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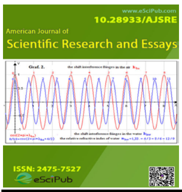

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Research on Thermal Protective Clothing Based on Temperature Distribution

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ABSTRACT

This paper studies the design of professional clothing for high-temperature operation. Based on the temperature distribution inside the garment and outside the human skin, a mathematical model is established to calculate the temperature distribution. For a three layers fabric material, the heat transfer equation for the fabric layer is established. The heat transfer of the air layer between the fabric and the skin is dominated by radiant heat exchange, effectively interpreting the heat transfer mechanism of the air layer, thereby constructing the energy heat balance equation of the air layer. Combined with the initial conditions and boundary conditions, the spatial and temporal dispersion of the finite explicit difference format is performed.

Keywords: Heat transfer;Heat radiation;Temperature distribution; Discrete

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1. Introduction

High temperature heat damage has always been a problem in labor production in the world. It is an important occupational hazard, especially for manual workers, and increased heat load in a hot environment can lead to increased disease. According to the results of domestic health inspections of thermal workers, it can be found that working in a long-term high temperature environment can cause the body temperature regulation of workers to be affected, and it is prone to headaches, multiple dreams, memory loss, irritability and other neurasthenia symptoms[1]. It may even lead to severe dehydration, circulatory failure, heat exhaustion or abnormal liver and kidney function. Therefore, workers in high temperature environments should take appropriate protective measures to reduce the damage to the body caused by high temperature environment. In addition to improving the working environment and equipped with protective equipment, workers usually choose to wear heat-resistant, breathable fabric-specific thermal protective clothing to directly avoid burns and reduce physical damage. There are usually three ways to transfer heat, namely heat radiation, heat conduction and heat convection. The principle of thermal protective clothing is to slow down the heat transfer rate and minimize the accumulation of heat on the skin. Therefore, thermal protective clothing not only needs to have good flame-retardant properties, but also requires high thermal insulation properties1.

2. Problem analysis

Special thermal protective clothing is usually composed of three layers of fabric materials I, II and III. The first layer is in direct contact with the external environment, and the third layer is closest to the skin. There is still a gap between the third layer and the skin, and the gap is described as the IV layer. In order to design a special thermal protective suit, the artificial temperature of the dummy was placed in a laboratory at 37 ° C high temperature environment to conduct an experiment to measure the external temperature of the dummy skin. Some parameters of the special clothing materials are shown in Table 1[3].

Table 1: Special clothing material parameter value

Layers	Density (kg/m^3)	Specific Heat Capacity (J/(kg·ºC))	Thermal Conductivity (W/(m·ºC))	Thickness (mm)
I	300	1377	0.082	0.6
II	862	2100	0.37	0.6-25
III	74.2	1726	0.045	3.6
IV	1.18	1005	0.028	0.6-6.4

Specific heat measures the ability of an object to absorb and dissipate heat. The higher the specific heat, the stronger the heat absorption or heat dissipation of the object[2]. Conductivity is the ability of an object to directly conduct heat. In the thickness parameter, if the thickness of the I layer and the III layer are 0.6 mm and 3.5 mm, respectively. We assume that the working time is 90 minutes, the ambient temperature is 75 degrees Celsius, the thickness of layer II is 6 mm, and the thickness of layer IV is 5 mm. The temperature distribution of the skin of the dummy is measured, and the corresponding mathematical model is established to calculate the temperature.

3. Model Preparation

The high-temperature work clothing is composed of three layers of fabric, and the external heat is transferred to the human skin through the three layers of fabric and an air layer, and they are respectively referred to as layer I, II, III and IV. Due to the low heat density of the garment surface, the thermal convection and heat radiation of the I to III layers are slight compared to the heat conduction inside the fabric, which can be ignored. According to the Fourier heat conduction law, in the dt time, the heat dQ flowing into the volume element through the area element dS is proportional to the temperature change rate $\frac{\partial u}{\partial n}$ in the normal direction outside the area element, and is also proportional to dS and dt , which can be expressed as follows.

$$dQ = k\frac{\partial u}{\partial n}dsdt$$

In the above formula, k is the thermal conductivity and $u(x,y,z)$ is the temperature in the thermal conductor. The total heat input into the thermal conductor through the curved surface is expressed as follows.

