Application of Finite Difference Algorithm for Temperature Distribution in Steady Environment

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Abstract

This paper is mainly aimed at establishing a model for the problem of burns of workers working in high-temperature environments. The heat conduction of the high-temperature work clothes is divided into transient and steady state. The heat conduction equation of the four-layer fabric of the high-temperature work clothes and the two layers of the dummy skin layer is established, and the boundary conditions and the connection conditions of the heat conduction equation are determined, but it is difficult in a short time. Calculate the exact solution, so the numerical solution is solved by the difference method to determine the boundary conditions. Through MATLAB simulation, the temperature values of different layers and different times are calculated, and the temperature changes of each layer are calculated and fitted with the actual data. The comparison results are basically the same, indicating that the model is suitable for the temperature variation distribution of heat-resistant protective clothing materials.

Keywords

Finite difference: heat transfer model; numerical simulation; boundary condition; MATLAB simulation.

1. Introduction

The use of high-temperature work clothing materials in normal human body, the experiment takes a long time, individual differences, large sample size and other shortcomings, and the real people in the high-temperature environment test damage to health, so the use of dummy simulation test becomes a high-temperature material test An indispensable stage. Due to the different conditions at the junction of the various layers of the material, the heat transfer mode is different, and the heat transfer mode of each layer needs to be determined according to the heat transfer principle.

In this paper, the heat transfer model and the solution of the finite difference equation are established by studying the heat transfer between the dummy layer inner surface void layer-surface skin-air layer-four layer protective clothing-environment, and the corresponding data is used to simulate the operation results to study the high-temperature operation. The temperature distribution of clothing materials on the surface of the human body.

2. Heat transfer model

2.1 Model assumptions

High-temperature work clothing is a clothing that protects the entire body under high temperature or strong radiation conditions. High-temperature work garments are usually composed of a fabric material that is heat resistant, has a low thermal conductivity, is breathable, and is effective to reflect radiation. The specific heat capacity, thermal conductivity, density and thickness parameters of high-temperature work garments are given in this paper, as shown in Table 1. However, considering that the temperature inside the dummy in the high-temperature working clothes is kept constant at 37 °C, we made two assumptions on the inside of the dummy skin, and determined the heat in the high-temperature working environment with reference to other parameters such as specific heat capacity and thermal conductivity of the human skin. The structural diagram of the external environment to the dummy in the work clothes is shown in Figure 1.

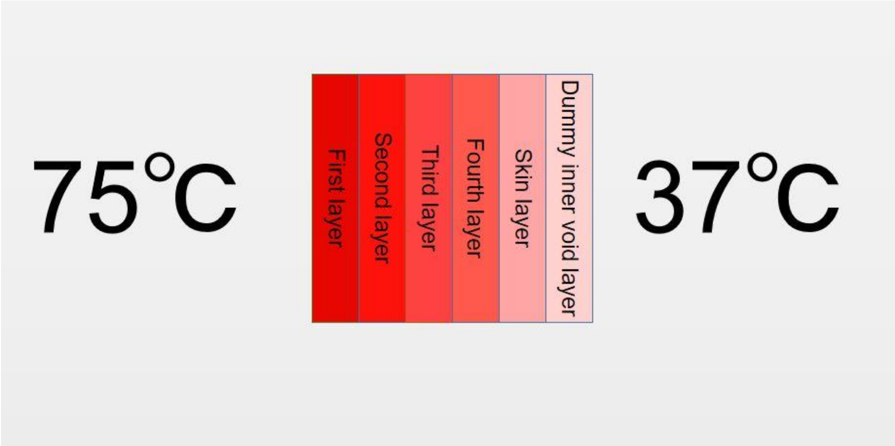

Figure 1 Heat transfer model between dummy void layer - surface skin - air layer - four layers of protective clothing – environment

For the thermal anti-air-air layer-skin system, the following assumptions are made: 1) Assume that during the heat transfer process, the structure of the special clothing material is almost constant, and its thermal conductivity is regarded as a constant; 2) the heat transfer direction is assumed to be vertical The direction of the skin can be regarded as one-dimensional; 3) assuming that the skin thickness of the dummy is 5.5 mm, the thermal conductivity of the dummy skin is 0.535 W/(m ° C), and the skin of the dummy is 3 mm from the internal heat source; 4) It is assumed that the surface of the professional clothing can be regarded as a flat wall with respect to the thickness of each layer of the material; 5) the data given by the hypothesis is consistent with the objective reality; 6) assuming that the steady state is under each layer of the high temperature working clothes It is uniform heat transfer; 7) Assuming only heat transfer is considered, the air layer is less than 6.4 mm, regardless of heat radiation and heat convection.

