The effect of high temperature overalls on body temperature

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Abstract. When working in a high temperature environment, people need to wear special clothing to avoid burns. High-temperature special clothing can avoid burns and greatly improve the safety of work. In order to design a special garment with high strength and heat insulation and low cost, we built a model by heat conduction equation to simulate the change of human body temperature at a certain temperature. By simulating the body temperature changes in the high temperature environment, it is judged whether the high temperature overalls meet the requirements.

1. Introduction
When working in a high temperature environment, people need to wear special clothing to avoid burns. Therefore, it is urgent to design a special garment having high strength heat insulation. 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. We use the heat transfer equation to simulate body temperature changes in high temperature environments. In the simulation process, we simulate from the "discrete" and "continuous" aspects, and then select the appropriate model from the simulation results.

To simplify our model, we assume that the initial temperature of the human skin surface is 37 °C and the ambient temperature is 75 °C. The thickness of the material is stable at different temperatures, and the heat is diffused according to the shortest path, and other heat radiation effects are not considered.

2. Parameters of high temperature work clothes
According to the search of related literature, we learned that the general high temperature professional clothing parameters are shown in Table 1.

| Layer | Density(kg/m³) | Specific heat(J/kg·°C) | Thermal conductivity(W/(m·°C)) | Thickness(mm) |
|-------|----------------|------------------------|-------------------------------|---------------|
| I layer | 300 | 1377 | 0.082 | 0.6 |
| II layer | 862 | 2100 | 0.37 | 6.0 |
| III layer | 74.2 | 1726 | 0.045 | 3.6 |
| IV layer | 1.18 | 1005 | 0.028 | 5.0 |

According to the actual situation, we have drawn the measured temperature of the outside of the human skin wearing the high temperature work clothes per second for 90 minutes in Figure 1.
In Figure 1, we can find that the surface temperature of the human body rises rapidly in the early stage, and it is basically stable in the constant temperature range in the middle and late stages. The parameters we obtained will be compared to the skin temperature we simulated later to select the best model.

3. Discrete state analysis
The initial value problem is determined as the first step in solving the problem. For the simplicity of the model, it is assumed that the temperature of each position in each layer is uniform and presented in a discrete state at time $t = 0$. We determined the initial values by consulting the heat transfer related expertise and debugging several times [1], and obtained the assumed values in Table 2.

| Layer | Initial Temperature |
|-------|---------------------|
| I layer | 75°C |
| II layer | 62°C |
| III layer | 55°C |
| IV layer | 37°C |

The thermal conductivity can only indicate the speed at which the object conducts heat. In this problem, the speed of a single speed cannot determine or determine the temperature of each layer. In order to incorporate other relevant influencing factors into the problem, we need to introduce a more specific and professional variable—thermal diffusivity $\alpha$ (m$^2$/s).

The thermal diffusivity $\alpha$, also known as the temperature coefficient of conductance, indicates the ability of an object to have a uniform temperature during heating problems. This comprehensive physical property has no effect on steady state heat conduction, but it is a very important parameter in the non-steady state heat conduction process.

$$\alpha = \frac{k}{\rho c}$$ (1)

In formula (1), it is the thermal diffusivity; it is the thermal conductivity; it is the heat capacity; it is the density. We will mainly apply the heat transfer equation in the model, which describes how the temperature in a region changes with time.

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha} \frac{\partial T}{\partial t} = 0 \quad (0 \leq z \leq L)$$ (2)
In formula (2), T is the temperature at the position; z is the shortest distance of the position for the outermost side of the IV layer; t is the time; L is the total value of the thickness of the four layers of I, II, III, IV, according to the given data The L is 15.2 mm.

The solid heat conduction process itself is a kind of non-stop movement of microscopic molecules, and the finer calculation can be used to summarize the law of temperature distribution. Therefore, we take the micro-element method - the average of 60 aliquots per layer for the next step.

First, the temperature of each layer in the discrete state is substituted into the model. Through the operation of equation (2), we obtain the temperature data of each layer in each layer in 90 minutes. For an intuitive comparison of the data, we extracted the data from the measured temperature outside the skin at the last 1 s and the temperature of the layer closest to the skin layer calculated in the model for rationality analysis.

