Optimization analysis of high temperature workwear based on one-dimensional multilayer flat wall heat transfer process

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Abstract. In order to design costumes that can satisfy high temperature working environment, this paper constructed a one-dimensional heat conduction model through Fourier law and finite difference method. As the actual situation is one-dimensional unsteady heat conduction, numerical analysis method and MATLAB programming are required to solve the problem. The accuracy of the model is confirmed by error analysis. Finally, the sensitivity of the model is estimated roughly. Correlation analysis is made on the measurement of heat release and the convergence rate of temperature field in the working process of high temperature working clothes, and the prospect of high temperature resistant clothing is predicted.

Keywords: Fourier law; Finite element difference method; Temperature distribution; Rate of convergence of the temperature field.

1. Introduction

At present, the flame retardant and protective properties of high-temperature clothing in the world have some defects, some of which are due to the improper selection of materials, some of which are due to the unreasonable arrangement of materials, such as the thickness distribution of three-layer insulation materials. High-temperature working environment is actually a complex and changeable working condition. Employees not only face the risk of instantaneous burn in high-temperature fire field, but also suffer from stress response of high temperature, high humidity and heat. Therefore, it is particularly important to improve the three performance of high temperature working suit. The flame retardant performance, protective performance and heat insulation performance of high temperature clothing are the standards for evaluating the quality of high temperature working clothing at present.

2. Model assumption

A: heat transfer is along the vertical skin direction, which is one-dimensional heat transfer.

B: only the convection heat transfer and heat conduction in the transfer process are considered.
3. Related nouns
   A. definition of beavor number Bi
      The unstable heat transfer process is generally divided into two links: the heat transfer link between
      the outer layer and the environment (heat transfer resistance) and the internal heat conduction link (heat
      transfer resistance).
   B. Differential equation of heat conduction
      \[
      \frac{\partial t}{\partial \tau} = a \Delta^2 t + \frac{\Phi}{\rho c_i}
      \]

4. Establishment of Model
   A. Preliminary analysis:
      It is a one-dimensional multi-layer flat wall heat transfer process to satisfy the high temperature
      operation, so we first analyze the one-dimensional single-layer flat wall heat transfer process and then
      further extend the model as shown in the figure 1.
      Numerical calculation of one-dimensional unsteady thermal conductivity.
      Assumed total time.
      T=50000s.

   Numerical solution of algebraic equations
   \[
   t(m,1) = 2*Fo*(t(m-1,2)+Bi1*t1)+(1-2*Bi1*Fo-2*Fo)*t(m-1,1);
   t(m,N+1) = 2*Fo*(t(m-1,N)+Bi2*t2)+(1-2*Bi2*Fo-2*Fo)*t(m-1,N+1);
   t(m,n) = Fo*(t(m-1,n-1)+t(m-1,n+1)+(1-2*Fo)*t(m-1,n));
   \]

Figure 1. A simplified diagram of the model

5. Analysis
   First of all, grid generation, Space grid \( \Delta X = 0.005 \), Time grid \( \Delta \tau = 25s \), Are defined as follows(I'm just
   writing constants in international units):Thermal conductivity \( \lambda = 0.43 \), Heat-transfer coefficient   \( h1 = 11,  \
   h2 = 23, a = 0.3437e-6, t0 = 5, t1 = 23, t2 = 5, Plate thickness   \( B = 0.1m \).

   Assume that M=floor(T/\( \Delta \tau \))Number of time, N=floor(B/\( \Delta X \)).
   The left edge,   \( Bi1 = h1*\Delta X / \lambda \), The right edge,   \( Bi2 = h2*\Delta X / \lambda \), Fo=a*\( \Delta \tau / \Delta X^2 \).
   Iteration, Solving algebraic equations
   \( t(m,1) = 2*Fo*(t(m-1,2)+Bi1*t1)+(1-2*Bi1*Fo-2*Fo)*t(m-1,1);  \
   t(m,N+1) = 2*Fo*(t(m-1,N)+Bi2*t2)+(1-2*Bi2*Fo-2*Fo)*t(m-1,N+1);
   t(m,n) = Fo*(t(m-1,n-1)+t(m-1,n+1)+(1-2*Fo)*t(m-1,n));

   t=5ºC
   Fluid Temperature 23ºC
   Fluid Temperature 5ºC
   -0.05  0.05
The first two is at different boundaries at any time, and the last one is at any time, at any place (Figure 2).

![Figure 2. Temperature distribution over time at different locations](image)

Optimization design of high temperature work wear based on one-dimensional multilayer flat wall heat transfer process (Figure 3).

