Research on Positive and Negative Problems of Thermal Protection System Based on Genetic Algorithm and Finite Difference

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***Abstract*—The mathematical research on thermal protective clothing mainly uses mathematical models to describe the thermodynamic laws of thermal protective clothing, air layer and skin system, and provides theoretical reference for the functional design of thermal protective clothing. In this paper, the heat transfer process is fully explained by a multi-layer thermal protective suit, an air layer and a skin system, and numerical solutions for related inverse problems are given.**

Keywords—Heat transfer equation, backward Euler method, Rayleigh number, thermal protection, genetic algorithm, simulated annealing algorithm, Monte Carlo algorithm

I. INTRODUCTION

Today, forest fires (such as the Sichuan fire in March) occur frequently around the world. The fire protection suits worn by firefighters during firefighting are the only life support for firefighters during firefighting, so this has caused us to study firefighters' firefighting. Interest in the thermal performance of protective clothing, we hope to provide effective technical protection for firefighters in the first line of fighting.

II. RELATED WORK

This paper mainly sets three research goals.

A. Building a Heat Transfer Model for Thermal Protective Clothing

According to the classical heat transfer model and the existing research results of the relevant research groups, we introduce the Rayleigh number and use Rayleigh criterion to introduce the influence of heat convection heat conduction, which is established by fully considering the heat conduction, heat convection and heat radiation. Complete thermal protective clothing - the body's heat transfer model. Hereinafter referred to as question one.

B. The Inverse Problem of Thermal Protective Clothing Design

In this paper, heat protection suits, air layers, and heat transfer models inside the skin are combined to form a complete heat transfer system. Based on this model, we come out from the actual problem, set the inverse problem of the protective clothing design under two different conditions, and solve it numerically. Hereinafter referred to as question two.

C. Exploring the Solution of the PDE Equation

After the heat transfer model is constructed, the complex PDE equations are obtained. To understand the equation without the analytical solution, we first use the method of directed difference to solve the numerical problem. It is further hoped that we can further optimize our solution by Monte Carlo simulation. The steps provide some reference for the next study. The following is referred to as question three.

D. Assumptions and Justifications

1) Does not consider the effect of the shape of the thermal protective suit on the surface temperature of the human skin.

2) Assume that the external temperature is constant or small, and that the temperature of the external contact point of the garment is equal to the ambient temperature.

3) Assume that the thickness of each protective layer of the thermal protective suit does not change during the experimental period.

4) Since the thickness of the air layer does not exceed 6.4 mm, the influence of heat convection is small, so the heat convection phenomenon is temporarily not considered.

5) Assume that during the heat transfer in the model, the heat absorbed in the plane perpendicular to the x-axis is the same, and the thermal protective clothing fabric does not melt or decompose.

6) Assume that the human body is static throughout the process.

7) Assume that the effect of moisture on temperature is not considered.

8) Assume that the temperature change between layers is continuous.

9) The inside of the protective suit can be assumed to be a closed system, ie the air layer can be simplified into a closed loop chamber.

10) Assume that the fabric involved in the problem is uniform and isotropic.

11) The emissivity of different materials is constant.

12) System heat transfer only considers heat radiation, heat convection, heat transfer heat transfer, and doesn't consider wet transfer.

13) It is assumed that there is only heat conduction inside the human body, and there is no heat transfer form such as heat convection and heat radiation.

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III. THE MODEL

A. Construction of Thermal Protective Clothing Heat Transfer Model

(1) Analysis of heat transfer model

(a) Model construction ideas

The actual conditions for solving problem one are as follows:

The experiment was carried out in an environment where the ambient temperature was 75 °C, the thickness of the II layer was 6 mm, the thickness of the IV layer was 5 mm, and the working time was 90 minutes.

First, we divide the whole model into blocks, and divide it into four connected areas: cloth layer, air layer, environment layer and human body according to the medium and heat transfer method, and analyze the heat transfer modes of each area separately. We establish a one-dimensional coordinate system with the environment-first left boundary as the O point and the first layer to the second layer, and obtain the following environment-cloth layer-air layer-body heat transfer system model (hereinafter referred to as cloth) Air-skin heat transfer system).

