Thermal Conductivity Simulation of High Temperature Overalls Materials

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Abstract. When workers work in high temperature environments, they need to wear high temperature work clothing to avoid burns. The garment is often composed of three layers of fabric material, which are referred to as layers I, II, and III from the outside to the inside, and there is a gap between the layer III and the skin. We refer to this void as the IV layer. In order to make the design of special clothing more efficient, reduce research and development costs, and shorten the development cycle, this paper uses mathematical models to determine the temperature changes outside the skin of the dummy. We assume that the body temperature of a dummy wearing a high temperature workwear can be controlled at 37°C. We have established a set of thermal differential equations as a heat transfer model for the four layers of high temperature work clothing. First, we consider three heat transfer modes of heat conduction, heat radiation and heat convection, and analyze the heat conduction form of each layer to obtain a one-dimensional unsteady heat transfer model. Then, the numerical solution of all partial differential equations is obtained by the finite difference method of Crank-Nicolson format, and the temperature distribution outside the skin of the dummy is obtained. Finally, this paper gives a proposal for the design work of four-layer high temperature work clothing in combination with the actual situation.

1. Introduction
With the development of technology and society, more and more workers need to work in harsh high temperature environment, which puts higher requirements on the protection performance of high temperature work clothes. The high temperature work clothes can reduce the heat transfer rate of the outside world, reduce the influence of the human skin on the high temperature environment, and protect the human body working in a high temperature environment.

At present, the main method for detecting the performance of high temperature work clothes is to randomly select a large number of samples for heat insulation test, although the results are more accurate, but also caused a lot of waste. In this paper, based on the parameters of the corresponding high temperature work clothes, the model is established to simulate the heat transfer of the high temperature work clothes, and the performance of the high temperature work clothes is evaluated.

High-temperature work clothing is often composed of three layers of fabric material, which are recorded as I, II, and III layers from the outside to the inside. There is also a gap between the layer III and the skin. We record this gap as the IV layer. This paper establishes a group. The system of thermal
differential equations is used as the heat transfer model for the four-layer high-temperature work clothing. First, we consider three heat transfer modes of heat conduction, heat radiation and heat convection, and analyze the heat conduction form of each layer to obtain a one-dimensional unsteady heat transfer model. Then the numerical solution of all partial differential equations is obtained by the finite difference method of Crank-Nicolson format. Finally, the temperature distribution outside the skin of the dummy is obtained, and this paper also proposes some design for the design of high temperature work clothes according to the established heat transfer model. Suggest.

2. Model assumptions
The values of some parameters of the high temperature work garments studied in this paper are from the relevant manufacturers, including the density, specific heat, thermal conductivity and thickness of the corresponding layers, and we are about the ambient temperature of 75℃, the thickness of the II layer is 6 mm, and the thickness of the IV layer is Modeling with a 5 mm working time of 90 minutes.

We assume that a dummy wearing a high-temperature workwear can control its body temperature at around 37oC, and its temperature change is continuous [1].

The model does not take into account the effects of humidity and gas heat radiation at any location, only thermal conduction in the direction perpendicular to the surface of the garment.

3. Model analysis
In order to solve the temperature distribution inside the thermal protective suit, we need to know the form of heat transfer in the protective suit. First of all, according to the knowledge of heat transfer, heat transfer is mainly divided into three forms: heat conduction, heat convection, and heat radiation. We consult the literature to judge the heat transfer form that a layer needs to consider, and we consider convection for the outermost fabric layer. With external heat radiation, we consider the heat radiation from the dummy for the air layer, and the other parts only consider heat conduction [2]. After obtaining the parameters related to thermal radiation, we establish partial differential equations for the fabric layer and the air layer, namely our thermal differential equations and the multi-layer heat transfer model with boundary conditions. Then we added a "dummy skin surface" between the air layer and the surface of the dummy skin to describe the problem of temperature mutating between the skin boundary and the air layer. For the five thermally conductive differential equations, based on their boundary conditions and initial conditions, we obtain a numerical solution of the temperature along the heat transfer direction with time, which is the temperature distribution.
4. Model building and solving

4.1. Model establishment

One-dimensional unsteady heat conduction differential equation:

$$\rho C \frac{\partial T}{\partial t} = -\frac{\partial}{\partial x} \left( -K \frac{\partial T}{\partial t} \right) + \phi$$

Boundary conditions: There are three types of boundary conditions. The fluid is not considered in this paper, so the first two types of boundary conditions are used.

