NUMERICAL PREDICTION OF DEGREE OF SKIN BURN IN THERMAL PROTECTIVE GARMENT AIR-GAP HUMAN BODY SYSTEM

by

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Thermal protective garment has been deemed as an important shielding against fire hazard and inflammable gas leakage. The coupling model of thermal protective garment, air-gap, and human body has been widely established, but the heat transfer in air-gap was commonly simplified, resulting in inaccurate results. This paper suggests a coupling heat transfer model of the microsystem consisting of thermal protective garment, air-gap, and human body, taking into account the heat transfer of air-gap, and human skin, its numerical solution is obtained by the finite element method. The degree of skin burn could be extracted and determined from the model, and the effect of heat source, fabric thickness, and air-gap thickness on the degree of skin burn are investigated.

Key words: *thermal protective garment, air-gap, degree of skin burn, human skin, finite element method*

Introduction

In order to protect human security, thermal protective garment as the main personal protective equipment has been widely applied in various flame and high temperature conditions. Therefore, it is essential to investigate the thermal response and insulation of thermal protective garment [1, 2]. Some researchers have done some important work in this issue by experimental and numerical methods [3, 4]. In general, the measurement of thermophysical properties of fabric can be divided into two categories, steady-state method and unsteady-state method. Torvi *et al.* [5] established a heat transfer model of one layer fabric subjected to the high heat fluxes used in bench top tests. Tian *et al.* [6] employed CFD to establish 3-D numerical simulation of heat transfer through simplified protective clothing during fire exposure. The heat transfer in air-gap located between thermal protective clothing and human skin is commonly simplified and assumed that the air-gap could not absorb and emit any radiation during the entire heat transfer. Ghazy *et al.* [7] proposed a more reasonable model considering the accurate condition in the air-gap, but the calculation process was seemed to be too com-

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plex to be handled easily. 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, the heat transfer of air-gap considering conduction and radiation heat transfer is established, and a numerical finite element method is employed to deal with the transient heat transfer of microsystem, the degree of skin burn is determined. Furthermore, some key parameters are investigated and compared.

Mathematical model

The schematic diagram of flame retardant cotton fabric, air-gap, and human skin microsystem model is shown in fig. 1. In this model, heat source releases high temperature, and the exposing heat flux transfers to the fabric *via* heat radiation ($q_{\rm rad}$) and heat convection ($q_{\rm cnv}$). And then, the fabric could absorb part of the heat with temperature rise and the residual heat would transfer into its neighbor part air-gap with heat conduction (q_{cnd}) and the heat radiation along with cooling some heat energy into outside ambient place ($q'_{\rm rad}$). In the air-gap part, the transferred heat could be partly absorbed by air-gap, and result in the temperature rise and the other part heat transfer could reach to the human skin and influence human body temperature distribution. By the way, in this model human skin is specified into three layers, epidermis, dermis, and subcutaneous, which could be more accurate to simulate human skin, furthermore, the effect of blood perfusion is also considered in this part.

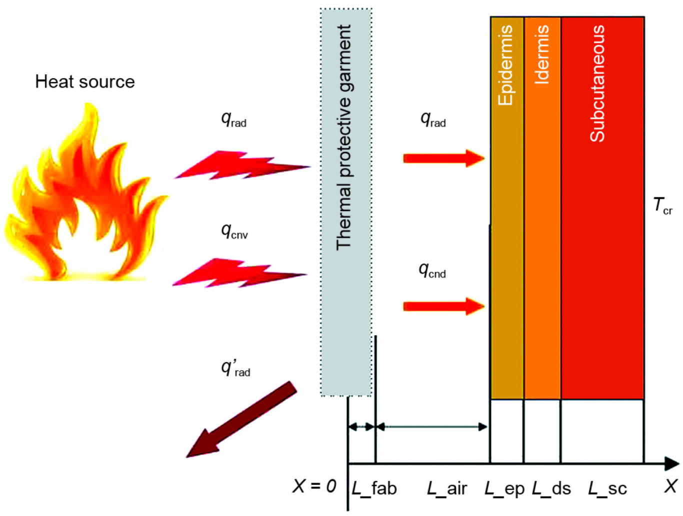

Figure 1. The thermal protective garment air-gap human skin system

The governing equations of thermal protective thermal garment, air-gap, and human skin are listed in the paper, especially, the heat transfer of air-gap is different from the previous works, which combines the effect of conduction and radiation heat transfer, in addition, human skin three layers considering blood perfusion is establish instead of simple single layer. In order to make the problem manageable, some assumptions and restrictions are defined here.

