), \ x \in (0, L_{fab}) \quad (6)$$

The boundary conditions at the the fabric layer surface (layer I) [2] respectively:

$$-k_{shl} \frac{\partial T}{\partial x}\Big|_{x=0} = (q_{conv} + q_{rad})\Big|_{x=0} \quad (7)$$

$$-k_{lin} \frac{\partial T}{\partial x}\Big|_{x=L_{fab}} = (q_{air} - k_{air} \frac{\partial T}{\partial x})\Big|_{x=L_{fab}} \quad (8)$$

$$(1-\xi_1)F_{rad}(0, t) + \xi_1 \sigma T^4(0, t) = F_{conv}(0, t) \quad (9)$$

Where ξ_1 is heat radiation coefficient (W/(s.m^2); q_{conv} is convection heat flux, q_{rad} is radiation heat flux and q_{air} is radiation heat flux (W/m^2) in the air-gap, which is derived by Beer's law; k_{air} is thermal conductivity of air (W/(m.K)).

At the boundary of layer I and layer II surface:
$$T_{msr}\Big|_{x=L_{shl}} = T_{shl}\Big|_{x=L_{shl}} \quad (10)$$

$$-k_{msr}\left.\frac{\partial T}{\partial x}\right|_{x=L_{shl}} = -k_{shl}\left.\frac{\partial T}{\partial x}\right|_{x=L_{shl}} \tag{11}$$

$$(1-\xi_2)F_{rad}(L_{shl}, t) + \xi_2\sigma T^4(L_{shl}, t) = F_{conv}(L_{shl}, t) \tag{12}$$

ξ_2 is heat radiation coefficient (W/(s.m^2).

At the boundary of layer II and layer III surface:

$$T_{lin}\big|_{x=L_{shl}+L_{msr}} = T_{msr}\big|_{x=L_{shl}+L_{msr}} \tag{13}$$

$$-k_{lin}\left.\frac{\partial T}{\partial x}\right|_{x=L_{shl}+L_{msr}} = -k_{msr}\left.\frac{\partial T}{\partial x}\right|_{x=L_{shl}+L_{msr}} \tag{14}$$

From [9] combined with formula (7), the heat radiation and heat convection of the fabric layer can be described as:

$$(q_{conv} + q_{rad})\big|_{x=0} = h_{c,fl}(T_g - T\big|_{x=0}) \tag{15}$$

Combine the thermal protective clothing model and formulas we can be determined the heat capacity as:

$$C^A = \rho c_p \tag{16}$$

$$k_{shl} = \tilde{\varepsilon}_{shl}k_{air} + (1-\tilde{\varepsilon}_{shl})k_{fab} \tag{17}$$

$$k_{lin} = \tilde{\varepsilon}_{lin}k_{air} + (1-\tilde{\varepsilon}_{lin})k_{fab} \tag{18}$$

$$k_{air}(T) = \begin{cases} 0.026 + 0.000068(T-300), & T \leq 700K \\ 0.053 + 0.000054(T-700), & T>700K \end{cases} \tag{19}$$

$$k_{fab}(T) = \begin{cases} 0.013 + 0.000018(T-300), & T \leq 700K \\ 1, & T>700K \end{cases} \tag{20}$$

In that, ρ is density of the fabric (kg/m3); c_p is specific heat capacity (J/kg. K) and $c_p = 1300 + 1.6(T-300)$; k_{air}, k_{fab} are thermal conductivity of air and fabric; $\tilde{\varepsilon}_{shl}$ and $\tilde{\varepsilon}_{lin}$ are porosity of layer I and II.

Heat transfer in the air layer: According to the assumption, it is possible to obtain the heat transfer model of the air layer[15]:

$$(\rho c_p)_{air}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{air}\frac{\partial T}{\partial x}) - \frac{\partial q_{air}}{\partial x}$$
$$(x,t) \in \theta_4 \times (0,t_{exp}); \theta_4 = (L_{fab}, L_{fab}+L_{air}) \tag{21}$$

Due to the thickness of the air layer was small which can be regarded as a rectangular closed cavity and Using the conduction/convection heat transfer principle in a limited space, considering the conduction/convection and fabric radiation in the air we can be determined the heat transfer in the air layer as:

$$k_{air}\left.\frac{\partial T}{\partial x}\right|_{x=L_{fab}} = k_{air}\left.\frac{\partial T}{\partial x}\right|_{x=L_{fab}+L_{air}} = h_{c,air}(T\big|_{x=L_{fab}} - T\big|_{x=L_{fab}+L_{air}}) \tag{22}$$

$$q_{air}\big|_{x=L_{fab}} = q_{air}\big|_{x=L_{fab}+L_{air}} = \frac{\sigma(T^4\big|_{x=L_{fab}} - T^4\big|_{x=L_{fab}+L_{air}})}{\frac{1}{\varepsilon_{lin}} + \frac{1}{\varepsilon_{skin}} - 1} \tag{23}$$

