Study on Heat Insulation Clothing Based on Parabolic Differential Model

Aniu Wang, Jianqiang Xu, Xingya Rui, Liufen Li

Abstract: With the development of industry, high temperature operation becomes a necessary work. To ensure the safety of the work, the need for thermal insulation of clothing. In this paper, a parabolic differential model is established to analyze the thermal insulation of professional clothing. The optimal thickness of the heat insulation clothing is obtained under different conditions by establishing the finite difference model to solve the differential equation. Hereby，there are some ways to design the performance of heat protective clothing to make sure that the cost is the lowest as possible in the case of effective heat insulation.

Index Terms: Parabolic differential model, Heat conduction, Simulation model.

I. INTRODUCTION

High temperature thermal radiation can lead to high body temperature and excessive sweating. Increased sweat secretion can lead to dehydration and loss of much electrolyte. Excessive physical exertion is a significant feature of the high-temperature operation process. The heat generated in the body will be transferred to the skin surface by increasing the cardiac output, which will cause the heart rate to increase and thus increase the load on the heart. As a result, people need to wear special clothing[1-3] to avoid burns or other diseases when working in high-temperature environments. The special clothing is usually composed of three layers of fabric materials, denoted as layer I, II and III, in which layer I is in contact with the external environment and there is interspace between layer III and skin, denoted as layer IV.

In order to design special clothing, the body temperature of the dummy in $37^\circ c$ was controlled and placed in the high temperature environment in the laboratory, and the temperature on the outside of the dummy's skin was measured.

We enjoy the benefits in smelting, power generation, printing, machinery manufacturing, however, little is known about the high temperatures and harsh conditions that these engineering processes endure[4-7]. It is necessary to study the insulation of special clothing so that workers can work more safely. Continuous optimization of thermal insulation performance, to explore the higher temperature of the engineering technology, for the general population to get more benefits is very important.

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II. RESEARCH ON HEAT INSULATION CLOTHING

Since the thermal aspects were used in the research, we inquired about the relevant contents of Fourier's law. First we need an expression about the dependence of thermal energy flow on temperature field. It can be seen from the data that qualitative properties of heat flow exist in heat science:

1. If the temperature is constant in a certain region, there is no heat flow.
2. If there is a temperature difference, the heat energy flows from the hotter area to the colder area.
3. For same materials, the greater the temperature difference, the greater the heat flow.
4. Even at the same temperature, the heat flow of different materials is different.

A. Symbol Description

Before establishing the equation, explain the following symbols (see Table 1):

Table 1. The Meaning of Symbols

Symbol	Meaning and description	Unit
$k_i (i=1,2,3,4)$	Pyroconductivity	$W/(m\cdot^\circ C)$
c_i	Specific heat	$J/kg\cdot^\circ C$
ρ_i	Density	kg/m^3
r_i	The temperature distribution function for layer i	——
$\varphi(t)$	The temperature of the outside of the skin as a function of time	——
x	The vertical distance between a point in the heat transfer process and the contact plane of the external environment.	mm
t	Time value	s
d_i	Each layer of clothing material thickness	mm

B. Parabolic Differential Equations

Parabolic differential equations are often used for uncertain industrial spatial distribution processes, such as rapid thermal processes and crystal growth processes. Clothing insulation itself is a gradual process of increasing, then decreasing, and finally stabilizing temperature over time. Therefore, the parabolic differential model can be established to study.

A schematic diagram of the special clothing filter heat structure as shown in Fig. 1 is made. It indicates the process of heat transfer from the clothing layer to the outside of the skin when exposed to the external environment.

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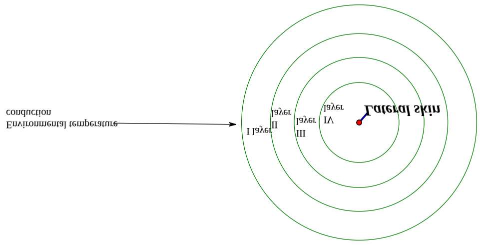

Figure 1 - Schematic Diagram of Clothing Filter Temperature Structure

Data of material parameters, layer II thickness and layer IV thickness were extracted, as shown in table 2 below:

Table 2- Clothing Material Parameters

Delamination	Density (kg/m^3)	Specific heat ($J/kg\cdot^\circ C$)	Pyroconductivity ($W/(m\cdot^\circ C)$)	Tickness (mm)
Layer I	300	1377	0.082	0.6
Layer II	862	2100	0.37	6
Layer III	74.2	1726	0.045	3.6
Layer IV	1.18	1005	0.028	5