Thermal radiation calculation formula: the thermal radiation emitted by an object is proportional to the fourth power of its own temperature.

$$Q_{rad} = \varepsilon \sigma (T_1^4 - T_2^4)$$

The heat flux calculation formula in one-dimensional case: where $k$ is the thermal conductivity, $T(x, t)$ is the temperature distribution, and the negative sign indicates that the thermal energy is transferred from the high temperature portion to the low temperature portion.

$$\phi_q = -k \frac{\partial T(x, t)}{\partial x}$$

In this paper, five heat conduction partial differential equations and boundary conditions are used to solve the distribution of temperature along the direction of heat conduction. For the outermost fabric, we consider three forms of heat transfer, namely heat conduction, heat convection and heat radiation from the outside. It is assumed that we do not consider the radiation released on the fabric layer itself. The fabric is solid, so we did not consider its convective heat transfer [3]. In addition, because the air layer is thin, we do not consider the convective heat transfer of the air layer [4].

We know that because of the high absorption rate of thermal radiation by fabrics, thermal radiation decays along the direction of heat conduction. We use the following exponential decay as a heat transfer attenuation model for thermal radiation [5].
\[ Q = \gamma q_{\text{rad}} e^{-\tau x} \gamma = \frac{-\ln(\tau)}{L_1}, \quad q_{\text{rad}} = \varepsilon\sigma(T_{\text{rad}}^4 - T_{\text{surf}}^4) \]

Where Tout is the ambient temperature and TSurf is the outer surface temperature of the first layer.

The establishment of partial differential equations and their boundary conditions for each layer:

**Level one:**

\[
\begin{align*}
& c_1\rho_1 \frac{\partial T_1}{\partial t} = \frac{\partial}{\partial x}(k_1 \frac{\partial T_1}{\partial x}) + \gamma q_{\text{rad}} e^{-\tau x}, t \in (0, T) \\
& -k_1 \frac{\partial T_1}{\partial x} \bigg|_{x=0} = q_{\text{rad}} \bigg|_{x=0}, t \in [0, T] \\
& T_1(x, 0) = T_0(x), x \in (0, x_1)
\end{align*}
\]

**Level two:**

\[
\begin{align*}
& c_2\rho_2 \frac{\partial T_2}{\partial t} = \frac{\partial}{\partial x}(k_2 \frac{\partial T_2}{\partial x}), t \in (0, T) \\
& T_2(x_1, t) = T_1(x_1, t), t \in [0, T] \\
& -k_2 \frac{\partial T_2}{\partial x} \bigg|_{x=x_1} = -k_1 \frac{\partial T_1}{\partial x} \bigg|_{x=x_1} \\
& T_2(x, 0) = T_0(x), x \in (x_1, x_2)
\end{align*}
\]

**Level three:**

\[
\begin{align*}
& c_3\rho_3 \frac{\partial T_3}{\partial t} = \frac{\partial}{\partial x}(k_3 \frac{\partial T_3}{\partial x}), t \in (0, t_{\text{work}}) \\
& T_3(x_2, t) = T_2(x_2, t), t \in [0, t_{\text{work}}] \\
& -k_3 \frac{\partial T_3}{\partial x} \bigg|_{x=x_2} = -k_2 \frac{\partial T_2}{\partial x} \bigg|_{x=x_2} \\
& T_3(x, 0) = T_0(x), x \in (x_2, x_3)
\end{align*}
\]

**Level four:**

\[
\begin{align*}
& c_4\rho_4 \frac{\partial T_4}{\partial t} = \frac{\partial}{\partial x}(k_4 \frac{\partial T_4}{\partial x}) - \gamma q_{\text{rad}} e^{-\tau x}, t \in (0, t_{\text{work}}) \\
& T_4(x_3, t) = T_3(x_3, t), t \in [0, t_{\text{work}}] \\
& -k_4 \frac{\partial T_4}{\partial x} \bigg|_{x=x_3} = -k_3 \frac{\partial T_3}{\partial x} \bigg|_{x=x_3} \\
& T_4(x, 0) = T_0(x), x \in (x_3, x_4)
\end{align*}
\]