2.2 Mathematical model

The surface of the dummy's skin and the temperature of each layer of the garment material are gradually increased from the initial temperature, and after a certain period of transient, the steady state is finally reached. Therefore, the temperature of professional clothing in a high-temperature environment can be divided into two states, transient and steady state.

We can think of the four layers of clothing material as a heat conduction problem consisting of four parts, each of which is uniformly heat transfer, and both satisfy the heat transfer equation, and the heat is gradually transferred from the outside to the inner layer, where the external temperature is 75. The °C remains unchanged and the surface of the dummy's skin is insulated from the outside world.

According to Fourier's law, the general equations and the solution conditions for the four-part temperature change are:

$$u_t - a_i^2 u_{xx} = 0 \qquad x_{i-1} < x < x_i (i = 1, 2. \cdots, 6) \tag{1}$$

Where $a_i^2 = \lambda_i / c_i \rho_i$, x_i is the distance from the right boundary of the 1st layer to the left boundary of the first layer, $x_0 = 0$, c_i is the specific heat of the i-th layer of the heat insulating clothing material, and ρ_i is the density of the i-th layer of the heat insulating clothing material, λ_i is the thermal conductivity of the i-th layer of the insulating garment material.

The boundary conditions are:

$$\begin{cases} u|_{x=0} = 75\ ℃ \\ u|_{x=x_6} = 37\ ℃ \end{cases} \quad (2)$$

The connection conditions are:

$$u_i(t)|_{x=x_i} = u_{i+1}(t)|_{x=x_i} \qquad i = 1, 2, \cdots, 5 \quad (3)$$

Make $u(x,t) = X(x)T(t)$ (4)

According to the two boundary conditions and the three connection conditions, the solution of the equations can be obtained by using the separation variable method and the impulse theorem, and finally, the relationship between the temperature of each layer and the position is obtained.

3. Thermal conduction model difference algorithm

In this paper, the finite difference method is used to solve the partial differential equations with multiple layers of thermal protective clothing, air layer and human skin as a whole. The boundary conditions of the radiation term and the existence of the convective coefficient with temperature change cause the nonlinearity of the partial differential equations. This paper uses the discretization equation to solve.

3.1 Discretization of equations

Control the volume of the equation to get:

$$\int_t^{t+\Delta t}\int_w^e \frac{\partial^2 T}{\partial x^2} dxdt = \frac{1}{\alpha}\int_t^{t+\Delta t}\int_w^e \frac{\partial T}{\partial t} dxdt \quad (5)$$

$$\int_t^{t+\Delta t}\left[\left(\frac{\partial T}{\partial x}\right)_e - \left(\frac{\partial T}{\partial x}\right)_w\right]dt = \frac{1}{\alpha}\int_w^e (T^{t+\Delta t} - T^t)dx \quad (6)$$

Where α is the convection coefficient as a function of temperature.

Unsteady term: select T with x step change, there is

$$\int_w^e (T^{t+\Delta t} - T^t)dx = (T_p^{t+\Delta t} - T_p^t)\Delta x \quad (7)$$

Diffusion term: select the first derivative to change display with time, there is

$$\int_t^{t+\Delta t}\left[\left(\frac{\partial T}{\partial x}\right)_e - \left(\frac{\partial T}{\partial x}\right)_w\right]dt = \left[\left(\frac{\partial T}{\partial x}\right)_e^t - \left(\frac{\partial T}{\partial x}\right)_w^t\right]\Delta t \quad (8)$$

Further, take T as a linear change with x, there is

$$\left(\frac{\partial T}{\partial x}\right)_e = \frac{T_E - T_P}{(\delta x)_e}, \quad \left(\frac{\partial T}{\partial x}\right)_w = \frac{T_P - T_W}{(\delta x)_W} \quad (9)$$

Finishing can get the total discrete equation as:

$$\frac{1}{\alpha}\frac{T_E^{t+\Delta t} - T_P^t}{\Delta t} = \frac{T_E^t - 2T_P^t + T_W^t}{\Delta x^2} \quad (10)$$

3.2 Calculation space and time step

The space step is:

$$\Delta x = L/N \quad (11)$$

Where L is the total length of the model and N is the number of copies.