(b) Three main ways of heat transfer [1]

There are three main ways in which system heat transfer can occur:

a) Thermally conductive objects rely on the thermal energy generated by the thermal motion of the particles to become heat conduction.

b) The phenomenon of radiant energy emitted by heat radiating objects due to heat is called heat radiation. The main theoretical formula is Steven Boltzmann's law and blackbody radiation.

c) Thermal convection heat convection can only occur in the fluid, and because the molecules in the fluid are simultaneously performing irregular movements, the thermal convection is inevitably accompanied by the phenomenon of heat conduction.

By the characteristics of the three heat conduction modes, based on the assumption that there is no air in the cloth layer or the air therein can be neglected, we can think that heat conduction and heat radiation have a great influence on the heat transfer in the cloth layer.

Below we solve the heat transfer mechanism of the above model separately.

(2) Complete process derivation of heat transfer

1) Derivation of the heat transfer equation of the cloth layer

Based on the assumptions of our model, the above cloth heat transfer model can be written as follows:

(a) Consider the transfer problem of the first layer under thermal radiation: energy at the x point (thermal energy), for the radiation situation, there is radiant heat to the left and right, by the energy conservation equation:

$$\frac{\partial e_L}{\partial t} = -\frac{\partial F_L}{\partial x} \qquad (1)$$

Here e_L is the energy density, $F_L(x,t)$ is the total heat flux radiated to the left at the x point, and the heat radiant energy at the x point is $\sigma u^4(x,t) - F_L$. If the unit machine is $\beta(\sigma u^4(x,t) - F_L)$, then the above expression becomes:

$$\beta(\sigma u^4(x,t) - F_L) = -\frac{\partial F_L}{\partial x} \qquad (2)$$

The same goes for the right side:

$$\beta(\sigma u^4(x,t) - F_L) = -\frac{\partial F_R}{\partial x} \qquad (3)$$

For the cloth layer, there is a correlation equation for conduction and radiation:

$$\begin{cases} c_1\rho_1 \dfrac{\partial u}{\partial t} = \dfrac{\partial}{\partial x}\left(k_1 \dfrac{\partial u}{\partial x}\right) + \dfrac{\partial F_L}{\partial x} - \dfrac{\partial F_R}{\partial x}, i = 1,2 \\ \beta(\sigma u^4(x,t) - F_L) = -\dfrac{\partial F_L}{\partial x} \\ \beta(\sigma u^4(x,t) - F_L) = -\dfrac{\partial F_R}{\partial x} \end{cases} \qquad (4)$$

(b) Boundary conditions of the cloth layer

The left boundary condition considers the left boundary condition of the cloth layer under the thermal radiation of air:

$$-k_e \frac{\partial u}{\partial x}\bigg|_{x=0} = (q_r'' + q_c'')|_{x=0} \qquad (5)$$

By consulting the relevant literature, we know that the heat flux generated by radiation and convection on the left boundary of the garment can be expressed as:

$$(q_r'' + q_c'')|_{x=0} = h_{g,f}\left(u_g - u_f\right) \qquad (6)$$

Here $h_{g,f}$ is a function of the heat flux and temperature produced by the radiation of air and clothing.

Right boundary condition The right boundary condition of the cloth layer is:

$$-k_e \frac{\partial u}{\partial x}\Theta x = l1 + l2 + l3x = qa,r'' + qa,c''\Theta x = l1 + l2 + l3x \qquad (7)$$

Here k_e is the effective conduction coefficient, and its value is:

$$k_e(T) = \lambda k_0 + (1-\lambda)k_f \qquad (8)$$

λ is the porosity of the garment. Our experiment here is carried out in a lower temperature environment, so the thermal conductivity of the fabric is:

$$k_f(u) = 0.13 + 0.0018(u - 300)u \leq 700K \qquad (9)$$

Let ξ_1, ξ_2 be the emissivity inside and outside the cloth layer. In fact, the solution can be obtained by solving the above partial differential equation.

