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PARAMETER DESIGN OF SPECIAL CLOTHING FOR HIGH TEMPERATURE OPERATION BASED ON HEAT CONDUCTION

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ABSTRACT

In this paper, the heat conduction model based on four-layer medium is established by using the heat conduction theorem. The problem is solved by the finite difference method. The temperature distribution map of each layer is obtained, and the two-layer search method is used to obtain the optimal thickness of the second layer and the fourth layer.

For the problem, first fit the data in Table 2, analyze the trend of temperature and time, and get the relationship. Because the temperature difference is small, the external temperature is not enough due to its excessive thermal radiation and thermal convection, so the impact of the two is ignored. Consider only heat conduction; then use the heat conduction theorem to list the second-order partial differential equations and mine the equations that establish the boundary conditions and initial conditions. Finally, the temperature distribution of each layer can be obtained by solving (Fig. 4). Look for the optimum thickness of layers II and IV, and the temperature at 30 minutes is already 47 °C. This lists the objective functions and constraints. By solving the solution, the sum of the optimal thicknesses under two conditions is 23.74 mm, the sum of the optimum thicknesses of the second layer and the fourth layer is 19.64 mm, and since the maximum thickness of the fourth layer is 6.4 mm, s is the second The thickness of the layer was 13.14 mm and a functional image of each layer of each temperature was fitted (Fig. 5).

Key words: *heat-transfer model; multilayer thermal protection; linear programming.*

1. INTRODUCTION

In human thermal protection, how to make people work in high temperature is a problem that needs to be solved nowadays. In high-temperature operation, people are in a high-temperature heat radiation environment, and the human body has high activity intensity. The structural design of functional clothing has become a hot spot. Chinese research generally uses warm body dummy to do simulation experiments. The warm body dummy is an instrument that simulates the heat exchange process between the human body and the environment. It can basically simulate the heat dissipation and dispersing system of a real person. When working in a high temperature environment, people need to wear special clothing to avoid burns. The special clothing is usually composed of three layers of fabric materials, which are referred to as layers I, II, and III, wherein the layer I is in contact with the external environment, and there is a gap between the layer III and the skin, and the gap is recorded as an IV layer. In order to design special clothing, the dummy whose body temperature is controlled at 37℃ is placed in a high temperature environment of the laboratory to measure the temperature outside the skin.

The main contributions of our paper are:

Experiments were carried out on the ambient temperature of 75℃, the thickness of the II layer of 6 mm, the thickness of the IV layer of 5 mm, and the working time of 90 min. The outside temperature of the dummy skin was measured. Some data are shown in Table 1. Please calculate the temperature distribution to generate a temperature profile. If the ambient temperature is 80, determine the optimal thickness of the layer II and IV, and ensure that the outside temperature of the dummy does not exceed 47℃ when working for 30 minutes, and the time of more than 44℃ does not exceed 5 minutes.

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Table-1: parameter values of special clothing materials

Layering	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

Table-2: Temperature of the outer skin of some dummy

time (s)	temperature(ºC)	time (s)	temperature(ºC)
0	37.00	600	47.11
10	37.00	700	47.46
20	37.02	800	47.68
50	37.55	900	47.82
100	39.37	1000	47.92
110	39.73	1100	47.98
150	41.07	1200	48.01
200	42.45	1300	48.04
250	43.56	1400	48.06
300	44.45	1500	48.07
350	45.17	1600	48.07
400	45.74	1645	48.08
500	46.57	1700	48.08

2. BASIC ASSUMPTION

2.1 Assume that there are no gaps between layers I, II, and III, ignoring the effects of heat radiation and heat convection;
2.2 Assume that the garment layer is a uniform material and remains invariable throughout the heat transfer process;
2.3 assuming that the heat conduction is perpendicular to the skin, the heat level is transmitted, and is treated as a one-dimensional state;
2.4 Assume that the initial temperature after the heat-resistant suit enters the high temperature working chamber is equal to 37 ° C and becomes 75 ° C;
2.5 Assume that the temperature is continuous during the change process.

