



RETRACTED: Genetic Algorithm to Optimize the Design of High Temperature Protective Clothing Based on BP Neural Network

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For the clothing design for high-temperature operation, the theory or method such as partial differential, nonlinear programming and finite difference method was first applied to construct the overall heat transfer model of "high temperature environment--clothing--air layer--skin" and draw the temperature distribution map. Secondly, according to the human body burn model, the optimal parameters of fabric thickness are obtained preliminarily. Finally, the weights and thresholds of BP neural network were optimized by genetic algorithm, and these optimized values were assigned to the optimized BP neural network, and the nonlinear thickness function was approximated and optimized with MATLAB.

Keywords: thermal protective clothing, temperature distribution, genetic algorithms, BP neural network, optimal design

1 INTRODUCTION

When working in a high temperature environment, people need to wear special clothes to avoid burns. Such clothing can promote heat emission, prevent heat stroke, burns and other hazards. With the improvement of heat protection demand, the material and design of high temperature special clothing need to be improved continuously in the experiment.

Bin Pan introduces the heat transfer model of single layer heat protective clothing, the mathematical model of heat transfer of air layer and skin layer and the evaluation model of burn from the angle of heat transfer law inside heat protective clothing. Finally, the related inverse problems are put forward in combination with burn criteria [1]. From the point of view of "protective clothing-air layer-skin", Linzhen Lu analyzed and studied the heat transfer model of-air layer-skin". Finally, the inverse problem determined by thickness, porosity and thermal conductivity was solved by numerical algorithm [2]. From the point of view of numerical simulation, Miao Tian et al. [3] evaluated the performance of thermal protective clothing, reviewed the heat transfer model, skin burn prediction model and so on. She summed up the development process, characteristics and shortcomings of the model, and finally predicted the development trend of the numerical simulation of thermal protective clothing.

In the field of thermal protective clothing, many researchers at home and abroad have carried out many studies on the effect of air layer thickness on the thermal insulation performance of thermal protective clothing, and have obtained certain research results. However, the current research mainly considers the air layer between human skin and thermal protective clothing. In this paper, the temperature distribution and optimum thickness of each layer of thermal protective clothing are studied from the point of view of mathematics and thermodynamics.

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2 DATA SOURCES AND BASIC ASSUMPTIONS

Data used in the model are derived from the attachment to the A questions of the 2018 National College students Mathematical Modeling Competition. In order to solve the problem, the following assumptions are put forward: 1) Assuming that the heat transfer is perpendicular to the skin, the heat transfer of the thermal protective clothing can be regarded as one-dimensional heat conduction. 2) It is assumed that the effects of sweat, humidity and water vapor of the human body are not taken into account in the high temperature operating environment. 3) Assuming that the contact between the layers is good, it can be approximately assumed that the temperature on the joint is equal everywhere. 4) Assume that the initial temperature of human skin in the experiment is 37°C.

3 SYSTEMATIC ANALYSIS OF “HIGH TEMPERATURE ENVIRONMENT-CLOTHING-AIR LAYER-SKIN” BASED ON HEAT TRANSFER MODEL

3.1 Research Ideas

Firstly, the partial differential equation model of one-dimensional unsteady heat conduction is a good choice because the temperature varies with time and space. Secondly, the initial conditions, boundary conditions and interface conditions of each layer are given. Finally, the finite difference method is used to calculate the equation value.

3.2 Model Preparation

3.2.1 Fourier Law

The direction of Local thermal heat flux at any time, any position in an isotropic continuous medium is opposite to the direction of temperature change (gradient direction) of the shop, and its values are proportional to the temperature gradient the point [4]. The heat flux is calculated as follows:

$$q = -K\text{grad}T = -K \frac{\partial T}{\partial n} n \tag{1}$$

Where the variable q is the heat flux (W/m²); the current temperature of the object is T ; the unit direction vector is n . According to the above formula, the transfer direction of heat flux q is opposite to that of gradient.