On the assumption that the material of each layer is evenly distributed, one-dimensional heat conduction equation can be established:

$$\frac{\partial r_i}{\partial t_i} = \frac{k_i}{C_i \rho_i} \frac{\partial^2 r_i}{\partial x^2} \quad (1)$$

Since the thermal conductivity is in equilibrium and the temperature is equal at the interface of the two adjacent layers, that is, the terminal temperature in the temperature distribution of layer i is equal to the first section temperature of the temperature distribution of layer i+1.So we get:

$$k\frac{\partial r_i}{\partial x} = k_{i+1}\frac{\partial r_{i+1}}{\partial x}, r_{i(\mathrm{end})} = r_{i+1(first)}, \quad x = D_i (i = 1,2,3,4) \quad (2)$$

On the basis of the above analysis, the temperature is known to be 75 when x=0, and the change of temperature is the change of the outer skin temperature when x=5. Therefore, the heat conduction differential equation of professional clothing is established as follows:

$$\begin{cases} \dfrac{\partial r_i}{\partial t} = \dfrac{k_i}{C_i\rho_i}\dfrac{\partial^2 r_i}{\partial x^2} \\ k_i\dfrac{\partial r_i}{\partial x} = k_{i+1}\dfrac{\partial r_{i+1}}{\partial x} \\ r_0(0,t) = 75^\circ C \\ r(D_5, t) = \varphi(t) \\ r_{i(\mathrm{end})} = r_{i+1(\mathrm{first})} \\ x = D_i \end{cases} \quad (3)$$

C. Finite Difference Model

Because it is very difficult to find the analytic solution of the partial differential equation set up above, the finite difference method is a kind of commonly used numerical solution method, which can get the approximate value of the solution of the differential equation by solving the differential equation. Therefore, for the above established differential equation, the finite difference method can be used to solve it to obtain the approximate numerical solution.

Take the distance x and time t as two variables, and establish the plane rectangular coordinate system. The x-t plane is divided into grids to make it discretization: m and n are respectively taken as the step lengths in the x and t directions. It is assumed that there are two sets of parallel lines $x = x_j = jm(j = \pm1, \pm2, \cdots), t = t_i = in(0,1,2,\cdots)$, and the nodes (x_j, t_i) are selected, which can be briefly denoted as:

$$(j,i) = (x_j, t_i),\ r(j,i) = r(x_j, t_i)$$

Select within the grid point (j,i), the forward difference quotient formula and the second - order center difference quotient formula are used. The difference approximation of the one-dimensional heat conduction equation is calculated:

$$\frac{r(j,i+1) - u(j,i)}{n} - \frac{k_i}{C_i\rho_i}\frac{r(j+1) - 2r(j) + r(j-1)}{m^2} = 0 \quad (4)$$

After calculating the terminal temperature of the layer i material by difference approximation, let j=1. Then, the terminal temperature of other layers can be calculated layer by layer according to formula (2).

According to the above steps, the solution is performed. Firstly, the functional relationship of skin lateral temperature change with time was obtained by fitting:

$$\varphi(t) = 8.52\times10^{-9}x^3 - 2.91\times10^{-5}x^2 + 0.032x + 36.8 \quad (5)$$

The corresponding function image and fitting effect are as follows:

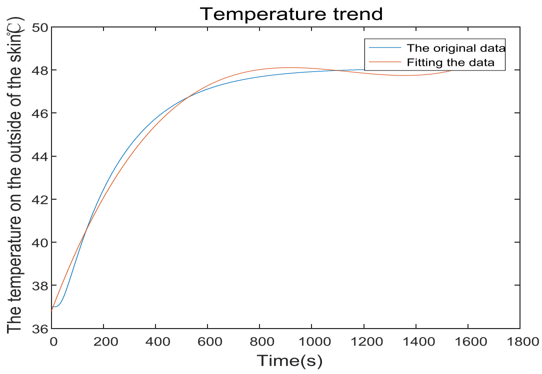

Figure 2 - a function of the temperature of the outer skin over time

In the initial stage of the graph curve of the original data, a small growth rate is accelerating, then it gradually becomes slow and gradually becomes stable. The fitting degree is 0.98912 and the mean variance is 0.6024.Therefore, the fitting effect is relatively good. The image of temperature distribution of layer I clothing material is obtained as shown in figure 3:

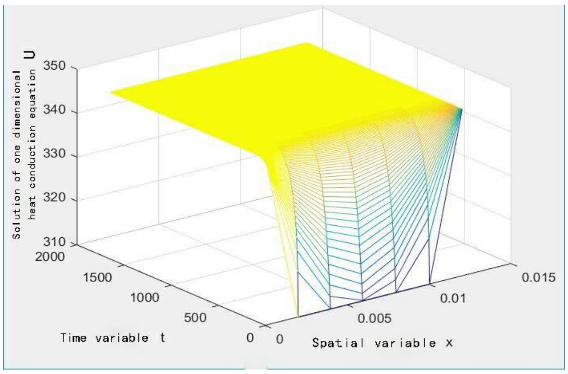

Figure 3 -Temperature Distribution at layer I

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It can be seen from the figure 3 that when one of the variables is fixed, the temperature is smaller and smaller with the increase of distance, but the change is opposite with time, increasing first and then decreasing.

D. Optimal Thickness after Changing Temperature Time

When the ambient temperature and working time are changed, the thickness of layer IV is reset to explore the optimum thickness of layer II under the constraint that the skin lateral temperature does not exceed 47 and the time beyond 44 is less than 5 minutes. It is equivalent to adding constraints to the above study, so it can be realized by linear programming model.

The differential equation after changing the condition is:

$$\begin{cases} \frac{\partial r_i}{\partial t} = \frac{k_i}{C_i \rho_i} \frac{\partial^2 r_i}{\partial x^2} \\ k_i \frac{\partial r_i}{\partial x} = k_{i+1} \frac{\partial r_{i+1}}{\partial x} \\ r_0(0,t) = 65^\circ C \\ r(D_4, t) = \varphi(t) \\ r_{i(end)} = r_{i+1(start)} \\ \varphi(t) = 8.52 \times 10^{-9} x^3 - 2.91 \times 10^{-5} x^2 + 0.032x + 36.8 \end{cases} \tag{6}$$

The thickness of layer II is $x_2 = D_2 - D_1$ .Therefore, we can see that the initial condition of the II layer can be $T(x_2, 0) = T(d_2 - 0.6, 0)$. Then the constraint conditions are expressed, that is,

$$\begin{cases} T(x, t \le 3300) \le 44\,^\circ C \\ T(x, t \le 3600) \le 47\,^\circ C \end{cases} \tag{7}$$

The optimal thickness of layer II material is 9 mm, which is obtained by combining the finite difference solution model with the linear programming constraint model. At this time, just meet the 60min when not more than 47 $^o C$, more than 44 $^o C$ of the time cannot exceed 5min.

E. Two Element Optimal Planning Thickness

Similarly, when the ambient temperature and working time are changed, when the thickness of two of the four layers is unknown, the optimal thickness problem of the bivariate programming is explored. After careful analysis of the material parameters of each layer, it is found that the specific heat capacity and density of the second layer are the largest, and that of the fourth layer are the smallest. Therefore, we know that the cost of layer II is the highest and that of tier IV is air, which requires the lowest cost.

According to the physics knowledge, the higher the specific heat capacity, the lower the temperature of the object in the same mass when absorbing the same heat, and because the greater the heat conductivity, the greater the heat conduction, so in unit time, the unit area of the second layer material than other three layer materials absorb the most heat, so the heat resistance effect is First-class.

Therefore, in accordance with the actual situation, in order to achieve the best results, as far as possible to make the thickness of layer II is smaller, layer IV is relatively larger. Therefore, to explore the bivariate optimal programming, the layer IV model can be represented by the layer II model according to the corresponding relationship, so as to reduce the element, so that it becomes a unit model, and then to solve the optimal thickness which not only satisfies the conditions, but also guarantees the fastest heat dissipation rate and the lowest cost.

