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The optimal design of fire fighting suits

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Abstract. Fire fighting suits are very important for fire rescue workers. However, at present, the design is not optimal. In this paper, we design an optimal fire fighting suits, considering the temperature distribution of a dummy with a constant temperature. Because the dummy has a constant temperature, it cannot simulate human metabolism, which means the design process should be an unsteady heat transfer process with an internal heat source. Hence, we have made a reasonable simplification of the process. According to the principle of heat balance, since the temperature is dynamic, a recursive relation about the temperature is established, and the optimal thickness of layer II is 15mm through simulation. By integrating the recursive formula, the functional expression of temperature with respect to time, layer II thickness and layer IV thickness can be obtained under certain approximation. Since the outside temperature of the dummy is constantly rising, it is only necessary to ask the temperature value of the 25th minute and the 30th minute for each thickness condition to reach the desired temperature limit. Therefore, different thickness values are circulated discretely to establish the optimal function of thickness, and the thickness of layer II is 2mm and that of layer IV is 4mm.

1. Introduction

In certain industrial production sites, workers need to cope with the high temperature environment on the test of fragile skin. High temperature special clothing is usually made of three layers of fabric materials, which can effectively isolate the high temperature, resist radiation and improve the safety and comfort of the working environment[1]. However, due to the lack of real environmental data, it takes a lot of energy to research and develop protective clothing. Therefore, the simulation design of protective clothing temperature is a process of great significance[2]. In order to effectively study the design parameters of special clothing, we need to put dummies at constant temperature environment, and keep the body temperature control at 37°C.

2. Model

2.1. Multi-layer cylinder model

Fire fighting suits consist of three layers. The gap between layer III and skin is called layer IV. The whole can be seen as the multi-layer cylinder model in figure 1, in which I, II, III and IV denote the different material in fire fighting suits.

2.2. Heat transfer analysis

In the process of heat transfer, thermal resistance can be used to simulate heat exchange[3]. It can be considered that layer I, II and III are thermal conducting layers, and layer IV is an air layer. Hence, the

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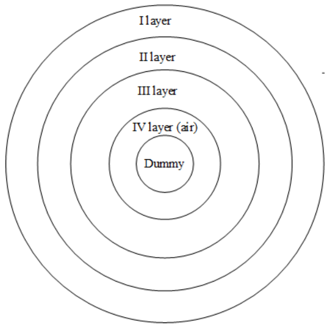

Figure 1. Multi-layer cylinder model.

thermal resistances model can be compared to the series resistance model, so the total thermal resistance is as follows:

$$R{=}R_1+R_2+R_3=\frac{\ln\frac{d_1}{d_2}}{2\pi\lambda_1 L}+\frac{\ln(\frac{d_2}{d_3})}{2\pi\lambda_2 L}+\frac{\ln(\frac{d_3}{d_4})}{2\pi\lambda_3 L} \quad (1)$$

where R_1, R_2 and R_3 are thermal resistances of different layers.

Assume the heat transferred by both sides of the multi-layer cylinder in unit time is:

$$q=\frac{\Delta t}{R} \quad (2)$$

Although a one-dimensional unsteady differential equation with internal heat source model of temperature distribution on the inner wall of the cylindrical wall of concrete has a more accurate description, we only care about the temperature on the outside of the skin[4]. Thus, we adopt the following thought which has carried on the reasonable assumption.

- IV layer absorbs heat, and the heat model is as follows:

$$Q_1=cm\Delta t \quad (3)$$

- Heat transfer in layers I, II and III:

$$Q_2=\int q\,d\tau \quad (4)$$

Since there is heat exchange between the dummy and the IV layer, it is usually carried out by thermal convection and radiation. However, since the dummy is given a constant temperature of 37°C, a coefficient is added here to represent the heat transfer process.

$$Q_1+h\Delta t'=Q_2 \quad (5)$$

where h is the convection coefficient of air on the surface of dummy model.

2.3. Simulation

The model is discretized according to the time interval of one second as follows:

$$\begin{cases} t_w=65 \\ t_1=37 \\ \frac{t_w-t_k}{R}d\tau=cm(\mathrm{t}_{k+1}-\mathrm{t}_k) \\ \mathrm{t}_k=t_{k+1} \end{cases} \quad k=1,2,3\cdots \quad (6)$$

$$m=\rho V=\rho(\pi(r+r_4)^2-\pi r^2)L \quad (7)$$

where c and m are the specific heat capacity and mass of the fourth layer.

In addition, r and L denote the radius of the dummy and the height of the dummy respectively. Iterative simulation has been carried out according to the above discrete equation to obtain the variation

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trend of temperature under different thickness of the second layer. The temperature on the outside of the dummy increases gradually with time. When the thickness of the II layer increases, the maximum temperature on the outside of the dummy also decreases. According to the calculation of the figure, when the thickness of the II layer decreases from 25mm to 15mm, the maximum temperature is lower than 47℃, and the temperature is approximately equal to 44℃ in 55 minutes. So the maximum temperature that can be obtained is not more than 47 degrees, and the temperature above 44 degrees is less than 5 minutes. The maximum thickness is 15mm.