3. PROBLEM ANALYSIS AND MODEL BUILDING

3.1 problem analysis

First, the logistic model is used to plot the temperature of the skin near the skin of Annex 1, as shown in Figure 1. The second-order partial differential equation of temperature of each layer with respect to time (t) and distance (x) is established according to the heat conduction theorem. Establish initial conditions and boundary conditions, calculate the temperature distribution of each point with time, and plot the temperature curve of each layer with time and the temperature-time-step size. If the temperature rises to 80 °C, find II and IV. When the thickness is optimal, considering that the material is too thick, it is not easy to wear and act, and the cost is expensive. Therefore, it is best to ensure that the skin temperature does not exceed 47 ° C and the working time of 44 ° C or more does not exceed 5 minutes, and the minimum material is required. It may be assumed that the temperature at 30 minutes is 47 °C. Using the linear programming idea, the objective function and constraints are listed. It is found that 55 °C has reached the heat conduction stability state under the external environment of 75 °C and the corresponding thickness, so the temperature of different distances is calculated in the steady state.

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3.2 data analysis

For the data given by the title, the trend is shown by using the Matlab toolbox.

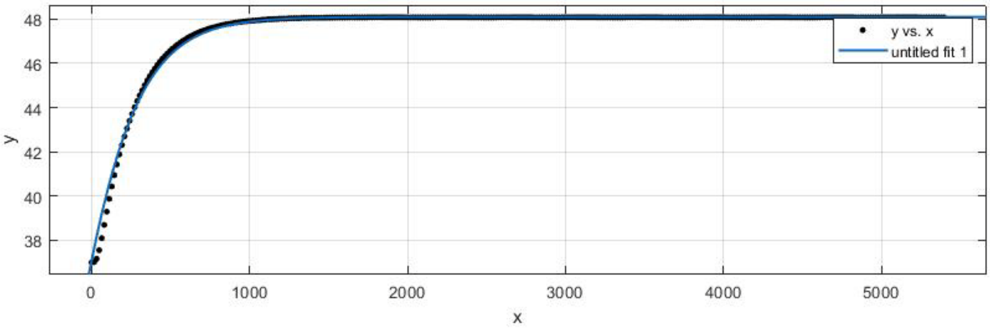

Figure-1: Time (x/s)-temperature (y/°C) of the skin outside

By observing the data and images, the temperature rises steadily before 1645s, reaches a steady state at 1645s, and the temperature stabilizes at 48.08 °C. Establish a logistic model and use Matlab to fit its functional relationship:

$$T=\frac{48.1}{1+\left(\frac{48.1}{37}-1\right)\times e^{-0.004189t}} \tag{1}$$

Note: t is time and T is temperature. It is easy to know that the degree of temperature rise decreases with time.

3.3 Heat conduction theorem

Heat conduction is an energy conversion caused by the temperature difference between the environment and the human body. The heat energy flows from high temperature to low temperature. High temperature resistant garments are generally composed of three layers of outer casing, waterproof and heat insulation. The schematic diagram is shown in Figure 2:

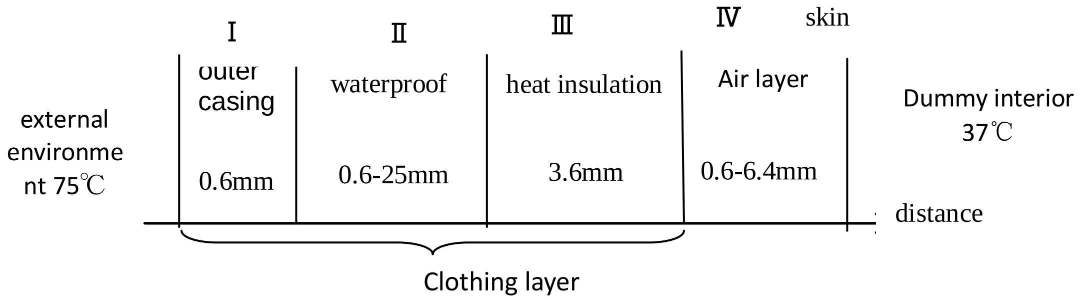

Figure-2: Environment - Clothing - Skin Schematic

The heat transfer process of the dummy at 75 °C is unsteady heat transfer. The unsteady heat transfer process can be divided into two stages. The heat conduction is initially affected by the initial temperature distribution of the garment, that is, the temperature distribution of the garment surface. As time increases, the influence of the initial temperature distribution of the object disappears. At this time, it is mainly affected by the boundary conditions and reaches a new stable state after a certain period of time.

The second-order partial differential equations of each layer are listed according to the heat conduction theorem[2][3]:

$$\begin{cases} \rho_{\mathrm{I}} C_{\mathrm{I}} \dfrac{\partial T_{\mathrm{I}}}{\partial t} = k_{\mathrm{I}} \dfrac{\partial^2 T}{\partial x^2} \\ \rho_{\mathrm{II}} C_{\mathrm{II}} \dfrac{\partial T_{\mathrm{II}}}{\partial t} = k_{\mathrm{II}} \dfrac{\partial^2 T}{\partial x^2} \\ \rho_{\mathrm{III}} C_{\mathrm{III}} \dfrac{\partial T_{\mathrm{III}}}{\partial t} = k_{\mathrm{III}} \dfrac{\partial^2 T}{\partial x^2} \\ \rho_{\mathrm{IV}} C_{\mathrm{IV}} \dfrac{\partial T_{\mathrm{IV}}}{\partial t} = k_{\mathrm{IV}} \dfrac{\partial^2 T}{\partial x^2} \end{cases} \tag{2}$$

$t \in (0,5400)$, $x = (0, 0.6\times 10^{-3})$

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Initial conditions：

$$T(X,0)=37\,℃ \tag{3}$$

Using Newton's cooling theorem：

$$T(t)=T(t_0)\times e^{-k(t-t_0)}$$

Deformation available

$$T(t+1)=T(t)+(T_{外}-T(t))\times e^{(-k(t-t_0))} \tag{4}$$

Calculate the temperature at the outermost temperature equilibrium by solving the above formula：

$$T(0,t)=75℃ \tag{5}$$

Boundary conditions：

$$\begin{cases} T_{\mathrm{I}}(x=0.6)=T_{\mathrm{II}}(x=0.6) \\ -k_{\mathrm{II}}\dfrac{\partial T_{\mathrm{II}}}{\partial t}\Big|_{x=o.6}=-k_{\mathrm{I}}\dfrac{\partial T_{\mathrm{I}}}{\partial t}\Big|_{x=o.6} \\ T_{\mathrm{III}}(x=6.6)=T_{\mathrm{II}}(x=6.6) \\ -k_{\mathrm{III}}\dfrac{\partial T_{\mathrm{III}}}{\partial t}\Big|_{x=6.6}=-k_{\mathrm{II}}\dfrac{\partial T_{\mathrm{II}}}{\partial t}\Big|_{x=6.6} \\ T_{\mathrm{III}}(x=10.2)=T_{\mathrm{IV}}(x=10.2) \\ -k_{\mathrm{IV}}\dfrac{\partial T_{\mathrm{IV}}}{\partial t}\Big|_{x=10.2}=-k_{\mathrm{III}}\dfrac{\partial T_{\mathrm{III}}}{\partial t}\Big|_{x=10.2} \\ T_{\mathrm{IV}}(x=10.2)=T_{皮肤}(x=10.2) \end{cases} \tag{6}$$

3.4 Finite difference

For solving such second-order partial differential equations [2][3], the finite difference method is one of the most extensive methods. The basic idea is to replace the differential equations and conditions of continuous variables with discrete difference equations. The solution to the problem is as follows:

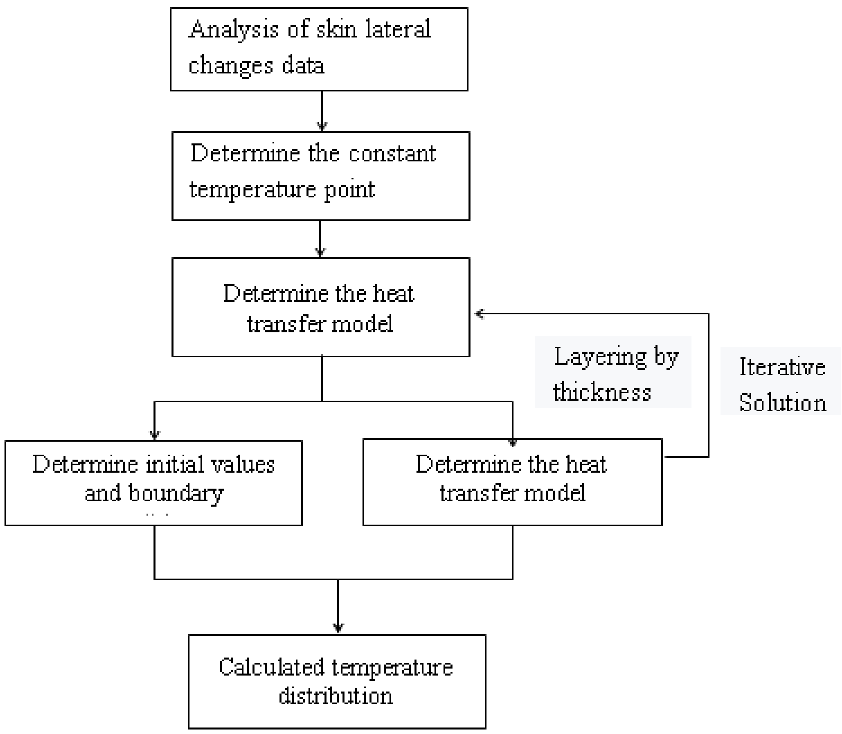

Figure-3: flow diagram

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First of all, discretize the second order partial differential equation：

$$C\frac{\partial T}{\partial t}=\mathrm{k}\frac{\partial^2 T}{\partial^2 x}$$

$$T(x,0)=37℃$$

$$T(0,t)=\varphi(t)$$

Discretize x to M+1 points

$$0=x_0<x_1<\ldots<x_M=L$$

$$\Delta x=\frac{L}{M} \qquad 令 x_i=i\Delta x, i=0,\ldots,M$$

Discretize time t to N+1 points

$$0=t_0<t_1<\ldots<t_N=t_{\exp} \ 令 t_j=j\Delta t \quad j=0,\ldots,N$$

Assuming $T(x_i,t_j)$is (i point j), an exact solution of the partial differential equation is U_i^j, then:

$$\begin{cases} C\dfrac{T_i^{j+1}-T_i^j}{\Delta t}=k\dfrac{T_{i-1}^{j+1}-2T_i^{j+!}+T_{i+1}^{j+1}}{\Delta x^2} & i=1,2,\ldots,M-1,\ j=0,1,\ldots,N-1 \\ T_i^0=37℃ & i=0,1,\ldots,M \\ \dfrac{T_1^j-T_0^j}{\Delta x}=\varphi^j & j=0,1,\ldots,N \\ T_M^j=\varphi^j & j=0,1,\ldots,N \end{cases} \tag{7}$$

Then integrate the above formula to get an equation:

$$T_i^{j+1}-T_i^j=\frac{k\Delta t}{C\Delta x^2}(T_{i-1}^{j+1}-2T_i^{j+!}+T_{i+1}^{j+1})$$