$$Q_1 = \int_{t_1}^{t_2}\left[\iiint_V k\left[div\left(Grad\ u\right)\right]dxdydz\right]dt$$

The energy required for the temperature rise is expressed as follows.

$$Q_2 = \int_{t_1}^{t_2}\left[\iiint_V c\rho\frac{\partial u}{\partial t}dxdydz\right]dt$$

If $Q_1 = Q_2$, then the three-dimensional heat conduction equation is obtained as follows.

$$k\left(u_{xx}+u_{yy}+u_{zz}\right)=c\rho u_t$$

In the above formula, k is the heat transfer coefficient, ρ is the density of the material, and c is the specific heat of the material. The heat is transferred from the outside to the human skin in only one direction, so the one-dimensional form of the heat conduction equation can be used, and the expression is as follows.

$$c\rho\frac{\partial u}{\partial t}=k\frac{\partial^2 u}{\partial x^2}$$

4. Model Establishment

4.1 Heat Transfer Model of Fabric Layer

In the I layer, the external temperature is $T_0 = T(0,t)$, which ignores the factors of thermal convection and thermal radiation. According to the one-dimensional form of the heat conduction equation, the following equation is obtained:

$$C_{\mathrm{I}}\frac{\partial T}{\partial t}=k_{\mathrm{I}}\frac{\partial^2 T}{\partial x^2},(x,t)\in(0,x_1)\times(0,t_0)$$

In the above formula, C_{I} is the sensible heat capacity of the I layer material, which can be expressed as $C_{\mathrm{I}} = c_{\mathrm{I}}\rho_{\mathrm{I}}$. k_{I} is the heat transfer coefficient of the I layer material, and T is the temperature distribution function of the I layer material, which is a function of the time t and the distance x from the outside. x_1 is the thickness of the layer I material, and t_0 is the total working time at high temperature.

Assuming that the work clothes are in a normal temperature state at time 0, the initial conditions for obtaining the equation are expressed as follows.

$$T(x,0)=T^0$$

The left boundary of the I layer material is a high temperature environment, the temperature is constant T^0, and the right boundary and the II layer material satisfy the following connection conditions:

$$-k_{\mathrm{II}}\frac{\partial T}{\partial x}\bigg|_{x=x_1} = -k_{\mathrm{I}}\frac{\partial T}{\partial x}\bigg|_{x=x_1}$$

The layer II material is between the layer I and the layer III, and the heat radiation is blocked by the layer I and layer III, with reference to the one-dimensional heat conduction equation:

$$C_{\mathrm{II}}\frac{\partial T}{\partial t}=k_{\mathrm{II}}\frac{\partial^2 T}{\partial x^2},(x,t)\in(x_1,x_2)\times(0,t_0)$$

$$T(x,0)=T^0$$

The right boundary and the III-layer material satisfy the convergence relationship expressed as:

$$-k_{\mathrm{II}}\frac{\partial T}{\partial x}\bigg|_{x=x_2} = -k_{\mathrm{III}}\frac{\partial T}{\partial x}\bigg|_{x=x_2}$$

The right side of the III-layer material is an air layer. Since the air layer is thin, the heat radiation of the human body and the thermal convection effect of the air layer can be neglected, and the heat conduction equation is combined with the following formula.

$$C_{\mathrm{III}}\frac{\partial T}{\partial t}=k_{\mathrm{III}}\frac{\partial^2 T}{\partial x^2},(x,t)\in(x_2,x_3)\times(0,t_0)$$

The initial condition is as follow.

$$T(x,0)=T^0$$

The right boundary of the III-layer material and the material of the IV layer satisfy the connection condition, which is expressed as follows.

$$-k_{\mathrm{III}}\frac{\partial T}{\partial x}\bigg|_{x=x_3} = -k_{\mathrm{IV}}\frac{\partial T}{\partial x}\bigg|_{x=x_3}$$

4.2 Heat Transfer Model of the Air Layer

When the thickness of the air layer between the fabric and the skin is less than 8 mm, the air layer gap is too small to form a convective motion, and the heat transfer of the air layer is mainly conducted. The energy heat balance equation between the air layers between the skin and the fabric is as follows.

