Clothing Design Model for High Temperature Work based on Heat Conduction

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Abstract. By analyzing the temperature changes of the three-layer high-temperature clothing and the air layer of the fourth layer, according to the calculation of the temperature distribution of the high-temperature clothing, the temperature changes of the high-temperature clothing are related to the heat, ignoring the heat transfer of heat radiation in the clothing and the internal heat sources between the layers, defining three variables of time, temperature and thickness, according to the law of conservation of energy and Fourier's law of heat transfer. The law obtains the heat conduction equation. The forward difference method in the finite difference method is used to solve the equation, and the numerical model is obtained. Then, the relationship diagrams of temperature, time and thickness are drawn. The experimental results show that the heat absorbed by the outside is consumed layer by layer in the process of heat transfer, and finally the air layer contacted with human body tends to 48 C. Finally, according to the formula Q = cm ΔU of heat absorption in physics, further analysis is carried out, and the optimal thickness of Layer II and Layer IV is obtained by using the optimization algorithm.

Keywords. high temperature workwear, conservation of energy, fourier's law, finite difference method, heat conduction.

1. Introduction

When workers work in high temperature environment, they will feel hot, dizzy, panic, irritation, thirst, weakness and fatigue after a long time. A series of physiological changes may occur, which endangers the health of the body. At this time, people need to wear special clothes to avoid the impact of high temperature. The existing models of high-temperature working clothes are divided into single-layer and multi-layer models based on single-layer or multi-layer materials. In the single-layer model, thermal protective clothing only has a shell. Gibson proposed a heat and mass transfer model for single-layer porous media at high temperature. The defect of this model is that the influence of thermal radiation is...
neglected[1]. In order to improve the model, Torvi proposed a heat transfer model of thermal protective clothing shell material considering different radiation conditions [2]. Later, on the basis of the single-layer model, many scholars studied the multi-layer model of heat and moisture transfer in high temperature working clothes [3-5]. These studies are based on the Torvi model. The special high-temperature work clothes in this paper are usually composed of three layers of fabric material. They are classified as layers I, II and III. Among them, layer I contacts with the external environment, and there is a gap between layer III and skin. The gap is classified as layer IV. In order to design special clothing, the dummy whose body temperature is controlled at 37 C is placed in the high temperature environment of the laboratory to measure the temperature of the outside skin of the dummy. In order to reduce the cost of research and development and shorten the research and development cycle, the mathematical model was used to determine the temperature changes on the outside of the dummy skin, and to solve the related problems.

Re-description of the same heat transfer process by different models deepens the understanding of heat transfer in textile materials, which is conducive to further research, and provides theoretical basis for ensuring the safe working time at high temperature and improving the performance of high temperature working clothing.

2. Heat Conduction Model

2.1. Model Hypothesis

Figure 1 shows that people need to wear special clothes to avoid burns when working in high temperature. Special clothing is usually composed of three layers of fabric material, marked as layer I, II and III, in which layer I contacts the external environment, and there is still a gap between layer III and skin, which is marked as layer IV.

For this system, the following assumptions are made: assume that the special fabric material for high temperature operation is isotropic. This system only considers the heat transfer of heat conduction, ignoring the heat transfer of heat radiation, moisture transfer and internal heat sources between layers. Heat transfer is perpendicular to the skin and can be regarded as one-dimensional. It is assumed that there is no melting or decomposition of thermal protective fabrics during heat transfer [3]. The thickness of the air layer in layer IV is not more than 6.4 mm, so the influence of heat convection is neglected. The temperature distribution between layers is continuous, but the temperature gradient is jumping.
2.2. Mathematical Model

2.2.1. Layer Distribution of Heat Conduction Model. It is necessary to calculate the temperature distribution of high-temperature working clothes. After analyzing each layer of high-temperature working clothes, it is found that the temperature change of high-temperature working clothes is related to heat. Variable factors affecting temperature change are found. Time, temperature and thickness are defined to find out the law of temperature change. According to the law of conservation of energy and Fourier's law of heat conduction, a preliminary model is established, and the forward difference method in the finite difference method is used to obtain the temperature distribution of each layer.