Finally available

$$\begin{pmatrix} 1+\dfrac{2k_{\mathrm{I}}}{C_{\mathrm{I}}\Delta x^2} & -\dfrac{k\,\Delta t}{C\,\Delta x^2} & \cdots & \cdots & \cdots & 0 \\ -\dfrac{2k_{\mathrm{I}}\Delta t_{\mathrm{I}}^2}{C_{\mathrm{I}}\Delta x_{\mathrm{I}}^2} & 1+\dfrac{2k\,\Delta t}{C\,\Delta x^2} & -\dfrac{k\,\Delta t}{C\,\Delta x^2} & \cdots & \cdots & 0 \\ & & & \ddots & & 0 \\ \vdots & \vdots & \vdots & \vdots & & \\ & & & & \ddots & \\ 0 & 0 & 0 & 0 & -\dfrac{k_{\mathrm{IV}}\Delta t}{C_{\mathrm{IV}}\Delta x^2} & 1+\dfrac{2k\ \ \Delta t}{C\ \ \Delta x^2} \end{pmatrix}\begin{pmatrix} T_1^{j+1} \\ T_2^{j+1} \\ T_3^{j+1} \\ \vdots \\ T_{M-1}^{j+1} \end{pmatrix}=\begin{pmatrix} T_1^j \\ T_2^j \\ T_3^j \\ \vdots \\ T_{M-1}^j \end{pmatrix}+\begin{pmatrix} T_0^j \\ T_0^j \\ T_0^j \\ \vdots \\ T_M^j \end{pmatrix} \tag{8}$$

3.5 For the two conditions given in the question at 80 °C:

Table-3: Control conditions

condition	content
First condition	The outside temperature of the skin does not exceed 47 ºC
Second condition	More than 45 ºC for less than 5 minutes

Create a linear system of equations and turn the above two conditions into conditions into the constraint function, as shown in the following equation:

Suppose layer II is represented as x_{II}, and layer IV is represented as x_{IV}

$$\min . y = x_{\mathrm{II}} + x_{\mathrm{IV}}$$

$$\begin{cases} 0.6\times10^{-3} \le x_{\mathrm{II}} \le 25\times10^{-3} \\ 0.6\times10^{-3} \le x_{\mathrm{IV}} \le 64\times10^{-3} \\ L = 4.2\times10^{-3} + x_{\mathrm{II}} + x_{\mathrm{IV}} \\ T(L,30s) \le 47℃ \\ T(L,25s) \le 44℃ \end{cases}$$

4. RESULTS AND RESULTS ANALYSIS

4.1 Model solving

(1) Through the MATLAB solution, the temperature distribution data of other layers can be obtained every second to plot the temperature-time change of each layer, as shown in the figure below.

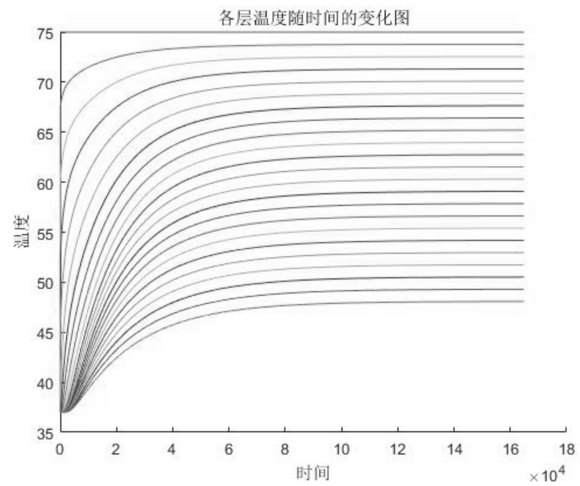

Figure-4: shows the temperature vs-time of each layer

(2) The optimum thickness of the layer II is 13.14 mm and the optimum thickness of the layer IV is 6.4 mm by MATLAB, and the function image is fitted.