The grid Fourier number is:

$$F_0 = \frac{\alpha \Delta t}{\Delta x^2} = \frac{\Delta t}{\Delta x^2}(小于0.5时稳定) \quad (12)$$

The time step is:

$$\Delta t = F_0 \frac{\Delta x^2}{\alpha} \quad (13)$$

3.3 Establish temperature matrix and boundary conditions

$$T = ones(N+1, M+1) \qquad (创建温度矩阵)$$

$$T(:,1) = Ti \qquad (初始条件温度)$$

$$T(1,:) = To \qquad (边界条件 x=0 处温度)$$

$$T(N+1,:) = Te \qquad (边界条件 x=L 处温度)$$

3.4 Difference method to solve the temperature

From the discrete equation, we can get:

$$T_E^{t+\Delta t} = F_0 (T_E^t - 2T_P^t + T_W^t) - T_P^t \quad (14)$$

Converted to the corresponding temperature matrix form:

$$T(m,k+1) = F_0 * [T(m+1,k) + T(m-1,k) - 2*T(m,k)] + T(m,k) \quad (15)$$

4. Model application

The boundary conditions and initial conditions are:

$$T(1,:) = 75\ ℃$$

$$T(:,1) = 37\ ℃$$

$$T(N+1,:) = 37\ ℃$$

As shown in Table 1, the initial conditions and initial values of the specific heat capacity, thermal conductivity, density, and thickness parameters of the high-temperature work clothing are substituted into the equation, and the three-dimensional map of the temperature of each fabric layer is calculated by MATLAB during 90 minutes working time. Figure 2 shows.

Table 1 Basic parameters of parameter values of high temperature insulation clothing materials

Layer	ρ(kg/m3)	Q(J/(kg·°C))	α (W/(m·°C))	d(mm)
I layer	300	1377	0.082	0.6
II layer	862	2100	0.37	0.6-25
III layer	74.2	1726	0.045	3.6
IV layer	1.18	1005	0.028	0.6-6.4
Skin layer	1200	2100	0.535	5.8
Inner boundary void layer	1.18	1005	0.028	3.8

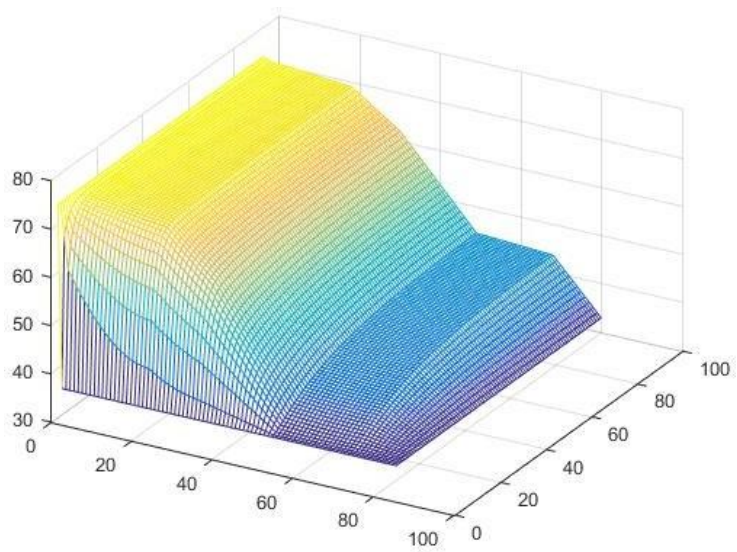

Figure 2 Temperature changes at different locations and at different times

In addition to calculating the temperature changes of the given four levels, the paper also considers the influence of the dummy model structure, and calculates the temperature change of the dummy skin layer and the inner boundary of the dummy, as shown in Figure 3.