3.2.2 Newton’s Law of Cooling

When convection heat transfer occurs, the calculation of heat flux is based on Newton’s cooling formula:

a. When the fluid temperature is lower than the object:

$$q = h(t_w - t_f) \tag{2}$$

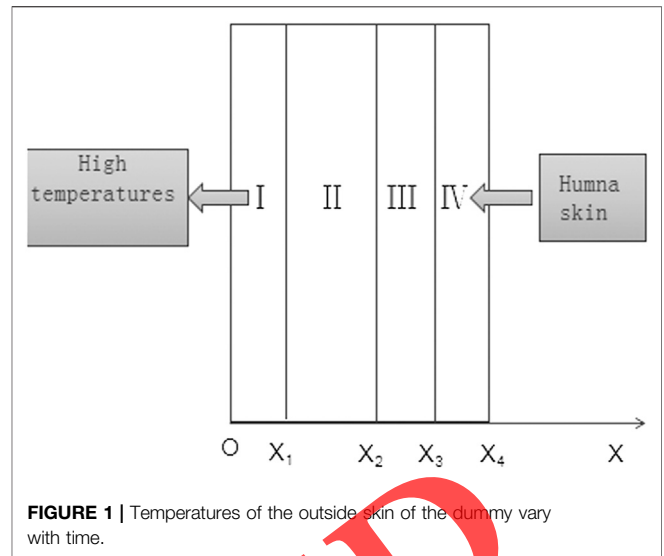


FIGURE 1 | Temperatures of the outside skin of the dummy vary with time.

b. When the fluid temperature is higher than the object:

$$q = h(t_f - t_w) \tag{3}$$

where t_f is the fluid temperature, t_w is the convective surface temperature, and h is the convective heat transfer coefficient.

3.3 Establishment of One-Dimensional Heat Conduction Model

3.3.1 Determination of One-Dimensional Heat Conduction Equation

The mathematical model of heat transfer of fabric and air layer under high temperature environment is put forward. The distribution of each layer of the “high temperature environment–clothing–air layer–skin” system is as shown in Figure 1.

Based on the above assumptions, we can treat the heat conduction of thermal protective clothing as one-dimensional unsteady heat conduction [5]. Thus, the heat transfer model can be written as follows:

$$\begin{cases} \frac{\partial T_1}{\partial t} = k_1 \frac{\partial^2 T_1}{\partial x^2}, 0 \leq x < x_1, \\ \frac{\partial T_2}{\partial t} = k_2 \frac{\partial^2 T_2}{\partial x^2}, x_1 \leq x < x_2, \\ \frac{\partial T_3}{\partial t} = k_3 \frac{\partial^2 T_3}{\partial x^2}, x_2 \leq x < x_3, \\ \frac{\partial T_4}{\partial t} = k_4 \frac{\partial^2 T_4}{\partial x^2}, x_3 \leq x < x_4. \end{cases} \tag{4}$$

In the formula, the T_i is the temperature field of the thermal protective clothing at the I, II, III and IV layers; the k_i is the thermal diffusion coefficient of the thermal protective clothing at

the I, II, III and IV layers; the t is the time; and the x is the horizontal coordinate.

3.3.2 Initial Conditions

An unknown function changes with different t , reflecting the relationship between a physical quantity at a certain time and the same physical quantity at an adjacent time. Therefore, in the process of solving the problem, we should first trace back to the condition of an earlier so-called “initial” moment, that is, to establish the initial condition.

When the initial temperature of the four dielectric layers is $T_0 = 37^\circ\text{C}$, the initial conditions of the heat conduction equation in the four regions can be obtained as follows:

$$\begin{cases} T_1(x, 0) = T_0, \\ T_2(x, 0) = T_0, \\ T_3(x, 0) = T_0, \\ T_4(x, 0) = T_0. \end{cases} \quad (5)$$

When $T_0 = 37^\circ\text{C}$ represents the initial temperature of the outer surface of the pseudo-human skin; the initial time temperature of each layer of medium is $T_i(x, 0)$.