Compound Equations for Solving Radiation and Conduction the initial conditions and boundary conditions for the radiation problem are given below [2]:

$$\begin{cases}(1-\xi_1)F_L(0,t)+\xi_1\sigma u^4=F_R(0,t), & 0<t<t_1\\(1-\xi_2)F_R(0,t)+\xi_2\sigma u^4=F_L(0,t), & 0<t<t_1\end{cases} \tag{10}$$

In order to simplify the operation, by consulting the relevant literature, we can know that the above equation can be decoupled into the following partial differential equations to write the equation of the above problem and the Neumann boundary condition as follows:

$$\begin{cases}c_1\rho_1\dfrac{\partial u}{\partial t}=\dfrac{\partial}{\partial x}\left(k_1\dfrac{\partial u}{\partial x}\right)+\Theta(u)(x,t)\in(0,l_1)\times(0,t)\\u(x,0)=u_1(x)\\-k_e\left.\dfrac{\partial u}{\partial x}\right|_{x=0}=(q_r''+q_c'')|_{x=0}\\-k_e\left.\dfrac{\partial u}{\partial x}\right|_{x=l_1}=\left(q_{a,r}''+q_c''\right)\Big|_{x=l_1}\end{cases} \tag{11}$$

$$\begin{gathered}\Theta(u)=-\beta^2\sigma e^{\beta x}\left[\int_0^x e^{-\beta y}u^4(y,t)dy+c_2\right]+\beta^2\sigma e^{-\beta x}\left[\int_0^x e^{\beta y}u^4(y,t)dy+c_1\right]-2\beta\sigma u^4(y,t)\\c_1=\frac{\xi_1}{\beta}u^4(0,t)-(1-\xi_1)c_2\\c_2=\frac{1}{(1-\xi_2)\beta(1-\xi_1)e^{-\beta L}-\beta e^{\beta L}}\left[(1-\xi_2)\beta e^{-\beta L}\int_0^L e^{\beta x}u^4(x,t)dxi\right.\\\left.+\beta e^{-\beta L}\int_0^L e^{\beta x}u^4(x,t)dx+(1-\xi_2)\xi_1 e^{-\beta L}u^4(0,t)+\xi_2 u^4(L,t)\right.\end{gathered} \tag{12}$$

Heat transfer model of the air layer

The flow state of the air is divided into static, stable laminar flow, unstable laminar flow and turbulent flow. By consulting the relevant data, we found that the heat transfer phenomenon of the air layer is extremely complicated, including the coupling of three modes of transmission. In order to simplify the model, we introduce the Rayleigh number Ra to judge whether the air layer will have natural convection.

$$Ra=\frac{g\beta\Delta T\delta^3}{\alpha v} \tag{13}$$

From the literature [3] to the fact that the static air has a small thermal conductivity and is an ideal insulating material. However, if the thickness of the air layer is continuously increased, the heat conduction of the air layer may gradually decrease, and the natural convection phenomenon of the air layer gradually becomes apparent. From the literature [4], we can get the convection phenomenon of the air layer neglected at $Ra\le 1708$ o'clock. When $Ra\ge 1708$ and $Ra\le 5830$, the natural convection phenomenon occurs in the air layer. At this time, the heat of the air layer heat conduction is much smaller than the heat transferred by the heat convection. It is also known from the literature [5] that Torvi obtained the dominant position of heat transfer when the thickness of the air layer was below 6.4 mm by flow visualization and numerical simulation. The natural convection phenomenon began to occur when the thickness of the air layer was greater than 6.4 mm. Therefore, considering the heat transfer problem of the air layer, in the case of different thickness of the air layer:

$$\begin{cases}\rho_0(u)c_0(u)\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial x}q_r(x) & ,l_0\le 6.4mm\\\rho_0(u)c_0(u)\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\left(h\frac{T_f-T_s}{l}\right)-\frac{\partial}{\partial x}q_r(x), & l_0\ge 6.4\text{mm}\end{cases} \tag{14}$$