The heat transfer in the microsystem is assumed as 1-D. The thermal protective garment 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.

The governing equation of thermal protective garment:

$$\rho C^A(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[k_{\mathrm{fab}}(T)\frac{\partial T}{\partial x}\right]-\frac{\partial q_{\mathrm{rad}}(x)}{\partial x} \tag{1}$$

where $q_{\mathrm{rad}}(x)$ is the portion heat flux due to thermal radiation from the heat source, this term can be derived as $q_{\mathrm{rad}}(x) = q_{\mathrm{rad}}(x = 0)[1 - \exp(-\gamma x)] = \sigma\varepsilon_g T_g^4[1 - \exp(-\gamma x)]/L_{\_\mathrm{fab}}$, T_g – the temperature of hot gas, C^A – the fabric apparent heat capacity that accounts for the evaporation of the moisture and the energy released from the thermochemical reactions, and ρ, k, T, and x have their usual meanings.

The fabric boundary conditions at two surface ($x = 0$ and $x = L_{\_\mathrm{fab}}$) are:

$$-k_{\mathrm{fab}}(T)\left.\frac{\partial T_{\mathrm{fab}}}{\partial x}\right|_{x=0}=h_{\mathrm{fab}}(T_g-T_{\mathrm{fab}}|_{x=0})-\sigma\varepsilon_{\mathrm{fab}}(1-\varepsilon_g)(T_{\mathrm{fab}}^4\big|_{x=0}-T_{\mathrm{amb}}^4) \tag{2}$$

$$-k_{\mathrm{fab}}(T)\left.\frac{\partial T_{\mathrm{fab}}}{\partial x}\right|_{x=L\_\mathrm{fab}}=-q''_{\mathrm{rad}}\big|_{x=L\_\mathrm{fab}}-k_{\mathrm{air}}(T)\left.\frac{\partial T_{\mathrm{air}}}{\partial x}\right|_{x=L\_\mathrm{fab}} \tag{3}$$

where h_{fab} and $\varepsilon_{\mathrm{fab}}$ are the convection heat transfer coefficient between the heat source and the fabric surface, respectively, $q''_{\mathrm{rad}}|_{x=L\_\mathrm{fab}}$ – the emitted radiation from the fabric backside surface, which can be derived from the following equations:

$$q''_{\mathrm{rad}}\big|_{x=L\_\mathrm{fab}}=\frac{\sigma(T_{\mathrm{fab}}^4\,|_{x=L\_\mathrm{fab}}-T_{\mathrm{ep}}^4\,|_{x=L\_\mathrm{fab}+L\_\mathrm{air}})}{\dfrac{1}{\varepsilon_{\mathrm{fab2}}}+\dfrac{1}{\varepsilon_{\mathrm{ep}}}-1} \tag{4}$$

The governing equation of the air-gap:

$$\rho C_{\mathrm{air}}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[k_{\mathrm{air}}(T)\frac{\partial T}{\partial x}\right]-\frac{\partial q_{\mathrm{air}}(x)}{\partial x} \tag{5}$$

where $q_{\mathrm{air}}(x)$ is the radiation heat flux within the air-gap, which is derived by Beer's law:

$$q_{\mathrm{air}}(x)=q_{\mathrm{air}}(x)\,|_{x=L\_\mathrm{fab}}\exp(-\kappa x) \tag{6}$$

The air-gap boundary conditions at two surfaces ($x = L_{\_\mathrm{fab}}$ and $x = L_{\_\mathrm{fab}} + L_{\_\mathrm{air}}$) are:

$$T_{\mathrm{air}}\big|_{x=L\_\mathrm{fab}}=T_{\mathrm{fab}}\big|_{x=L\_\mathrm{fab}},\qquad T_{\mathrm{air}}\big|_{x=L\_\mathrm{fab}+L\_\mathrm{air}}=T_{\mathrm{ep}}\big|_{x=L\_\mathrm{fab}+L\_\mathrm{air}} \tag{7}$$

The governing equation of human skin is listed:

$$\rho C_{\mathrm{ep}}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k_{\mathrm{ep}}\frac{\partial T}{\partial x}\right) \tag{8}$$

$$\rho C_{\mathrm{ds}}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k_{\mathrm{ds}}\frac{\partial T}{\partial x}\right)+(\rho C_P)_b\,\omega_b(T_{\mathrm{cr}}-T) \tag{9}$$

$$\rho C_{\mathrm{sc}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{\mathrm{sc}} \frac{\partial T}{\partial x} \right) + (\rho C_P)_{\mathrm{b}} \omega_{\mathrm{b}} (T_{\mathrm{cr}} - T) \tag{10}$$

where ω_{b} is the blood perfusion rate within the dermis and subcutaneous layers, T_{cr} – the human core body temperature. The corresponding parameters of human skin can be found from [8].