When calculating the temperature data of each layer position by the formula (2), it is necessary to calculate using the difference method [3]. The difference method uses the difference between two adjacent numerical points to replace the derivative or partial derivative in the partial differential equation.

\[
\frac{\partial y}{\partial x} = \Delta y' = y_{x+1} - y_x \tag{3}
\]

This paper calculates the central difference format, namely:

\[
\frac{T_{i+1} - 2T_i + T_{i-1}}{(\Delta x)^2} = \frac{\partial^2 T}{\partial x^2} \tag{4}
\]

When performing the differential [2] calculation, it is still necessary to know the starting temperature of each layer and the boundary temperature between the layers. Since the topic only provides the real-time temperature of the skin. Therefore, this paper makes assumptions about the boundary temperature. Based on the outermost and innermost temperatures, a discrete value assumption is made for the boundary values between the layers. It is assumed that the boundary temperature of the first layer and the second layer is 70 degrees Celsius; the boundary temperature of the second layer and the third layer is 62 degrees Celsius; and the boundary temperature of the third layer and the fourth layer is 55 degrees Celsius. In this paper, we simplify this heat conduction process into a one-dimensional unsteady heat conduction process. By reading the relevant literature, it can be known that the temperature of the heat conduction phenomenon is diffused to both sides in practice, and the temperature increases with time is getting lower and lower, and iterative simulation shows that the curve of heat conduction with space is similar to a parabola. Therefore, the initial temperature is assumed by a parabola.

| Table 3. Measuring temperature and model temperature distribution. |
|-----------------|--------|--------|--------|--------|--------|--------|
| Time(s)         | 0      | ...    | 3240   | 3780   | 4320   | 4860   | 5400   |
| Actual value (°C) | 37     | ...    | 48.08  | 48.08  | 48.08  | 48.08  | 48.08  |
| Model calculated value (°C) | 37     | ...    | 37.36  | 37.41  | 37.46  | 37.50  | 37.56  |

It can be seen from Table 3 that within 54min-90min, the actual data proves that the measured temperature outside the skin of the dummy tends to be stable, which is constant at 48.08 °C. However, the data calculated by the model shows that the layer of the IV layer is closest to the skin of the dummy. The temperature is still rising slightly but does not exceed 38 °C. Therefore, we conclude that the initial state assumption that the temperature of each location in each layer is uniform and presented as a discrete state is not applicable to the mathematical model.

4. Continuous state analysis

We again assume that the temperature of each position in each layer is continuous, and assume that the temperature of the outermost layer in each layer (y1, y2, y3, y4 = 1) is 75°C,70°C,62°C,55°C.
In summary, the model is:

\[
\frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha} \frac{\partial T}{\partial t} = 0 \quad (0 \leq z \leq L)
\]

\[
\alpha = \frac{k}{c\rho}
\]

\[
T(0, t) = 75
\]

\[
L = 15.2 \text{mm}
\]

\[
T(y_i, 0) = \begin{cases} 
75-1.98*0.0006*y_i^2 & (1 \leq y_i \leq 60) \\
70-2.04*0.001*y_i^2 & (1 \leq y_i \leq 60) \\
62-3.15*0.0005*y_i^2 & (1 \leq y_i \leq 60) \\
55-2.36*0.004*y_i^2 & (1 \leq y_i \leq 60)
\end{cases}
\]

Where \(y_i\) represents the \(i\)-th layer material, and the correspondence between \(y_i\) and \(z\) is as follows:

\[
\frac{T_{i+1} - 2T_i + T_{i-1}}{\left(\Delta x\right)^2} = \frac{\partial^2 T}{\partial x^2}
\]

After recalculating according to the final model, the data of Figure 1 is obtained, and the obtained data (Fig. 2) is compared with the actual data (Fig. 3).

Figure 2. Data of each layer temperature under continuous conditions.
Through the data observation in Figure 3, we choose to use the Pearson correlation coefficient method to determine whether the mathematical model is in line with the actual situation. The Pearson correlation coefficient is a statistic used to reflect the degree of linear correlation between two variables. The correlation coefficient is represented by \( r \), where \( n \) is the sample size and is the observed and mean of the two variables. \( r \) describes the degree of linear correlation between two variables.

\[
\begin{align*}
    r &= \frac{\sum_{i=1}^{n} \left[ (x_i - \bar{x})(y_i - \bar{y}) \right]}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \\
\end{align*}
\]

In the formula, \( x_i \) corresponds to the actual temperature value; \( y_i \) corresponds to the model to obtain the data. After calculation, \( r=0.983603479 \), the value of \( r \) is between -1 and +1. The larger the absolute value of \( r \), the stronger the correlation. It can be concluded that the model is in line with the actual situation and is suitable for this kind of problem.

5. Conclusion
We built the model according to the heat transfer equation, and found that the model and the actual fit are not good in the discrete state. When the situation is continuous, the model can fit well.

References
[1] Wan Changfeng, Lin Ji, Hong Yongxing. Simulation of transient heat conduction and Matlab toolbox development by boundary node method[J].Energy and Environment,2017,(2):12-17.
[2] Li Can, Gao Yandong, Huang Suyi. MATLAB Numerical Calculation of Heat Conduction Problem[J]. Journal of Huazhong University of Science and Technology(Natural Science Edition), 2002, (9): 91-93.
[3] Sun Ping, Luo Zhendong, Zhou Yanjie. POD-based difference scheme for heat conduction convection equation[J].Chinese Journal of Computational Mathematics,2009,(3):323-334.