**Level five:**

\[
\begin{align*}
& c_5\rho_5 \frac{\partial T_5}{\partial t} = \frac{\partial}{\partial x}(k_5 \frac{\partial T_5}{\partial x}), t \in (0, t_{\text{work}}) \\
& T_5(x_4, t) = T_4(x_4, t), t \in [0, t_{\text{work}}] \\
& -k_5 \frac{\partial T_5}{\partial x} \bigg|_{x=x_4} = -k_4 \frac{\partial T_4}{\partial x} \bigg|_{x=x_4} \\
& T_5(x, 0) = T_0(x), x \in (x_4, x_5)
\end{align*}
\]

The first layer is the outermost layer, and Condition 1 gives the heat conduction differential equation, taking into account the heat conduction caused by external heat radiation and temperature
difference. Condition 2 gives one of the boundary conditions of the thermal differential equation, that is, the temperature at the junction of the fabric layer is continuous. Condition 3 gives the second boundary condition, that is, the heat fluxes on both sides of the surface are equal in magnitude and in the same direction.

The second, third, and fourth layers of the thermal differential equation are similar to the first layer except that the effects of thermal radiation between the fabric layers are not considered.

In addition, we established the dummy surface of the dummy. The boundary condition on the right side of the surface is 37 degrees Celsius, and the left boundary is the temperature of the outer surface of the dummy. This reasonably solves the situation that the temperature difference between the two sides of the fourth layer is not equal and the boundary conditions are lacking. And in the actual solution, because the thickness of the virtual layer is very thin, there is almost no influence on the internal thermal radiation, so the impact on the final result is negligible.

4.2. Model solution

We use the finite difference method to obtain the numerical solution of each layer of the thermal differential equation.

Using the discretization method, the mesh is meshed and the difference format is constructed. The meshing is to divide the region into two rectangular parallel lines into a rectangular mesh, and h and τ are respectively the space step and the time step. Considering the huge gap between time span and space span, we take h=0.001 and τ=0.001 in the solution. At this time, the mesh ratio is r=k/h^2 =10^3 ≫ 0.5

In this case, both the classical explicit format and the classical implicit format have very poor convergence and stability, and it can be proved that the Crank-Nicolson format is unconditionally stable and the result is more reliable, so we use the Crank-Nicolson format for calculation [5].

The discrete equations of each layer of the thermal differential equation are obtained by the Crank-Nicolson format.

At the same time, we discretize the boundary conditions of each layer of the thermal differential equation, and use the "catch-up method" to solve the layer by layer.

4.3. Solution result

![Figure 3. Dummy skin outer temperature change diagram.](image)

Figure 3. Dummy skin outer temperature change diagram.
5. Conclusion
This paper establishes a mathematical model to simulate the thermal conductivity of a common four-layer high-temperature work garment during normal operation.

The high-temperature work clothing studied by the model consists of three layers of fabric material, which are recorded as I, II, and III layers from the outside to the inside, and there is a gap between the layer III and the skin. We record this gap as IV layer. This paper establishes a set of thermal differential equations, which is the heat transfer model of the four-layer high-temperature work clothing. First, we consider three heat transfer modes of heat conduction, heat radiation and heat convection, and analyze the heat conduction form of each layer. For the outermost fabric layer, we consider the influence of convection and external heat radiation. We consider the effects of heat radiation from the dummy, while for the other parts, we only consider heat conduction, so we get a one-dimensional unsteady heat transfer model. Then the paper uses the finite difference method of Crank-Nicolson format to solve the numerical solution of all partial differential equations by using Matlab. The temperature distribution outside the skin of the dummy and the temperature distribution of the whole garment are obtained.

Through the research in this paper, we believe that in the design process of high temperature work clothing, the thickness of the first layer and the third layer should be increased as much as possible, because our model indicates that the two layers have the largest barrier effect on heat transfer, but the thickness After a certain range is exceeded, the role of each layer is no longer obvious, so the relevant manufacturers should weigh the relationship between profit and quality.

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