The skin boundary conditions at two surfaces ($x = L_{\_\mathrm{fab}} + L_{\_\mathrm{air}}$ and $x = L_{\_\mathrm{fab}} + L_{\_\mathrm{air}} + L_{\_\mathrm{ep}} + L_{\_\mathrm{ds}} + L_{\_\mathrm{sc}}$) are:

$$-k_{\mathrm{ep}}(T) \frac{\partial T_{\mathrm{ep}}}{\partial x}\bigg|_{x=L\_\mathrm{fab}+L\_\mathrm{air}} = q''_x\big|_{x=L\_\mathrm{fab}+L\_\mathrm{air}} - k_{\mathrm{air}(T)} \frac{\partial T_{\mathrm{air}}}{\partial x}\bigg|_{x=L\_\mathrm{fab}+L\_\mathrm{air}} \tag{11}$$

$$T_{\mathrm{sen}}\big|_{x = L\_\mathrm{fab}+L\_\mathrm{air}+L\_\mathrm{ep}+L\_\mathrm{ds}+L\_\mathrm{sc}} = T_{\mathrm{cr}} \tag{12}$$

The initial condition of this system is $T_{\mathrm{fab}}\big|_{t=0} = T_{\mathrm{air}}\big|_{t=0} = T_{\mathrm{amb}}$ and the temperature in skin linearly increases from the epidermis outlayer (32 °C) to the dermal base (37 °C) and T_{cr} is the human core body temperature. The corresponding boundary conditions, initial condition and parameters can be found from [8].

Determining degree of skin burn

Damage to the skin commences when the temperature in the tissue rises above 44 °C. The integral of Henrique and Moritz [9] was employed to predict times to receive skin burn injuries:

$$\Omega(t) = \int_0^t P \exp\left\{ -\frac{\Delta E}{\mathrm{R}[T(\tau) + 273]} \right\} \mathrm{d}\tau \quad \text{when} \quad T(\tau) > 44 \tag{13}$$

where $P = 3.1 \cdot 10^{98}\mathrm{s}^{-1}$ is the accepted values for the pre-exponential factor, the ratio of the activation energy to the universal gas constant as $\Delta E/\mathrm{R}$ = 75000 K. The $\Omega(t)$ is a highly non-linear function and the generally used definitions of burns in terms of $\Omega(t)$ are: first degree burn occurs at $\Omega(t)$ = 0.53, second degree burn at $\Omega(t)$ = 1.0, and third degree burn at $\Omega(t) = 10^4$.

Results and discussion

The effect of heat source (T_{g} = 500-2500 K) on degree of skin burn can be illustrated in fig. 2, It can be found that human skin surface performs high temperature curve from fig. 2(a) with increasing degree of heat source. 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. Furthermore, from fig. 2(b), the heat source T_{g} = 500 K results in the longest first degree burn, second degree burn, and third degree burn while the heat source T_{g} = 2500 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 [10, 11].

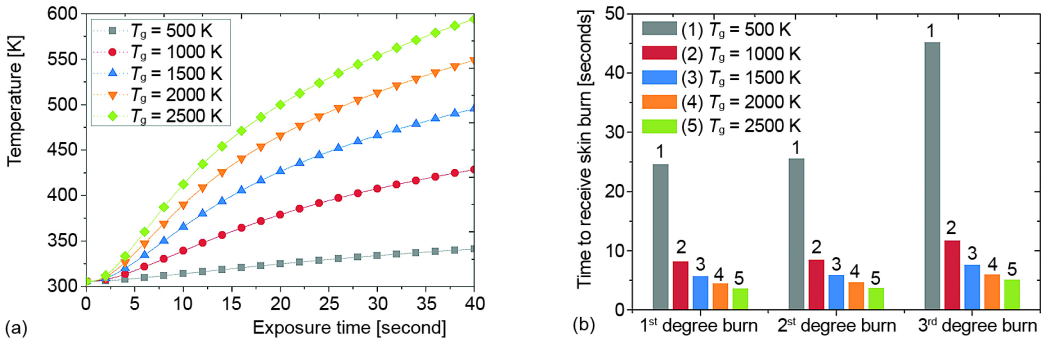

Figure 2. The effect of heat source on (a) temperature curve of human skin surface and (b) degree of skin burn

With increasing thickness of air-gap, the temperature located at human skin surface is with tardiness response as shown in fig. 3(a), 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. From fig. 3(b), the effect of air-gap on degree of skin burn is linearly changed with increasing thickness, indicating thick air-gap could absorb more heat energy from heat conduction and heat radiation, and air-gap plays an important role in this microsystem [12, 13].