The temperature change of high-temperature work clothes is related to heat. If the thickness of high-temperature work clothes is \( x \) and the temperature is \( u \), the heat intake of high-temperature work clothes is equal to the heat required by the medium when the temperature rises, regardless of the heat source and radiation inside the high-temperature work clothes\[1\][2]. Taking the section from \( X \) to \( x + dx \) on the \( x \)-axis, its mass can be expressed as \( m = \rho DV \) (which is expressed as \( \rho \) below). Let the heat in the work clothes conduct vertically along the \( x \)-axis, the intensity (heat flux) is \( Q(x, t) \), and the temperature distribution is \( u(x, t) \), as shown in Figure 2.

![Fig. 2 Simplified model of heat conduction process](image)

The following equation can be obtained from the law of conservation of energy:

\[
\frac{c}{\rho} \frac{dm}{du} = [q(x, t) - q(x + dx, t)]dt = q_x(x, t)dt
\]

\[
\therefore \frac{c}{\rho}dm = c \rho dx du
\]

\[
\therefore c \rho dx du = -q_x dx dt
\]

\[
\therefore \frac{c}{\rho} \frac{du}{dt} = -q_x
\]

Therefore

\[
\frac{c}{\rho} u_t = -q_x
\]

(1)

According to Fourier law of heat conduction, the heat per unit area \( q \) through the vertical \( x \) direction in unit time is proportional to the rate of change of temperature in space.

\[
q = -k \frac{\partial u}{\partial x}
\]

(2)

Substitute the equation (2) into the equation (1), and the final heat conduction equation can be obtained:

\[
\frac{\partial u}{\partial t} = k \frac{\partial^2 u}{\partial x^2}
\]

(3)

Where \( c \) is the specific heat capacity; \( \rho \) is the density; \( Q \) is the heat absorbed by the fabric \( J \); \( K \) is the heat conductivity; \( U \) is the temperature.
2.2.2. Optimal thickness of layer II. When the ambient temperature is 65 °C and the thickness of layer IV is 5.5mm, the optimal thickness of layer II is determined to ensure that the outer skin temperature of the dummy does not exceed 47 °C and the time beyond 44 °C does not exceed 5 minutes when working for 60 minutes.

High temperature uniform absorption of heat in each layer in the process of heat transfer, consumption, step by step a Q1 to the ith layer absorbs heat, Q4 is IV layer air layer heat, Q3 for III layer heat, assuming that the temperature change of the temperature change in Q3 and Q4 is the same, according to the Q1, Q3 and Q4 three variables about II layer is deduced the relation between the heat Q2, then according to the optimal solution algorithm to the optimal II layer thickness.

Let the heat of the air layer of the third layer and the fourth layer of the high-temperature work clothes be Q1, Q2, Q3 and Q4 respectively. The heat that the high-temperature work subject to the external absorption is Q1. According to the law of energy conservation, it can be obtained:

$$Q_1 - Q_2 - Q_3 = Q_4$$

According to the heat absorption formula in physics:

$$Q = cm\Delta u$$

Where Q1 is the heat of the ith layer; Q2 is the heat of the second layer; Q3 is the heat of layer III; Q4 is the heat of the fourth layer; M is mass.

2.2.3. Optimum Thickness of Layers II and IV. When the ambient temperature is 80, the optimum thickness of Layer II and Layer IV should be determined to ensure that the temperature of the outside skin of the dummy does not exceed 47 °C and that the time of exceeding 44 °C is not more than 5 minutes when working for 30 minutes.

In the layer-by-layer heat consumption, the heat of Layer II and Layer IV is taken as unknown quantity, and the Layer I and Layer III are known. According to the law of conservation of energy, the preliminary model of this problem can be obtained. Then, further analysis can be carried out by using $Q = cm\Delta u$, and the optimal thickness of Layer II and Layer IV can be obtained by using the optimization algorithm.

The heat of the air layer of layer I, layer II, layer III and layer IV of the high temperature work clothing is Q1, Q2, Q3 and Q4 respectively. The heat absorbed by the outside is Q1. According to the law of conservation of energy, it can be obtained that:

$$Q_1 - Q_2 - Q_3 = Q_4$$

According to the heat absorption formula in physics, we can see that:

$$Q = cm\Delta u$$

Q1 is the heat of Layer I, Q2 is the heat of Layer II, Q3 is the heat of Layer III, Q4 is the heat of Layer IV and M is the mass.