Heat flux from the cloth layer through the air layer to the body layer:

$$q_{rad}''|_{x=l_1+l_2+l_3+l_4}=\frac{\sigma\left(u_f^4-u_s^4\right)}{\frac{A_e}{A_f}\left(\frac{1-\epsilon_f}{\epsilon_f}+\frac{1}{F_{f\to s}}\right)+\frac{1-\epsilon_a}{\epsilon_s}} \tag{15}$$

Here we can take 1 for the fabric's viewing angle coefficient to get:

$$q_{\text{airrad}}''|_{x=l_1+l_2+l_3+l_4}=\frac{\sigma\left(u_f^4-u_s^4\right)}{\frac{1-\epsilon_f}{\epsilon_f}+\frac{1-\epsilon_s}{\epsilon_s}+1} \tag{16}$$

Heat flux from heat conduction and convection to the surface of the human body:

$$q_{a,c/c}''\Big|_{x=l_1+l_2+l_3+l_4}=h_{c,d}\left(u_f-u_s\right) \tag{17}$$

$h_{c,d}\left(u_f-u_s\right)$ can be seen as a function of the thickness of the air layer and temperature, in line with the relationship expressed by:

$$h_{c,d}=Nu\frac{k_0}{l_4} \tag{18}$$

Nu of them are Nussel's constants.

(3) Using the finite element method to numerically solve differential equations

Below we solve this equation:

$$c_1\rho_1\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\left(k_1\frac{\partial u}{\partial x}\right)+\frac{\partial F_L}{\partial x}-\frac{\partial F_R}{\partial x} \tag{19}$$

among them,

$$\begin{aligned}c_1\rho_1\frac{u_{i+1}^{j+1}-u_i^{j+1}}{dt}=&\frac{k\left(u_{i+1}^{j+1}\right)-k\left(u_i^{j+1}\right)}{h}\frac{u_{i+1}^{j+1}-u_i^{j+1}}{h}\\&+k\left(u_i^{j+1}\right)\frac{u_{i+1}^{j+1}-2u_i^{j+1}+u_{i-1}^{j+1}}{h^2}+\Theta_i^{j+1}\end{aligned} \tag{20}$$

Let $s=\frac{dt}{h}$ for the radiation term, we use Simpson interpolation numerical integration calculation, The left boundary condition is discretized as:

$$-k_e\left(u_1^{j+1}\right)\frac{u_1^{j+1}-u_0^{j+1}}{h}=h_{c,f}\left(u_g-u_0^{j+1}\right) \qquad (21)$$

Can also be written:

$$\begin{gathered}(1+w_1)u_0^{j+1}-u_1^{j+1}=w_1u_g\\ w_1=\frac{h_{c,f}}{k_e}\end{gathered} \qquad (22)$$

In the same way, the right border is written:

$$\begin{gathered}u_{M_1-1}^{j+1}-(1+w_3)u_{M_1}^{j+1}+w_3u_0^{j+1}=w_2\left[\left(u_{M_1}^{j+1}\right)^4-\left(u_0^{j+1}\right)^4\right]\\ w_2=\frac{\sigma h}{k_e\left(\frac{1-\epsilon_f}{\epsilon_f}+\frac{1-\epsilon_a}{\epsilon_s}+1\right)}\\ w_3=\frac{h_{c,g}h}{k_e}\end{gathered} \qquad (23)$$

(a) Heat transfer in different layers

The differential solution of the actual process is as follows:

$$\begin{bmatrix}1+2A & -A & \cdots & 0 & 0\\ -A & 1+2A & \cdots & 0 & 0\\ \cdots & \cdots & \cdots & 1+2A & -A\\ \cdots & \cdots & \cdots & -A & 1+2A\end{bmatrix}\begin{bmatrix}u_i^1\\ u_i^1\\ u_i^1\\ u_i^1\end{bmatrix}=\begin{bmatrix}u_i^0\\ u_i^0\\ u_i^0\\ u_i^0\end{bmatrix}+A\begin{bmatrix}u_i^1\\ 0\\ 0\\ u_i^0\end{bmatrix} \qquad (24)$$

Can also be written as:

$$AU_1=U_0+Add \qquad (25)$$

The backward solution avoids the problem of only convergence. If considering radiation problems, join matrix Ra

$$AU_1^1=BU_1^0+Add^0+Ra \qquad (26)$$

Consider six different layers of material problems: the algorithm is as follows:

Step 1: Solve the temperature of the previous layer to determine the initial temperature of the next layer:

$$AU_1^1=BU_1^0+Add^0+Ra \qquad (27)$$

Step 2: Update the Add matrix of the previous layer;

$$Add_{-1}^1=U_0^1 \qquad (28)$$

Step 3: Update the Add matrix of the next layer;

$$Add_{-1}^2=U_{-1}^1 \qquad (29)$$

Step 4: Solve the radiation matrix Ra in different media A, that is, determine the number of iterations of different proportions to reach the initial values of different regions. Repeat this solution process to obtain the temperature conditions in different layers.

(b) Solution Results

According to the matrix equation above, iteratively obtains the distribution of the four layers of temperature at different times, so this problem can be obtained by this equation. Through Pyhon programming we obtained the numerical solution of the above nonlinear partial differential equation. When we do not consider the first layer to absorb heat radiation, we get the relationship between the outside temperature of the skin.

When we consider the first layer of absorption of heat radiation we get the relationship between the outside temperature of the skin.

It is easy to know that our model and the actual situation are basically the same convergence speed, and the convergence position error is small.

(4) Using Monte Carlo Algorithms Solving Partial Differential Equations

(a) Monte Carlo algorithm for resolving partial differential equations

The Monte Carlo algorithm is an approximate solution that uses a large number of experiments to solve related problems. It can greatly speed up the solution of partial differential equations, and can reduce the error of the results by controlling the experimental amount. In order to improve the efficiency of the algorithm, the Monte Carlo algorithm is proposed based on the above finite element method for solving differential equations.

The calculation results are shown in Fig. 1:

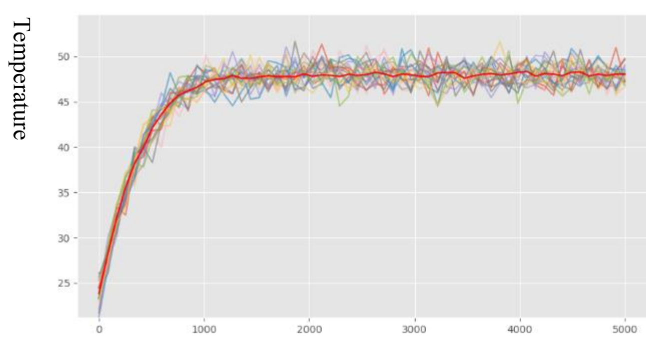

Fig. 1. Monte Carlo algorithm.

B. Anti-problem Solution for Thermal Protective Clothing - Waterproof Layer

The conditions assumed in our first counter-problem are as follows:

When the ambient temperature is 65 °C and the thickness of the air layer is 5.5 mm, the optimal thickness of layer II is determined to ensure that the outside temperature of the human skin does not exceed 47 °C for 60 minutes and the time exceeds 44 °C for less than 5 minutes.

Through the problem analysis, we can find that the first inverse problem is to find the optimal thickness of the second layer when the ambient temperature is 65 °C and the thickness of the IV layer is 5.5 mm. So the key to the problem is how to define the optimal thickness. Determine the optimization goal.

(1) Optimal thickness definition

We first give the definition, we take the thickness when the thermal protection performance is optimal as the optimal thickness required by the problem. Here we need to point out that the thermal protection performance we are considering is the size of the thermal protection capability of the thermal protection suit - the overall system of the human body, including the reflection of the heat accumulation phenomenon. Based on the relevant literature, we believe that the thermal storage performance can be reflected by the maximum temperature of the thermal protective clothing-air layer system. Through the derivation of the above model, we can find that the temperature at the skin does not decrease with time. Therefore, we can simplify the above constraints into two processes: the temperature at 55 minutes is not more than 44 °C, and the temperature is not more than 47 °C at 60 minutes. We consider the heat accumulation process of the fabric layer.

