Research on Heat Transfer of Multi-Media Protective Clothing Based on Unsteady State

Shiqi Yue*, Fei Zhang, Chenzi Qu, Xuehui Han
North University of China, Taiyuan, China, 030051

*Corresponding author e-mail: 1669953027@qq.com

Abstract. At present, the problem of heat insulation thickness of heat-resistant clothing becomes more and more serious. To solve this problem, the steady-state heat conduction principle is used to solve the optimal value critical problem in unsteady heat conduction, and the feasibility is established. The critical equilibrium time physical quantity is created for approximate representation. System steady state time. Secondly, the steady-state thermal conduction thermal resistance circuit model is combined with the nonlinear programming model for solving the optimal solution. The proportional relationship between thickness and temperature difference and critical equilibrium time is used as the constraint condition to solve the optimal material thickness in different environments.

1. Introduction
In recent years, the challenges facing China's public security situation have become more and more serious. The seriousness, suddenness and disaster of various disasters cannot be ignored. The occurrence of emergencies has caused a large number of economic losses and casualties [1]. Public safety has become an important guarantee for the current operation of the country, so the demand for public safety technology has reached an unprecedented level [2]. Emergency, disaster carrier and emergency management are the three key issues in public safety research, and human being is the most important research object of disaster-resisting carriers. Therefore, human thermal protection has become an important part of public security research.

2. Research review
In order to carry out experiments more efficiently, a large number of scholars have made important research in the field of warm-up dummy. Zhu Lijun et al. [3] analyzed the relationship between ambient temperature and air insulation value by analyzing the results of multiple groups of nude experiments. Li Shuzheng [4] deeply studied the PID control algorithm and used Labview for software programming to realize the automatic control of the surface temperature of the dummy. Yang Kai [5] analyzed the steady-state and unsteady heat transfer of the warm-wound simulated skin, and constructed a liquid-cooled clothing model under the two conditions of the warm-wound covering the simulated skin and not covering the simulated skin. Wang Leilei et al. [6] used the gravity center Lagrange interpolation method to analyze the heat conduction problems of the know-type, quadratic and triangular FGMs. Yu Jia et al. [9] used a least squares support vector machine to explore the optimal thickness of two-dimensional steady heat conduction. Xu Yanjie et al. [10] used the
generalized finite difference method to simulate the temperature field of two-dimensional unsteady heat conduction. Huang Zhiguo et al. [8] used the Main and Spencer functional gradient plate theory to solve the thermal response of steady-state heat conduction. Xie Jiaxuan et al. [11] studied the steady-state heat conduction problem in orthotropic media, and used the improved complex variable moving least squares approximation to establish the approximation function of the two-position temperature field. Zhao Qinghai et al. [6] proposed a steady-state heat conduction topology optimization scheme for multi-material structures considering periodic constraints. Most of the above studies are directed to the steady-state unsteady heat conduction of two-dimensional objects, and there are few studies on three-dimensional objects. The use of machine learning methods and statistical methods to investigate the steady-state critical temperature are based on assumptions and no threshold range is given.

This paper explores the process variation of heat conduction and designs a near-steady-state model to solve the critical problem of the optimal value of unsteady heat conduction. Firstly, the steady state of the system is proposed (the energy energy transfer inside the system does not change the temperature of each part, that is, the energy absorbed by each part is equal to the energy released). The state, dimension and form of heat conduction were determined, and the human thermal conduction was divided into two types: large flat wall and cylindrical model. The steady state model was constructed and the critical equilibrium time (a time when the heat conduction process reached steady state) could be approximated. The time it passes to the next level of heat becomes a lower value, which is the critical equilibrium time), using a nonlinear programming model and calculating the optimal solution of the thickness.

3. Proximity model theory

3.1. Research ideas

This article explores the most extensive thickness of protective clothing. The experiment was carried out under an external ambient temperature of 65 °C. A nonlinear programming model is established. The proportional relationship between thickness and temperature difference and critical equilibrium time is taken as the constraint condition, and the thickness is optimal as the objective function to solve the optimal solution of the equations. The flow chart of the research idea is shown in Figure 1 below.

![Figure 1. Research flow chart](image)

3.2. Derivation and meaning of critical equilibrium time

In order to find the constraint relationship of working time to the objective function, the whole heat conduction process was analyzed.

Because of the non-steady-state heat conduction of the heat conduction heat shield, when it reaches equilibrium, its heat conduction is steady-state heat conduction, so the process is a process in which the temperature is continuously raised to reach a stable state, and the temperature at the steady state is the object can reach The highest temperature.