ε_{lin}, ε_{skin} are emissivity of layer III anh skin; $h_{c,air} = Nu\frac{k_{air}(T)}{L_{air}}$ and Nu is Nusselt number which is the ratio of convective to conductive heat transfer across a boundary.

$$T(x,0) = T_1(x), x \in \theta_4 \tag{24}$$

Heat transfer in the skin layer: Combine skin tissue structure and Pennes' bioheat transfer model, The governing equation of human skin is listed:

$$(\rho c_p)_{skin}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{skin}\frac{\partial T}{\partial x}) + (\rho c_p)_b \omega_b(T_{cr} - T)$$
$$(x,t) \in \theta_5 \times (0,t_{exp}) \tag{25}$$

The thermal conductivity of the skin (k_{skin}); ω_b is Blood perfusion rate; T_{cr} is body core temperature (310.15K); $\theta_5 = (L_{fab}+L_{air}, L_{fab}+L_{air}+L_{skin})$; $L_{skin} = L_{ep} + L_{ds}, L_{sc}$; L_{ep}, L_{ds}, L_{sc} is thickness of epidermis, dermis and subcutaneous layer.

$$-k_{air}\left.\frac{\partial T}{\partial x}\right|_{x=L_{fab}} = (q_{air,rad} - k_{air}\frac{\partial T}{\partial x})\big|_{x=L_{fab}+L_{air}} \tag{26}$$

$$T\big|_{x=L_{fab}+L_{air}} = T_{cr}; T(x,0) - T_1(x), x \in \theta_5 \tag{27}$$

Determining Degree of Skin Burn: In order to predict the time to skin burns to improve the performance of the thermal protective clothing system. The integral of Henrique and Moritz [9] was employed to predict times to receive skin burn injuries and damage to the skin commences when the temperature in the tissue rises above 44 °C.

$$\psi = \int_0^t Pe^{(-\frac{\Delta E}{RT(x,\tau)})} d\tau \tag{28}$$

where $P = 3.1\times10^{98}$ s^{-1} is the accepted value for the pre-exponential factor, the ratio of the activation energy to the universal gas constant as $\Delta E/R = 75000$ K. ψ is a highly nonlinear function and the generally used definitions of burns in terms of ψ are: first-degree

burn occurs at $\psi\big|_{Lx=L_{fab}+L_{air}+L_{ep}}$ = 0.53, second-degree burn at $\psi\big|_{Lx=L_{fab}+L_{air}+L_{ep}}$ = 1.0, third-degree burn at $\psi\big|_{Lx=L_{fab}+L_{air}+L_{ep}+L_{ds}}$ = 10^4.

RESULTS AND DISCUSSION:

Simulation and discussion parameters affecting thermal response: The model was programmed using matlab and the default physical model heat transfer in solids module considering surface to surface radiation was employed based on formula (1) to (28). Heat transfer in the microsystem of thermal protective garment, air gap and human skin during fire exposure can be treated as unsteady-state heat transfer. All the physical properties for simulation are shown in Table 1 and the default data is taken from Chitrphiromsri & Kuznetsov (2005)[9].

Table 1: Physical properties of simulated parameters.

Physical property	Default value	Range
Degree of heat source T_g(K)	800	373-1500
Thickness of thermal protective clothing L_{fab} (mm)	0.8	0.4-2
Thickness of air gap L_{air} (mm)	0.6	0.2-2
Specific thermal capacity of clothing C (J/(kg. K)	1500	1000-2000
Thermal conductivity of clothing k_{fab}(W/(m.K)	0.03	0.02-0.1

The heat source is the starting point of the entire heat transfer and thermal attack, and its intensity dominates the performance of the thermal protective clothing. Hence, we simulated four levels of heat source from 373 K to 1500 K. The temperatures of the clothing outer surface and the skin surface are illustrated in Fig.2, along with the corresponding retardation time and temperature maximum.
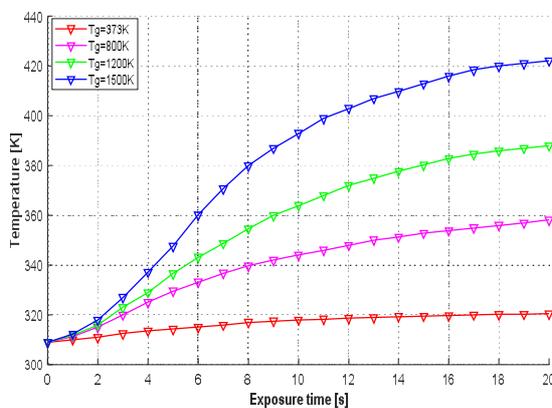
Figure 2: The effect of heat source on temperature curve of human skin surface.