So we can establish the following single-input single-object constrained optimization problem.

$$\mathrm{Min}u_{\max}(x), x \in (L_1, L_2) \qquad (30)$$

$$S.t\begin{cases}0.6 \le l2 \le 25\\ u_{t=60} \le 47\\ u_{t=55} \le 44\end{cases} \qquad (31)$$

(2) Variable step size search

The variable step search seeks the corresponding optimal solution by changing the precision of the search and the number of searches. The process of calculating the objective function is the heat transfer equation established by our research target. The goal of this problem is to calculate temperature changes at the same location at different times, traversing different thicknesses l_2. Here we are based on the optimized function

$$\min\{u_{\max}(x), x \in (0, l_1 + l_2 + l_3 + l_4)\} \qquad (32)$$

Take different steps to solve. Finally, by using the above solution several times, comparing each solution, we found that the requirement was met at 13.35 mm, and the maximum heat of the cloth layer was the smallest in multiple comparisons. So we can think that the thickness of the second layer is 8.73 mm to meet the requirements.

(3) Determination of the optimal thickness by the fixed step method

If we traverse the domain of the definition in a certain step, ie

$$l_2(i) = l_2(0) + i * (l_2(\max) - l_2(\min))/2 \qquad (33)$$

among them

$$l_2(0) = 0.6 \le l_2(1), \le l_2(N) = 25 \qquad (34)$$

The skin outer surface temperature of the original heat transfer system at 60 minutes and 55 minutes was then calculated for each second layer thickness. We have found that the relationship between the thickness of the second layer and the temperature of the outer surface of the skin at two times can be obtained by appropriately adjusting the traversal step size. The relationship is shown in Fig. 2.

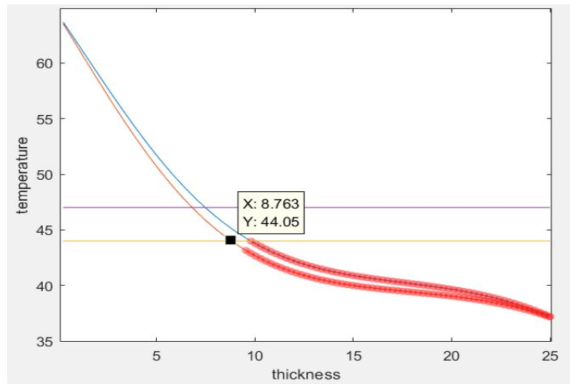

Fig. 2. Relationship between thickness of the second layer and skin surface temperature.

Among them, the coordinates of 4 intersection points can be obtained. It can be known that the thickness can be satisfied after the thickness is greater than 8.85 mm. When we bring all the thicknesses satisfying the problem conditions into the original model to solve the maximum temperature of the second layer, we find that it is just right. When L2 = 8.85 mm, it is not only satisfied that the time exceeding 44 °C in 60 minutes does not exceed 5 minutes, and the final temperature does not exceed 47 C, and the heat accumulation at this time is exactly the smallest in the corresponding feasible domain. So we think the most suitable thickness for the second layer is 8.85 mm.

C. Anti-Problem Solution for Thermal Protective Clothing - Air Layer

The problem we have solved in solving the second inverse problem is as follows:

When the ambient temperature is 80 °C, determine the optimal thickness of the layer II and the air layer, to ensure that the outside temperature of the human skin does not exceed 47 °C when working for 30 minutes, and the time of more than 44 °C does not exceed 5 minutes.

When the thickness of the fourth layer changes, the heat transfer equation of the fourth layer may change, that is, the thickness change of the air layer affects the magnitude of the Rayleigh number and the test conditions are inconsistent with the literature, so it is necessary to consider Ra every time. When it is greater than 1708, the air buoyancy overcomes the viscous resistance. After the air turns into a laminar flow state, the heat transfer mode becomes natural convection and the convection after the radiation increases the heat transfer rate, and the heat insulation performance may decrease, so the thickness is increased. In the large process, the thermal insulation performance will have a maximum value, that is, the optimal air layer thickness. The thickness of the second layer is still constrained by phenomena such as radiation heat storage, so we adopt a heuristic search algorithm based on genetic algorithm.