3. Optimization

Considering the optimal calculation of the two variables in the third question, it can be calculated on the basis of the second question[5]-[7]. Since the optimal calculation of multiple variables is involved, the approximate function of temperature on time, the thickness of layer II and the thickness of layer IV can be calculated. First, the differential equation needs to be integrated:

$$\frac{t_1 - t_k}{R} d\tau = c\rho V\left(t_{k+1} - t_k\right) \tag{8}$$

$$(t_1 - t)d\tau = c\rho VRdt \tag{9}$$

$$\frac{1}{c\rho V}T = -\ln(1 - \frac{t}{t_1}) \cdot R + C \tag{10}$$

where C is a constant and can be calculated as -0.05415076.

Since the coefficients of different layers are unknown, $k_2 = 1$ and $k_4 = 1$ can be set to more effectively illustrate the optimal thickness problem

$$\min y = k_2 r_2 + k_4 r_4 + Const$$

$$\text{subject to} \begin{cases} t = t_1[1 - \mathrm{e}^{\frac{C - \frac{1}{c\rho V}T}{R}}] \\ t \le 47 \\ t(3300) \le 44 \end{cases} \tag{11}$$

Since the dummy has thermal equilibrium, a correction coefficient can be added as follows:

$$t = t_1[1 - e^{\frac{B - \frac{1}{c\rho V}T}{R}}] \cdot \varepsilon \tag{12}$$

However, the temperature measured outside the dummy gradually increased with time, so we only need to consider the temperature at the 30th minute and the temperature at the 25th minute in different thickness cases. Take the interval of 0.1ms for simulation, and get the temperature values of the 30th minute and the 25th minute under different thickness through simulation as shown in the figure 2.

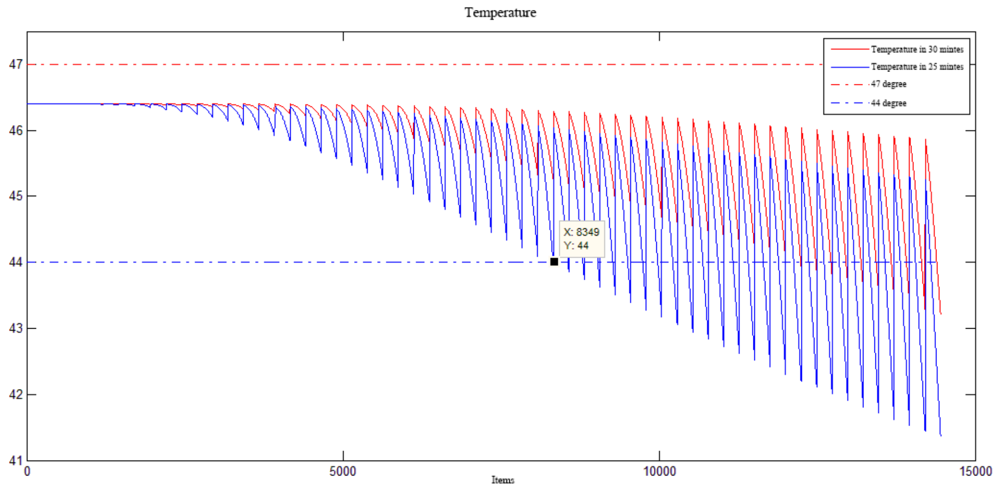

Figure 2. Temperature values at the 30th minute and the 25th minute at different thicknesses.

In figure 2, it exactly meets the requirements at point 8347. Hence, the optimal thickness is obtained. The optimal solve of fire fighting suits are that the thickness of layer II is 2mm and thickness of layer IV is 4mm.

4. Conclusion

Unlike the human body, there is no evaporative heat dissipation in the dummy. However, the temperature of the dummy is always 37℃, so the thermal conductivity model is relatively complex. This model is to simplify the complex heat conduction model and consider it as a multi-layer cylinder heat conduction model. In order to more accurately simulate the temperature change of human in the real environment, a heat transfer coefficient should be added for the dummy to simulate the process of evaporation heat transfer and radiation heat transfer.

References

[1] Ohwada T, Sone Y, Aoki K. (1990) Numerical analysis of the poiseuille and thermal transpiration flows between two parallel plates on the basis of the boltzmann equation for hardsphere molecules. Physics of Fluids A Fluid Dynamics, 1(12):2042-2049.

[2] Phelps H, Sidhu H. (2015) A mathematical model for heat transfer in fire fighting suits containing phase change materials. Fire Safety Journal, 74:43-47.

[3] Konstantinov M, Lautenschlager W, Shishkin A. (2014) Numerical Simulation of the air flow and thermal comfort in aircraft cabins. Notes on Numerical Fluid Mechanics and Multidisciplinary Design, 124(3).

[4] Dear R J D, Arens E, Zhang H. (1997) Convective and radiative heat transfer coefficients for individual human body segments. International Journal of Biometeorology, 40(3):141-156.

[5] Maughan J R, Incropera F P. (1987) Experiments on mixed convection heat transfer for airflow in a horizontal and inclined channel. International Journal of Heat and Mass Transfer, 30(7):1307-1318.

[6] Sanitjai S, Goldstein R J. (2004) Forced convection heat transfer from a circular cylinder in crossflow to air and liquids. International Journal of Heat and Mass Transfer, 47(22):4795-4805.

[7] Kilic M, Sevilgen G. (2008) Modelling airflow, heat transfer and moisture transport around a standing human body by computational fluid dynamics. International Communications in Heat and Mass Transfer, 35(9):1159-1164.