3.3.3 Determination of Boundary Value Conditions(Third Kinds of Boundary Value Problems)

According to the first layer fabric directly contact with the heat source of the T_1 , the first boundary condition is obtained. At the same time, considering that the low temperature and constant temperature heat source in the dummy body will absorb heat and cool the skin surface of the dummy. But the temperature will continue to rise, after a period of time to achieve dynamic balance to maintain a constant temperature on the skin surface. Therefore, considering the third kind of boundary conditions, the second boundary condition of the heat conduction equation is obtained by using the differential form of Newton’s law of cooling as follows [6]:

$$\begin{cases} T_1(0, t) = T_0, \\ \frac{\partial T_4}{\partial t} = h \times [T_4(x_4, t) - T_0] \end{cases} \quad (6)$$

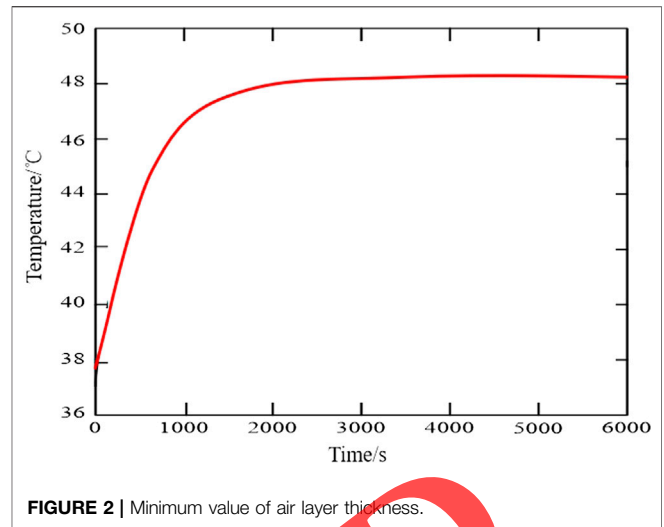
where T_0 indicates that the initial temperature of the outer surface of the pseudo-human skin is 37°C , h indicates the heat exchange coefficient.

3.4 Solution of the Model

3.4.1 Backward Differential Method

Because the boundary conditions of heat exchange are complex and the partial differential equation of heat conduction is multi-order, it can not be solved by general analytical method, so the finite difference method is used to solve the one-dimensional heat conduction equation [7].

The finite difference method uses the idea of region transformation to discretize the time-space range of the solution, and the continuous region is divided into regular grids. By using the temperature value at the intersection point of the grid to simulate the temperature field of the whole plate structure, the differential equation is replaced by the difference



form when the grid is divided, and then a discretion of equations is constructed [8].

The forward difference method is simple and easy to use. But its feasibility is limited by the time difference step size (τ) and the space difference step size (x), so the feasibility test is needed, and the feasibility test formula is used:

$$r = \partial \frac{\Delta\tau}{\Delta x^2} < 0.5 \quad (7)$$

After testing the step ratio r it is difficult to meet the requirement of less than 0.5, and the method of forward difference in this model will be unstable. Therefore, the model is not suitable for the solution of forward difference, so the numerical solution is obtained by backward difference method.

The internal backward difference method is simple, and the derivation results are given as follows:

$$(1 + 2\lambda)u_{ij} - \lambda(u_{i-1,j} - u_{i+1,j}) = u_{ij-1} \quad (8)$$

The edge value is brought into the calculation:

$$(u_{1,j-1} - 2\lambda\Delta x h_1 T_0) = (1 - 2\lambda - 2\lambda\Delta x h_1)u_{1,j} - 2hu_{2,j} \quad (9)$$

3.4.2 Results Analysis

Using the measured temperature information of the lateral skin of the dummy in Annex 2, the curve of the temperature of the lateral skin of the dummy with time is drawn.

From **Figure 2**, it can be seen that the temperature difference of high and low temperature heat source in 1000 s is large, and the thickness of fabric medium is small, which makes the outer temperature of dummy skin rise sharply in a short period of time and can not achieve a good heat resistance effect. At the same time, it can be found that the lateral temperature will not change after 48°C . Because the low temperature heat source has dissipated function, the temperature distribution on one side of the skin can finally reach a dynamic balance with the low temperature heat source. At this point $x = x_4$, combined with

Newton's cooling law, that is, the third type of boundary conditions there:

$$\left. \frac{\partial T}{\partial x} \right|_{x=x_4} = h[T(x_4, t) - T_0] \quad (10)$$

Finally, the value of heat exchange coefficient h is determined according to time.