Suppose that the thickness of each layer is:

$$\begin{matrix} x_1 = 0.6mm, x_2 = (d_2 - 0.6)mm, \\ x_3 = 3.6mm, x_4 = (d_4 - 3.6)mm \end{matrix} .$$

So, according to the parabolic differential equation of layer II,

$$\begin{cases} \frac{\partial r_i}{\partial t} = \frac{k_i}{C_i \rho_i} \frac{\partial^2 r_i}{\partial x^2} \\ k_i \frac{\partial r_i}{\partial x} = k_{i+1} \frac{\partial r_{i+1}}{\partial x} \\ r_0(0,t) = 65^\circ C \\ r(D_4, t) = \varphi(t) \\ r_{i(end)} = r_{i+1(start)} \\ \varphi(t) = 8.52 \times 10^{-9} x^3 - 2.91 \times 10^{-5} x^2 + 0.032x + 36.8 \end{cases}$$

The differential model of IV layer is derived from the formula of each layer thickness.

$$\begin{cases} \frac{\partial r_i}{\partial t} = \frac{k_i}{C_i \rho_i} \frac{\partial^2 r_i}{\partial x^2} \\ k_i \frac{\partial r_i}{\partial x} = k_{i+1} \frac{\partial r_{i+1}}{\partial x} \\ r_0(0,t) = 80^\circ C \\ r(D_4, t) = \varphi(t) \\ r_{i(end)} = r_{i+1(start)}, \quad t \le 900\ s \\ \varphi(t) = 8.52 \times 10^{-9} x^3 - 2.91 \times 10^{-5} x^2 + 0.032x + 36.8 \end{cases}$$

There is also a linear programming model with constraints.

$$s.t. \begin{cases} r(d_2 - 0.6, d_4 - 3.6, 1800) \le 44\,^\circ C \\ r(d_2 - 0.6, d_4 - 3.6, 1500) \le 47\,^\circ C \\ T(ambient - temperature) = 80\,^\circ C \end{cases}$$

Because it is a linear programming problem, we can choose more convenient software *lingo* to solve the above constraints. There is no clear objective value in the constraints. Combining with the actual situation, and related physical knowledge, it is known that the higher the specific heat capacity of the same mass object, the lower the temperature will be when absorbing the same heat. Because heat conductivity represents the ability of a body to conduct heat, that is, the greater the heat conductivity, the more heat will be transmitted, so in a unit time, the second layer material per unit area absorbs the most heat than the other three layers of material, the best heat resistance effect, so it can be assumed that it is a high-tech heat resistance material, however, this kind of material. Material cost is often higher than the market of ordinary heat-resistant materials, so in the design of clothing, usually also consider the relationship between cost and heat-resistant effect.

The material cost is regarded as the objective function, but because it has no specific relationship with the given material parameters,

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it can only be analyzed according to common sense, and cannot be compared with the actual calculation results. Running the program, under the ambient temperature of $80^{o}C$, to ensure that 30 minutes of work, the dummy skin outside the temperature is less than or equal to $47^{o}C$, at the same time, more than $44^{o}C$ time does not exceed 5 minutes. The optimal thickness of II and IV layers is 12mm and 5mm respectively.

III. CONCLUSION

The parabolic differential model is established to express the conduction process and the finite difference equation is used to solve the model by analyzing the material data of each layer of clothing and the data of temperature variation with time obtained from the dummy experiment. The results show that the design of thermal insulation clothing should be based on the working environment and working time of the worker to determine each layer of clothing and material thickness. Because of the design of thermal insulation clothing is still in the commercial scope, the design of clothing to consider the impact of cost.

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REFERENCES

1. Artamonov, Vladimir S., Denis M. Gordienko, and Anatoly S. Melikhov. "Fire safety of ground-based space facilities on the spaceport “Vostochny”.", Acta Astronautica, 135 (2017): 83-91.
2. Ilott, Sarah. "“We are here to speak the unspeakable”: voicing abjection in Raj Kamal Jha’s Fireproof.", Journal of Postcolonial Writing, 50.6 (2014): 664-674.
3. Todorova, Bogdana. "The new challenges on the Silk Road.", Journal of Literature and Art Studies, 5.10 (2015): 911-916.
4. Zhu, Yun Pei, et al. "Surface and interface engineering of noble-metal-free electrocatalysts for efficient energy conversion processes.", Accounts of chemical research 50.4 (2017): 915-923.
5. Vojvodic, Aleksandra, et al. "Exploring the limits: A low-pressure, low-temperature Haber–Bosch process.", Chemical Physics Letters, 598 (2014): 108-112.
6. Binder, Maximilian, et al. "Automated Manufacturing of Sensor- Monitored Parts: Enhancement of the laser beam melting process by a completely automated sensor integration.", Laser Technik Journal, 15.3 (2018): 36-39.
7. Nakata, Shogo, et al. "Wearable, flexible, and multifunctional healthcare device with an ISFET chemical sensor for simultaneous sweat pH and skin temperature monitoring.", ACS sensors, 2.3 (2017): 443-448.