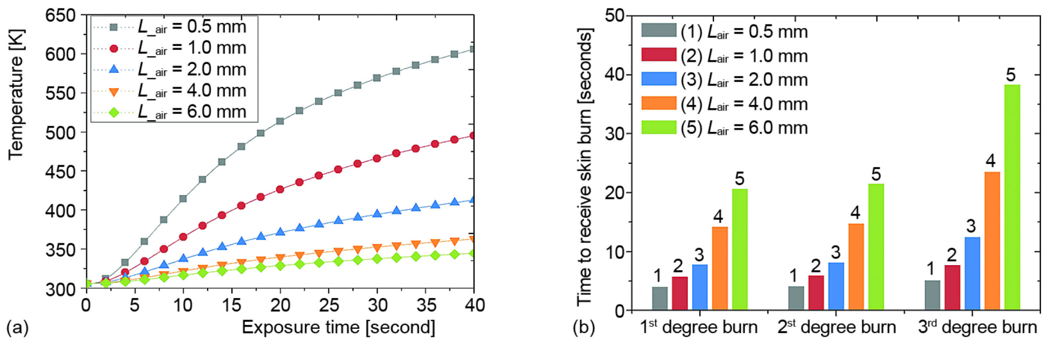

Figure 3. The effect of air-gap thickness on (a) temperature curve of human skin surface and (b) degree of skin burn

The effect of the fabric thickness is investigated in this part, fig. 4(a) exhibits the effect of the fabric thickness (range from 0.3-2.0 mm) on the thermal response of the microsystem. With the increasing thickness, the temperature tends to the lower level indicating that the fabric could absorb more heat from the cone heater and leaking less heat to the following air-gap, and human skin. For instance, when the fabric reaches to 2 mm, the temperature located at the skin surface only increases 70 K with reasonable thermal protective performance. In a word, the thicker fabric could absorb more heat and perform well shielding properties. From fig. 4(b), degree of skin burn also become better with thicker fabric, with the increasing thickness, the temperature tends to the lower level indicating that the fabric could absorb more heat from the cone heater and leaking less heat to the following air-gap, and human skin. For instance, when the fabric reaches to 2 mm, the temperature located at the skin surface only increases 70 K with reasonable thermal protective performance. In a word, the thicker fabric could absorb more heat and perform well shielding properties.

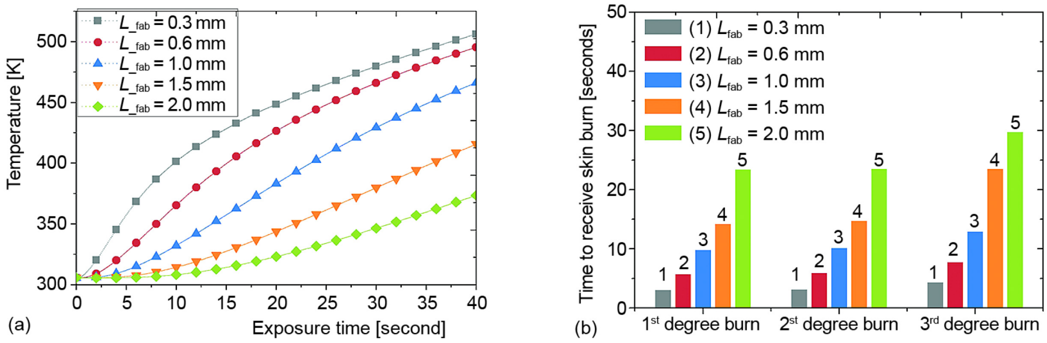

Figure 4. The effect of fabric thickness on (a) temperature curve of human skin surface and (b) degree of skin burn

Conclusion

In this paper, a microsystem consisted of thermal protective thermal clothing, air-gap, and human skin is established and the temperature distribution and heat flux in this system are numerical simulated *via* finite element method. Furthermore, 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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