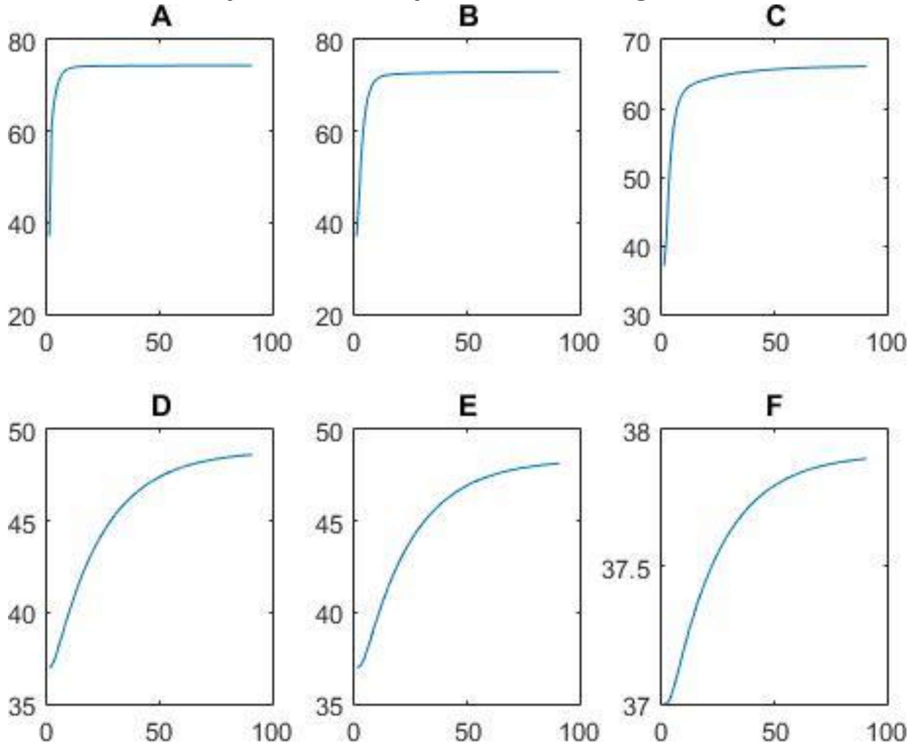

Figure 3 Temperature vs. time of each layer

Among them:

Figure A is a graph showing the temperature change at the interface between the first layer and the second layer;

Figure B is a graph showing the temperature change at the interface between the second layer and the third layer;

Figure C is a graph showing the temperature change at the interface between the third layer and the fourth layer;

Figure D is a graph showing the temperature change at the interface between the fourth layer and the fifth layer;

Figure E is a graph showing the temperature change at the interface between the fifth layer and the sixth layer;

Figure F is a temperature change diagram of the internal interface of the sixth layer and the dummy;

5. Conclusion

Working in a high-temperature environment, the requirements for protective clothing are relatively demanding. As a necessity to cope with the complexity, suddenness and technological development of disasters at this stage, the requirements for performance in different environments have also become more and more important.

In this paper, the heat transfer model of the skin-air layer-protective suit-environment is used to deduct the equation discretization, and the stability has not been considered. How to optimize the parameters to improve the protective performance of the thermal protective suit will be the next step. Direction of the research.

References

[1] Lu Linzhen. Heat transfer model and optimal parameters of multi-layer thermal protective clothing [D]. Zhejiang University of Science and Technology, 2018.

[2] Liang Kunyu. Mathematical physics method [M]. Beijing: Higher Education Press, 2017: 117-164

[3] Chen Zhuo, Zhou Ping. The principle of transfer process [M]. Changsha: Central South University Press, 2011: 188-193

[4] Lu Jinxi, Guan Zhi. Numerical Solution of Partial Differential Equations (Second Edition) [M]. Beijing: Tsinghua University Press 2015: 83-92

[5]Gu Xuezhen, Zheng Yansen, Lin Jingming, Chen Detai. The sweating amount and salt requirement of high-temperature workers--observation (one of the research on beverage problems of high-temperature workers)[J].Journal of Shanghai First Medical College,1958(S1) :39-47.

[6] Liu Xijun, Tang Wei. Experimental study on basic heat transfer performance of thermal insulation mortar and ordinary mortar[J]. Journal of Hunan Institute of Engineering(Natural Science Edition), 2013, 23(04): 84-86.