(1) Establishment of optimization model

$$\min\{u_{\max}(x), x \in (0, l_1 + l_2 + l_3 + l_4)\} \tag{35}$$

$$\begin{cases} 0.6 \le l2 \le 25 \\ 0.6 \le l4 \le 6.4 \\ u_{t=30} \le 47 \\ u_{t=25} \le 44 \end{cases} \tag{36}$$

(2) Genetic algorithm

For the extreme value problem of the above binary single target, we will use genetic algorithm to solve the minimum value in the given domain. We will run the maximum of 50 times as the optimal solution. Due to the slow convergence rate and long execution time, the genetic algorithm is used for searching:

(a) Preliminary search solution set:

Under different lengths, search in a larger step size to roughly find the range of the optimal solution, and thus get the sub-set we want to segment.

(b) Determine the encoding method of the chromosome:

Here, the basic binary coding method is adopted, and the lengths of one layer and four layers required by the present problem are divided into sub-strings, and then the sub-strings are connected into a "chromosome" string as an independent variable of the solution.

(c) Initialize the population:

After the binary code of the randomly generated gene length, it is necessary to verify that the binary code is transcoded to find whether the two solutions satisfy the different conditions, whether the obtained solution is within the solution interval, and whether the solution satisfies:

$$\begin{aligned} u_{25} &\le 44°C \\ u_{30} &\le 47°C \end{aligned} \tag{37}$$

That is, less than 44 degrees at 25 minutes and less than 47 degrees at 30 minutes. If the binary code of the group satisfies the above requirements, it is included in the initial population, otherwise the binary code of the gene length is re-randomly generated and then tested.

(d) Determine the adaptive function

There are two optimization goals in this paper, the first layer thickness and the third layer thickness, which are combined with implicit difference and boundary conditions. The method weights and then sums the two optimization objectives and boundary conditions and transforms them into a single-objective optimization problem.

$$\min\{u_{\max}(x), x \in (0, l_1 + l_2 + l_3 + l_4)\} \tag{38}$$

$$\begin{cases} 0.6 \le l2 \le 25 \\ 0.6 \le l4 \le 6.4 \\ u_{t=30} \le 47 \\ u_{t=25} \le 44 \end{cases} \tag{39}$$

Here we define the objective function to be solved as a function with weights:

$$\min u_{25} + \lambda_1 |u_{25} - 44|^2, u_{30} + \lambda_2 |u_{30} - 47|^2 \tag{40}$$

The parameter here is a large value as a penalty term, and the search area is gradually reduced after each step to reduce the amount of calculation.

(e) Screening for outstanding individuals:

Screening for excellent per-body roulette methods, in roulette, that is, the probability that each individual is selected for heredity is proportional to the value of its fitness. That is to say, the higher the fitness, the greater the probability of being selected. In this question, the value is selected as follows: Total fitness calculation for a generation of population:

$$\begin{aligned} \text{sum}F_{30} &= \sum_{i=0}^{n} u_i\, 30 \\ \text{sum}F_{25} &= \sum_{i=0}^{n} u_{i25} \end{aligned} \tag{41}$$

The selection probability Ps_i of a certain body i in the population is calculated:

$$Ps_i = u_i / \text{sum}F_{25} \tag{42}$$

Let the wheel rotate 100 times, and then select the individual to form a new generation of population each time.

(f) Design of genetic operators:

After determining the binary coding of the chromosome, consider the intersection and mutation of the chromosome.

a) Crossover operation: We specially designed a genetic algorithm combining the uniform two-point crossover operator to generate random numbers 0 and 1, and when the random number is 0, cross the two chromosomes to represent the length of 1; When the random number is 1, the part representing the length of l2 in the two chromosomes is crossed, so that two independent variables of different lengths can be obtained, and the local optimum can be jumped out.

b) Mutation operation: first randomly generate the binary code position where the variant gene is located, and then determine whether the binary code is 0 or 1, and if the binary code bit is 1, the binary code bit mutates to 0 after the mutation operation. If the binary code bit is 0, the binary code bit mutates to 1 after the mutating operation.