In this paper, if the system steady state is reached within 60 minutes, and the temperature at this time does not exceed 47 °C, the temperature of the entire heat conduction process will not exceed 47 °C.
If the steady state is reached at 55 min and the equilibrium temperature is above 44 °C, the temperature of the entire heat transfer process must not exceed 5 min over 60 min.

Therefore, it is necessary to have the time when the system reaches the steady state. Although the system with unknown parameters cannot solve the steady state time, the proportional relationship between the system time of the unknown parameter and the system time of the known parameter can be determined. In this paper, the time to reach the steady state of the system in the three-layer protective suit can be approximated as the sum of the critical equilibrium time of the four-layer medium. As can be seen from Figure 5 below, when the system begins to transfer heat to the next layer, more heat is transferred. When the unsteady heat conduction is about to reach steady state, the heat transferred to the next layer is much smaller than before the start of the transfer. Therefore, for the next layer, the two processes are equivalent to two incremental changes.

Figure 2. Heat flow time distribution map

The meaning of the critical equilibrium time: the time when a heat conduction process reaches a steady state, which can be approximated as the time when the heat transfer to the next layer becomes a lower value, which is the critical equilibrium time. The significance is that for a heat conduction system, since each layer cannot reach the steady state alone, but the entire system reaches the steady state at the same time, it is impossible to find the time required for the single layer to reach the steady state, then the criticality can be approximated. Balance time to replace the time that a single layer reaches equilibrium.

Figure 3. Temperature difference distribution map
In this paper, the difference between the human body temperature in the previous calculation data is used as the data set (for the data of the equilibrium state, the data that has just reached the balance of the last ten time points), the line chart is drawn, as shown in Figure 6 above. According to this figure, time can be divided into four categories. The differences are 0.01, 0.02, 0.03, and 0.04, respectively, and the specific times are shown in Table 1 below.

**Table 1. Critical Balance Timetable**

| Temperature difference °C | time limits            | Critical equilibrium time s |
|---------------------------|------------------------|----------------------------|
| 0.01                      | 16~30, 391~1645        | 1268                       |
| 0.02                      | 31~40, 243~390         | 156                        |
| 0.03                      | 41~52, 151~242         | 102                        |
| 0.04                      | 53~150                 | 97                         |

4. **Proactive steady state model solving**

4.1. **Equivalent circuit model**

First, to determine the whole process of heat conduction, and finally the steady state situation, then for the steady state heat conduction, the concept of thermal resistance is introduced in this paper, and the whole steady state heat conduction process is understood as the equivalent circuit shown in Figure 4 below.

\[ T_{i-5} \] represents the temperature between the layers of heat conduction, where \( T_i \) represents the ambient temperature and \( T_5 \) represents the steady state temperature of the human body. \( R_{i-4} \) represents the thermal resistance of the four media, \( d_{i-4} \) is the thickness of each layer of media, and \( \lambda_{i-4} \) is the thermal conductivity of each layer of media.

\[
\begin{align*}
& T_1 \\
& R_i = \frac{d_i}{\lambda_i} \\
& T_2 \\
& R_2 = \frac{d_2}{\lambda_2} \\
& T_3 \\
& R_3 = \frac{d_3}{\lambda_3} \\
& T_4 \\
& R_4 = \frac{d_4}{\lambda_4} \\
& T_5
\end{align*}
\]

![Figure 4. Equivalent thermal resistance circuit diagram](image)

Second, determine the amount of temperature drop when the first layer of heat conduction reaches steady state, as shown in Table 2 below.

**Table 2. Temperature difference table**

| Unit: C | I layer | II layer | III layer | IV layer |
|---------|---------|----------|-----------|----------|
| Large flat wall | 0.7 | 1.55 | 7.63 | 17.05 |
| Cylinder | 0.562 | 1.36 | 7.298 | 17.7 |

Third, according to Fourier’s law, the law of conservation of energy and the Taylor's formula (take the first-order approximation), according to the results derived from the previous formula, the heat flux density and the temperature of the first thermal resistance reduced in the series circuit model are solved as follows: The formula (1, 2) is shown:
$$q = \frac{T_1 - T_5}{d_1 + \frac{d_2}{\lambda_1} + d_3 + \frac{d_4}{\lambda_4}} \quad \text{(Large flat wall)}$$  \hspace{1cm} (1)

$$q_i = \frac{d_i}{\lambda_i} = \frac{d_i^*}{\lambda_i} \quad * q \quad \text{(Large flat wall)}$$  \hspace{1cm} (2)