3. Numerical Algorithm for heat Conduction Model

3.1. Layer Distribution of Heat Conduction Model

In this paper, the finite difference method is used to solve the heat conduction equation. According to the analysis of the problem, the forward difference method is used to solve the equation. The forward difference scheme is as follows [8].
Combining with the heat conduction equation, we can get the result.

\[ a^2 = \frac{k}{c \rho} \]

Let's set a stability factor \( S \), order \( S = \frac{ka^2}{h^2} \), then we can get it.

\[ u_{i+1}^j = Su_{i+1}^j + (1 - 2S)u_i^j + Su_{i-1}^j \]

### Table 1. Relevant parameters used in solving process

| Layer  | Density(kg/m\(^3\)) | Specific hot (J/(kg.\(\circ\)C)) | Thermal conductivity(W/(m.\(\circ\)C)) | Thickness(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             |

3.2. **Optimum Thickness of Layer II**

According to the meaning of the question, we can know that the temperature of Q4 varies from 37 \( \circ \)C to 47 \( \circ \)C, assuming that the temperature of Q3 varies in accordance with that of Q4, but in fact the temperature of Q3 varies from 37 \( \circ \)C to 45 \( \circ \)C. From this we can see that:

\[ Q2 > Q1 - Q3 - Q4 \]  \hspace{1cm} (5)

Derived from known formulas

\[ m = \rho dx \]  \hspace{1cm} (6)

From (6) to (4), it can be simplified (5).

\[ C_1 \rho_1 dx \Delta u_1 > C_2 \rho_2 dx \Delta u_2 - C_3 \rho_3 dx \Delta u_3 - C_4 \rho_4 dx \Delta u_4 \]

3.3. **Optimum Thickness of Layers II and IV**

The temperature of Q4 varies from 37 \( \circ \)C to 47 \( \circ \)C. It is assumed that the temperature of Q3 varies from 37 \( \circ \)C to 47 \( \circ \)C. In fact, the temperature of Q3 varies from 37 \( \circ \)C to 47 \( \circ \)C. The heat of Layer II and Layer IV is as follows:

\[ Q2 = Q1 - Q3 - Q4 \]

\[ Q4 = Q1 - Q2 - Q3 \]

4. **Model validation**

4.1. **Layer Distribution of Heat Conduction Model**

Using MATLAB to draw the heat conduction model [6], a three-dimensional relationship diagram of time, temperature and thickness (i.e. temperature distribution diagram) is obtained as follows.
4.2. Optimum Thickness of Layer II
If the working time is 60 minutes and the temperature does not exceed 47 °C, the working time will reach 55 minutes when it reaches 44 °C. Fig. 5 is as follows:

4.3. Optimum Thickness of Layers II and IV
If the working time is 30 minutes and the temperature does not exceed 47 °C, the working time needs to reach 25 minutes when it reaches 44 °C, as shown in Figure 6 below:
5. Concluding Remarks
In this paper, a three-dimensional model of time, temperature and thickness is established through analysis, so that a more intuitive and three-dimensional table can show the temperature change of high-temperature working clothes. And this paper makes full use of the law of conservation of energy and Fourier's law to optimize the model of high temperature working clothes under heat conduction, which provides a better idea for the research of high temperature working clothes. At the same time, this paper uses layer-by-layer analysis method to build the model, which can make the model more specific. However, in the process of building the model, the factors such as heat radiation transmission, moisture transfer and internal heat sources between layers are neglected, which make the model too idealized, and these factors should be fully considered in the application of practical problems.

6. Outlook
In recent years, the research on the design of special clothing for high temperature work has gradually become a hot topic of academic research. The research on strengthening functional protective materials and clothing for high temperature work clothing is one of the important measures for national security development and revitalization of textile industry. Therefore, the research and design of special clothing for high temperature work is very promising. In practice, taking into account the factors of heat radiation transmission, moisture transfer, and internal heat sources between layers, the model can be used more widely. Good thermal insulation performance can better assist high-temperature workers to perform their tasks, which can make a qualitative leap in the national security development and textile industry.

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