$$C_{\mathrm{IV}}\frac{\partial T}{\partial t}=k_{\mathrm{IV}}\frac{\partial^2 T}{\partial x^2}-\frac{\partial q}{\partial x},(x,t)\in(x_3,x_4)\times(0,t_0)$$

The right boundary of the air layer and the layer material satisfy the convergence condition expression as follows.

$$-k_{\mathrm{IV}}\frac{\partial T}{\partial t}\bigg|_{x=x_3}=-k_{\mathrm{III}}\frac{\partial^2 T}{\partial x^2}\bigg|_{x=x_3}$$

The right boundary is the body surface, and the temperature is the body surface temperature after the heat insulation, which can be expressed as following.

$$T(L,t)=T_e$$

The initial condition can be expressed as follow.

$$T(x,0)=T^0$$

The IV-layer material is an air layer, usually thin, which can be considered to be a rectangular closed cavity for the small thickness of the air layer. The conduction and convection heat principles in the limited space are assumed, and the heat conduction of the air layer is assumed to be a steady state process. It is assumed that the absorption of thermal radiation by the air layer is exponentially attenuated, which is obtained by the corresponding calculation equation as follows.

$$q(x)=q(x_3)e^{-\kappa x}$$

The third type of boundary conditions radiated on both sides of the air layer are:

$$q(L_1)=\frac{\sigma(T_{fab}^4\big|_{x=L_1}-T_{ep}^4\big|_{x=L_2})}{\frac{1}{\varepsilon_{fab}}+\frac{1}{\varepsilon_{ep}}-1},\quad q(L_2)=\frac{\sigma(T_{fab}^4\big|_{x=L_1}-T_{ep}^4\big|_{x=L_2})}{\frac{1}{\varepsilon_{fab}}+\frac{1}{\varepsilon_{ep}}-1}e^{-\kappa L_2}$$

In the above formula, ε_{fab} and T_{fab} are the emissivity and right boundary temperature of the first three layers of the fabric, respectively. ε_{ep} and T_{ep} are the emissivity and skin temperature as the air layer.

4.3 Finite Explicit Difference Format Model

This paper studies the differential equation of the heat conduction phenomenon, which is a parabolic equation. The numerical solution of the differential equation is the main approximate solution for solving the equation, and the approximate value of the discrete point can be obtained. There are two main types of numerical solutions for solving differential equations, the finite difference method and the finite element method4. In this paper, we apply the finite explicit difference method to discretize the heat transfer equations of four different materials and the third type of boundary conditions of the equations. The specific difference steps are as follows:

First, the spatial and temporal regions are meshed, and the finite mesh nodes are used instead of the continuous solutions of the equations.

$$h=x_{i+1}-x_i,\quad x_i=ih,\quad i=1,2,\cdots,m-1$$
$$\tau=t_{j+1}-t_j,\quad j=0,1,\cdots,n-1$$

The difference format of the heat transfer equations of the first three layers is expressed as follows.

$$C_M(T_i^j)\frac{T_i^{j+1}-T_i^j}{\tau}=\frac{k(T_{i+1}^{j+1})-k(T_i^{j+1})}{h}\cdot\frac{T_{i+1}^{j+1}-T_i^{j+1}}{h}+k(T_i^{j+1})\frac{T_{i+1}^{j+1}-2T_i^{j+1}+T_{i-1}^{j+1}}{h^2}$$

We set: $s=\frac{\tau}{\rho h^2},r=\frac{\tau}{\rho}$,and we can get the following.

$$-s\frac{k(T_i^j)}{c(T_i^j)}T_{i-1}^{j+1}+\left[1+s(\frac{k(T_i^j)+k(T_{i+1}^j)}{c(T_i^j)})\right]T_i^{j+1}-s\frac{k(T_{i+1}^j)}{c(T_i^j)}T_{i+1}^{j+1}=T_i^j$$

The difference format of the left boundary condition of the first three layers of material is expressed as follows.

$$-k_M(T_1^{j+1})\frac{T_1^{j+1}-T_0^{j+1}}{h}=h_a(T_g-T_0^{j+1})$$

The discrete format of the right boundary condition of the first three layers of material is expressed as follows.