Heat source with higher temperature could contain more heat energy, and transfer more heat flux into thermal protective garment, and resulting in higher temperature response of human skin surface. In Fig.3 the heat source Tg = 373 K results in the longest first degree burn, second degree burn, and third degree burn while the heat source Tg = 1500 K has the shortest degree of skin burn only after five seconds exposure time. Therefore, the temperature of heat source is the key outside factor to affect the degree of skin burn, such factor should be considered when evaluating thermal protective properties of insulating materials. In addition, thermal protective properties of insulating materials under fabric air-gap human skin microsystem should be recommended and performs more accurate results than the single insulating materials evaluation.

In the Fig.4 with increasing thickness of air-gap, the temperature located at human skin surface is with tardiness response. Which indicating the thicker air-gap could absorb more heat energy and shield heat flux transferring into skin surface. Therefore, air-gap plays an important role in shielding heat flux into skin, and the insulating performance could be more remarkable for the thick air-gap configuration.
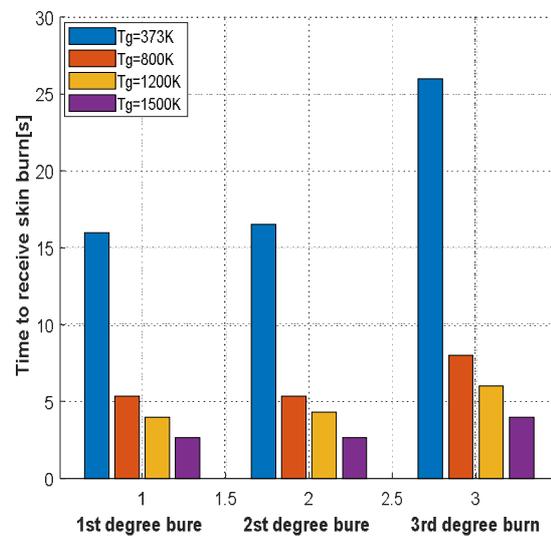
Figure 3: The effect of heat source on degree of skin burn.

The effects of fabric thickness with different thickness (0.4mm-2mm) were simulated and the results are listed in Fig.5. It can be seen that temperature increase rate decreased with increasing garment thickness during exposure time (0–20s) owing to the increasing thermal resistance of the fabric. On entering post-fire exposure, the garment with the thinner thickness had a quick cooling down performance because of the corresponding smaller thermal resistance. With the in-

creasing thickness of the garment, time to receiving skin burns gradually prolonged from the fire exposure to the post-fire exposure period. Such a result proved that the thicker fabric with has better thermal protective performance.
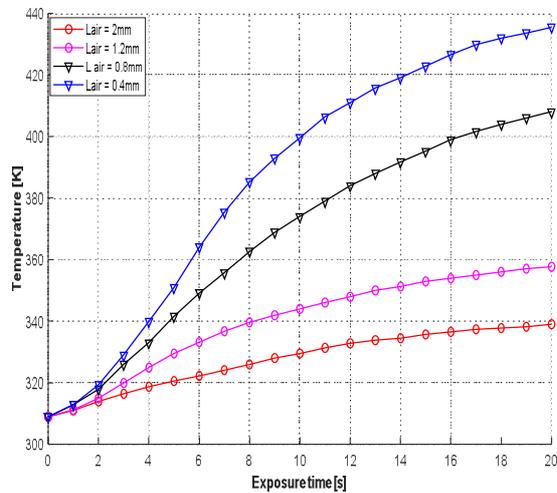
Figure 4: The effect of air-gap thickness on temperature curve of human skin surface.
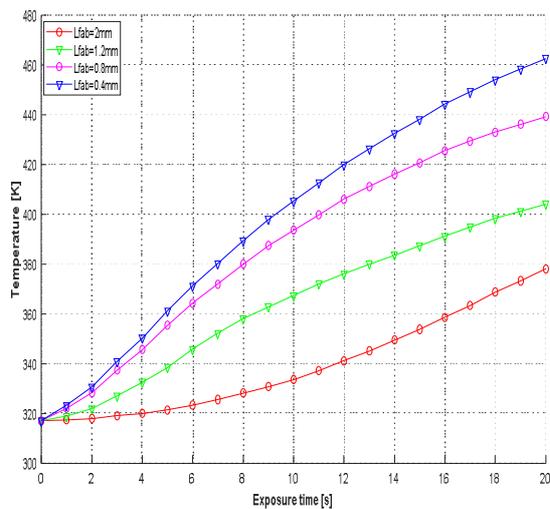
Figure 5: The effect of fabric thickness on temperature curve of human skin surface.

CONCLUSION: A heat transfer model of the thermal protective clothing, air gap and skin microsystem was established and the resulting temperature distribution of the skin layer reflected the postponed temperature increase during post-fire exposure. The result simulation demonstrated that the effect of fabric and air-gap thickness, degree of heat source on degree of skin burn are investigated and compared. It is found that the volumetric heat capacity of fabric is the key parameter to affect the thermal shielding performance of

thermal protective clothing, and the thicker fabric thickness and air gap thickness are both to improve the thermal protective properties of the microsystem.

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