(g) Set the parameters related to the genetic algorithm:

There are three parameters of the genetic algorithm, namely the population size P, the crossover probability pc, the mutation probability pm and the maximum genetic algebra pD. The size of the population in this paper is 100. The larger the population size, the easier it is to find the optimal solution. A crossover probability of 0.6 and a crossover probability of 0.6 ensure sufficient evolution of the population. The probability of variation is 0.005. Generally speaking, the possibility of variation is small, and the probability of variation is 0.005, which is more in line with the natural law. The maximum genetic algebra is 200, and the maximum genetic algebra is 200 to ensure that the optimization results are fully converged. Through the above process, we obtain that the above optimization target is satisfied at = 6.21053 mm and = 5.14286 mm. Therefore, it can be considered that under the above conditions, under the condition that the temperature limit of the problem is satisfied, it is also possible to satisfy the thickness under the temperature constraint that the thickness combination heat accumulation amount is the smallest.

(3) Determination of optimal thickness by the fixed step method

Similar to the first inverse problem, we perform a fixed-step discretization segmentation on the two-dimensional plane, and then we get N points, which are taken into the research target and considered in the Ra model to obtain the relevant points and the relationship between skin surface temperature at minute is shown in Fig. 3.

The relationship between the correlation point and the skin surface temperature at 30 minutes is shown in Fig. 4.

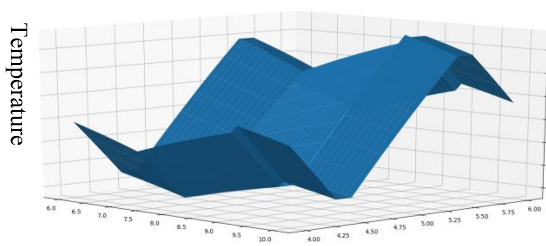

Fig. 3. Skin surface temperature map at 25 minutes.

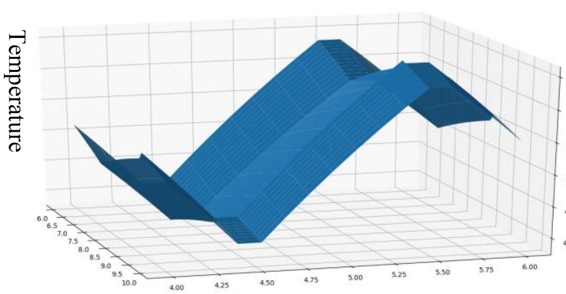

Fig. 4. Skin surface temperature map at 30 minutes.

If only the outer surface temperature of the skin is considered to be the lowest, the thickness of the second layer is 7.23077 mm, and the thickness of the fourth layer is 4.533 mm. By traversing the points in the feasible domain, the maximum temperature of the corresponding thermal protection system at all points is calculated, and finally the most advantageous thickness combination is obtained (5.14286, 6.2103). That is, when the thickness of the second layer is 6.201053 mm and when the thickness of the fourth layer is 5.14286 mm, it can be regarded as an optimum thickness combination.

IV. Research Conclusions

For the two inverse problems we assumed:

1) When the ambient temperature is 65 °C and the thickness of the air layer is 5.5 mm, the optimal thickness of layer II is determined. When the working temperature is 60 minutes, the outside temperature of human skin does not exceed 47 °C, and the time exceeding 44 °C does not exceed 5 minutes.

2) When the ambient temperature is 80 °C, determine the optimal thickness of the layer II and the air layer, and ensure that the outside temperature of the human skin does not exceed 47 °C when working for 30 minutes, and the time exceeding 44 °C does not exceed 5 minutes.

We have the following optimal solution:

For the first problem, we obtained that the thermal protective clothing system satisfies the overall thermal protection performance when the thickness of the second layer is 8.85 mm.

For the second problem, we get the best thermal protection of the thermal protective clothing system with a thickness of 6.21105 mm in the second layer and a thickness of 5.14286 mm in the fourth layer. If only the outer surface temperature of the skin is considered to be the lowest, the thickness of the second layer is 7.23077 mm, the thermal performance of the fourth layer with a thickness of 4.533 mm is optimal.

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