$$-k_M(T_{m_1}^{n+1})\frac{T_{m_1}^{n+1}-T_{m_1-1}^{n+1}}{h}=\frac{\sigma\left[\left(T_{m_1}^{j+1}\right)^4-\left(T_0^{j+1}\right)^4\right]}{\frac{1-\tilde{\varepsilon}_M}{\tilde{\varepsilon}_M}+\frac{1-\tilde{\varepsilon}_{M+1}}{\tilde{\varepsilon}_{M+1}}+1}+h_M(T_{m_1}^{j+1}-\hat{T}_0^{j+1})$$

According to the discrete format of the fourth layer, there is

$$\rho c_{\rho}\frac{T_i^{j+1}-T_i^j}{\tau}=\frac{k(T_{i+1}^{j+1})-k(T_i^{j+1})}{h}\cdot\frac{T_{i+1}^{j+1}-T_i^{j+1}}{h}+k(T_i^{j+1})\frac{T_{i+1}^{j+1}-2T_i^{j+1}+T_{i-1}^{j+1}}{h^2}$$

The difference format space has a second-order precision $O(h^2)$, and the matrix form of the linear equations can be obtained as follows(Assume that the exact solution of the heat conduction equation is u_i^j).

$$\begin{pmatrix} u_1^{j+1} \\ u_2^{j+1} \\ \vdots \\ u_{m-2}^{j+1} \\ u_{m-1}^{j+1} \end{pmatrix}=\begin{pmatrix} u_1^{j} \\ u_2^{j} \\ \vdots \\ u_{m-2}^{j} \\ u_{m-1}^{j} \end{pmatrix}+\begin{pmatrix} 1-r & \frac{r}{2} & & & \\ \frac{r}{2} & 1-r & \frac{r}{2} & & \\ & \ddots & \ddots & \ddots & \\ & & \frac{r}{2} & 1-r & \frac{r}{2} \\ & & & \frac{r}{2} & 1-r \end{pmatrix}\begin{pmatrix} u_1^{j} \\ u_2^{j} \\ \vdots \\ u_{m-2}^{j} \\ u_{m-1}^{j} \end{pmatrix}+O(h^2),\quad r=\frac{\tau k_M}{\rho c h^2}$$

In summary, the temperature change model of heat transferred to human skin through the high temperature work garment is as follows.

$$\begin{cases} C_{\mathrm{I}}\frac{\partial T}{\partial t}=k_{\mathrm{I}}\frac{\partial^2 T}{\partial x^2},(x,t)\in(0,x_1)\times(0,t_0) \\ C_{\mathrm{II}}\frac{\partial T}{\partial t}=k_{\mathrm{II}}\frac{\partial^2 T}{\partial x^2},(x,t)\in(x_1,x_2)\times(0,t_0) \\ C_{\mathrm{III}}\frac{\partial T}{\partial t}=k_{\mathrm{III}}\frac{\partial^2 T}{\partial x^2},(x,t)\in(x_2,x_3)\times(0,t_0) \\ C_{\mathrm{IV}}\frac{\partial T}{\partial t}=k_{\mathrm{IV}}\frac{\partial^2 T}{\partial x^2}-\frac{\partial q}{\partial x},(x,t)\in(x_3,x_4)\times(0,t_0) \end{cases}$$

Boundary conditions are

$$\begin{cases} T(0,t)=T_0 \\ T(x,0)=T_0 \\ -k_{\mathrm{I}}\frac{\partial T}{\partial x}\Big|_{x=x_1}=-k_{\mathrm{II}}\frac{\partial T}{\partial x}\Big|_{x=x_1} \\ -k_{\mathrm{II}}\frac{\partial T}{\partial x}\Big|_{x=x_2}=-k_{\mathrm{III}}\frac{\partial T}{\partial x}\Big|_{x=x_2} \\ -k_{\mathrm{III}}\frac{\partial T}{\partial x}\Big|_{x=x_3}=-k_{\mathrm{IV}}\frac{\partial T}{\partial x}\Big|_{x=x_3} \\ T(L,t)=T_e \end{cases}$$

5. Conclusion and outlook

In this paper, the heat transfer model based on temperature distribution is established for the fabric layer and the air layer respectively, which is convenient for calculating the external temperature of the dummy according to different situations, thus providing support for the design and development of the heat protection suit. However, in future research, we also need to consider the existence of water vapor in the thermal protective suit leading to the existence of wet transfer. We need to consider all aspects of the performance of thermal protective clothing to design safe and comfortable thermal protective clothing for high temperature environmental workers.

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