![Figure 3. Temperature profiles at different locations at different times](image)

B. The one-dimensional flat wall heat transfer process is extended to multilayer. Formula follows:
When the thermal resistance of each layer increases continuously and the temperature change rate of each layer decreases gradually, by selecting appropriate materials, burns can be effectively avoided.

6. Research status

6.1. Reduce the thermal stress and improve the thermal comfort performance.
At present, the high-temperature operating suit is also called cooling suit, which is divided into three types of cooling suits with liquid, gas and phase change material as the cooling source. At present, the paper introduces the advantages of using crystalline hydrated salt or molten salt inorganic phase change material as the main material, such as small volume change and high thermal conductivity.

6.2. Inhibiting temperature mutation and improving thermal protection performance.
For the thermal protective performance is the biggest potential phase change materials, but inhibit the feasibility of the heat work serving temperature mutations to be analyzed, the structure of the external heat load and fire clothing changes, so the clothing of temperature gradient between the layers is also changing, relative to the fixed phase change temperature of phase change materials, it is not easy to find the phase transition layer in the system fixed way configuration solution.

7. Impact of other environmental factors on performance

7.1. thermal radiation factors:
at present, most studies are focused on the impact analysis of single-layer materials, and further studies are needed for the experiments combining multi-layer materials with other factors.

7.2. Sun factor:
The YG611E color fastness tester was used to light the polysulfone yarn and fabric at different time. The findings are as follows: At the beginning of xenon arc irradiation, the stretching strength and breaking power of single arylsulfone yarns were slightly improved. But the total decreases with the extension of light time; After 30 h xenon arc lamp irradiation, the flame retardant performance of polysulfone fabric changed little.

8. Protective properties of materials
Under the condition of the same heat flux, the time for different tissue materials to rise the same temperature is different, which is the protective property of tissue materials.
Table 1. Protective properties of different materials with different heat flux

| Name of the material | The flame retardant cotton | aramid fiber III A | aramid fiber 1313 | CVC The flame retardant cotton |
|----------------------|---------------------------|------------------|------------------|-------------------------------|
| Density of heat flow /KW·m⁻² | 63 | 63 | 63 | 63 |
| Take time to go up by 297.15k/min | 7.2 | 5.4 | 5.5 | 5.49 |

Conclusion: according to table data can get, aramid fiber III A rise time of the shortest, and the flame-retardant cotton of the rise time longest.

9. Determination of heat release in the cooling process of high temperature coveralls
The high-temperature operating suit plays a role of heat insulation, the whole heat exchange process is in the process of unsteady heat transfer, the heat leakage is very small, the high-temperature operating suit itself heat capacity. In the process of steady heat transfer, the greater the thickness of the flat wall structure heat insulation layer is, the greater the thermal resistance will be, which is beneficial to reduce heat leakage. However, as the thickness increases, the heat capacity of the material increases accordingly. It is of great practical significance to find the change rule of heat release and cooling time for the high-temperature working suit with heat insulation requirement.

Analysis of equivalent heat release Q'.
Use formula $Q' = \frac{Q}{A_{pc8}} \Delta T$ to calculate data for curve fitting, and get the empirical formula.

10. The convergence rate of temperature field is discussed
The criterion number of Fo has a great influence on the convergence of the series solution. The higher the number of Fo criterion is, the faster the convergence rate is. The smaller the Fo criterion is, the slower the convergence rate of the series solution is.

The number of Bi criteria also has a great influence on the convergence of the series solution: the smaller the number of Bi criteria, the faster the convergence of the series solution; the larger the number of Bi criteria, the slower the convergence rate of the series solution.

11. Development prospect of high temperature resistant clothing
1. At present, the material with the best high temperature resistance performance in the market is ceramic fiber, and the working temperature of its filter material can be up to about 1700K, such as the sialate-silicon carbide composite ceramic filter material produced by 3M company. However, China only started the research in this field in the 1970s, which started relatively late and the technology is not mature, but it is also conducive to the diversification of preparation technology in the future. Ceramic fiber has a broad prospect in the ultra-high temperature flue gas environment.

2. The upper limit of high temperature resistance of basalt fiber is also up to about 600K, which can work in the environment of oxidation, acid and alkali corrosion, with high dust removal efficiency. Besides, many companies in China have been researching and developing.

3. Glass fiber is a kind of traditional high-temperature resistant material, but it has poor wear resistance and folding resistance. Traditional raw materials can no longer meet the changing working environment, so it is necessary to develop some composite materials. Even with composites, the cost is not high.

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