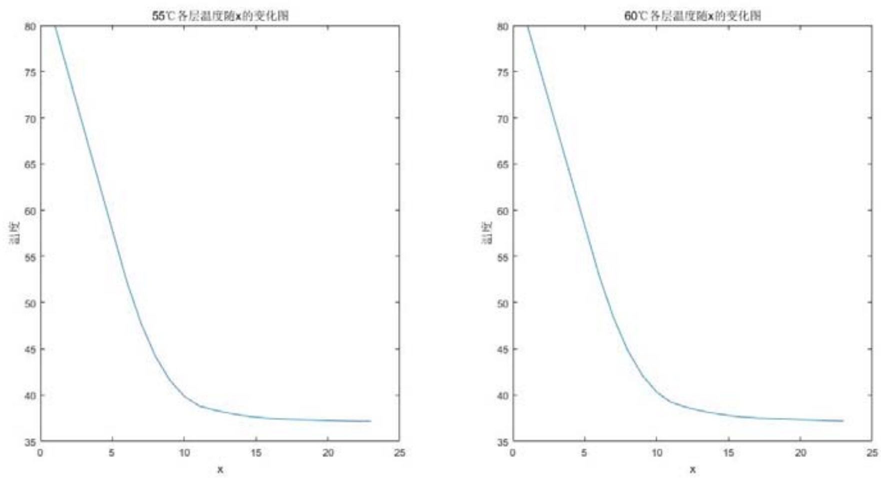

Figure-5: Variation of temperature of each layer with x at 25 minutes and 30 minutes

4.2 Result analysis and error analysis

4.2.1 Result analysis

Figure 4:

(1) The uppermost layer is the outermost layer, and the closer to the lower layer, the closer it is to the skin.

(2) larger as time increases, and the outermost layer first reaches the outside temperature.

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(3) At the beginning, the rise of the adjacent layers is basically the same, and the temperature increase of the outermost layer is the largest. Finally, the temperature of each layer is basically stable, and the highest temperature is the outermost layer when stable. The lowest is the recent skin layer, which is almost close to the outside temperature of the skin.
(4) It shows that the thermal protective clothing has a good effect, and the temperature outside the skin is basically close to the temperature directly acceptable to the human skin.

Draw a three-dimensional graph with temperature-time-step size. As shown in Figure 6.

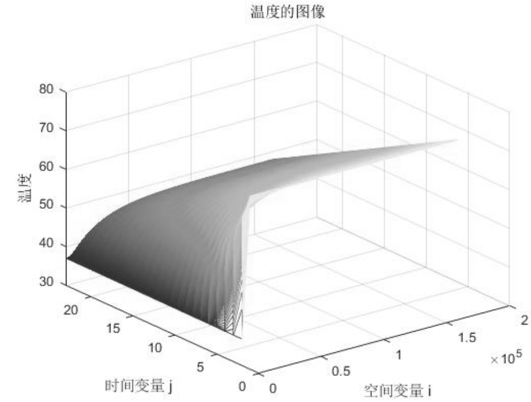

Figure-6: Temperature-time-step curve

For the three-dimensional map, the steady state temperatures of the layers are fixed to observe the trend. There are obviously three temperature turning points, which are the critical points of the protective material. This is because the thermal conductivity and specific heat capacity of each layer cause the heat to be transferred to make a large change in temperature. The closer the temperature is to the outer layer, the closer it is to the outside temperature, and the innermost layer is closer to the outer skin temperature (48.08 ° C). It shows that the effect of thermal protective clothing is better, and it can better prevent the damage of high temperature to the human body.

5. CONCLUSION

According to the conclusions drawn from the research in this paper, the thickness of each layer of the heat-resistant suit under different conditions can be calculated according to the actual needs. Moreover, the temperature change of each layer can be obtained, and the heat-proof process of the heat-proof suit is obtained, and relevant measures are formulated according to the temperature change process of the human body wearing the heat-proof suit to prevent the human body from being burned.

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