Fourth, determine the new steady-state solution equation with parameters. Where \(r_i^*\) is the unknown thickness of the material, \(T_i^*\) is the newly set ambient temperature, \(T_5^*\) is the temperature of the human body and \(44 < T_5^* < 47\).

$$q_i = \frac{d_i}{\lambda_i} = \frac{d_i^*}{\lambda_i} \quad * \frac{T_1^* - T_5^*}{d_1 + \frac{d_2}{\lambda_1} + d_3 + \frac{d_4}{\lambda_4}} \quad \text{(Large flat wall)}$$  \hspace{1cm} (3)

4.2. Multivariate Nonlinear Programming Model Solving

Because the heat flux density of each layer is the temperature loss of the layer, a nonlinear programming model is established according to the situation in this paper, where

$$Z_1 = \frac{0.6}{0.082} + \frac{d_i^*}{0.37} + \frac{3.6}{0.045} + \frac{5}{0.028} \quad \text{(thermal resistance sum)}, \quad Z = \frac{0.6}{0.082} + \frac{6}{0.37} + \frac{3.6}{0.045} + \frac{5}{0.028},$$

and \(q_{\min}\) is the known parameter of heat conduction. The steady state value of the thermal conductivity density, \(q_{\max}\) is the initial value of the thermal conductivity of the heat conduction of known parameters. The last constraint is the steady-state time-limited relationship, which means: the time it takes for the system to reach the new steady state = \(\sum a_{i} c_{i}\), where \(a_{i}\) is the temperature drop of the \(i\) layer in the new steady state, and \(b_{i}\) is the temperature drop of the I layer. \(c_{i}\) is the critical equilibrium time of the medium steady state, which is a multiple of the ratio of the temperature reduction of the two systems.

Objective function \(\min d_i^*\):

\[
\begin{align*}
0.6 & \leq d_i^* \leq 25 \\
18 & \leq \Delta T = 65 - T_i^* \leq 21 \\
\frac{Z_i \times q_{\min}}{Z_i} & \leq 65 \times 0.082 \times 10^3 \\
\frac{0.6 \times \Delta T}{Z_i} & \leq 0.37 \times 10^3 \\
\frac{d_i^* \times \Delta T}{Z_i} & \leq 0.045 \times 10^3 \\
\frac{5 \times \Delta T}{Z_i} & \leq 0.028 \times 10^3 \\
55 \times 60 & \leq \frac{0.082 \times \Delta T}{Z_i} \times 10^3 \\
0.7 & \leq \frac{d_i^* \times \Delta T}{Z_i} \times 10^3 \\
156 & \leq \frac{3.8 \times \Delta T}{Z_i} \times 10^3 \\
102 & \leq \frac{5 \times \Delta T}{Z_i} \times 10^3 \\
97 \leq 60^* 60 & \leq 1268 + \frac{0.082 \times \Delta T}{Z_i} \times 10^3 \\
1.55 & \leq \frac{d_i^* \times \Delta T}{Z_i} \times 10^3 \\
7.63 & \leq \frac{3.8 \times \Delta T}{Z_i} \times 10^3 \\
17.05 & \leq \frac{5 \times \Delta T}{Z_i} \times 10^3 \\
97 \leq 60^* 60
\end{align*}
\]
Solving the nonlinear programming equations, using the combination of the exhaustive method and the optimal value comparison method, the loop nested structure is used to satisfy the constraints. Based on the results of the program operation, the optimum thickness of the example material was determined to be 5-7 mm.

5. Conclusion
This paper uses the multivariate nonlinear programming model to explore the problem of heat conduction in protective clothing, and demonstrates the method of solving the critical problem of non-steady-state optimal value by steady-state heat conduction, and proposes a critical value that can approximate the steady-state time of the system. Equilibrium time, the physical quantity, the solution of the steady state of different parameters adopts the ratio utility relationship, combines the steady-state thermal conduction thermal resistance circuit model with the best quality nonlinear programming model, and has an accurate solution to the optimal solution. Strong promotion value.

In this paper, the establishment of two models of large flat wall and cylinder and solving them separately are beneficial to more accurately solve the heat conduction process of different objects, which has the promotion value.

This paper analyzes the problem from the perspective of statistical analysis, qualitative and quantitative analysis. This method is also suitable for analysis with other numerical processing and predictive arguments, and has practical significance and value in real life.

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