4 OPTIMIZATION DESIGN OF OPTIMAL THICKNESS BASED ON BP NEURAL NETWORK AND GENETIC ALGORITHM

4.1 Research ideas

The thickness of fabric layer in thermal protective clothing is an important factor to improve the performance of thermal protective clothing, so the determination of thickness parameters has become one of the important directions in the study of thermal protective clothing. In the "high temperature environment-clothing-air layer-skin" system, we assume that the porosity and tortuous coefficient of the fibers and the thermal conductivity of the fabric materials are known. The minimum burn degree of human body is taken as the objective function, and the constraint condition is obtained from the heat transfer equation, the initial boundary value condition and the interface condition of each layer. Finally, the optimal thickness of layer I and IV of fabric is obtained by neural network and genetic algorithm.

4.2 Establishment of Uni-Variate Optimization Model

4.2.1 Determination of Decision Variables

The degree of skin burn in high temperature environment is an important index to measure the performance of thermal protective clothing. Here take layer II as an example.

4.2.2 Determination of Objective Function

By consulting data, the condition that human skin is not burned in high temperature environment [9-16] is $\varphi < 1$. When the experiment time $t^* = 30\text{min}$, the degree of safety burn $\varphi^* = 1$, the objective function $Q(L)$ the thickness of layer II is:

$$\begin{cases} Q(L) = \int_0^{t^*} |\varphi(t; l_2) - \varphi^*|^2 dt, \\ \varphi(t; L_4) < \varphi^*. \end{cases} \quad (11)$$

The parameter value of special clothing material gives the range of material thickness, that is $0.6 \leq l_2 \leq 25$.

4.2.3 Solution of the Mode

Through analysis, it is considered that the accuracy is 0.1 mm, and the range $0.6 \leq l_{air} \leq 25$ is relatively small. The number of feasible solutions in this range is less than 250, so the global optimal solution can be obtained by ergodic search algorithm. The MATLAB is used to solve the problem. Because the thickness

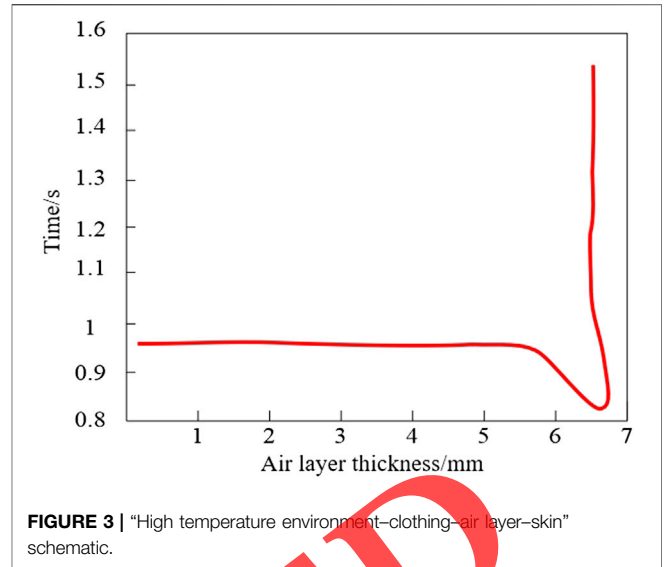


FIGURE 3 | "High temperature environment-clothing-air layer-skin" schematic.

of the air layer has the upper and lower limits, when, a least square solution can be found to get the minimum value point.

Figure 3 shows that when the upper limit of the air layer is 7 mm, the $l_2 = 6.76 \times 10^{-3}m$ can achieve the optimal thermal protection effect in the specified time.

4.3 Establishment of Cultivable Optimization Model

4.3.1 Determination of Decision Variables

Based on the above model, an unknown quantity is added to the thickness of layer IV. So the decision variables are thickness l_2 and thickness l_4 .

4.3.2 Determination of Objective Function

Goal function 1: the sum (H) of layer II and layer IV thickness is minimal, that is

$$H_{\min} = l_2 + l_4 \quad (13)$$

Goal function 2: the sum (M) of the weight of layer II and layer IV materials is minimal, that is

$$M_{\min} = S\rho_2 l_2 + S\rho_4 l_4 \quad (14)$$

4.3.3 Determination of constraints

When the ambient temperature is 80°C , make sure that the outside temperature of the dummy skin does not exceed 47°C and the time beyond 44°C does not exceed 5 min. Because the temperature of the skin's outer surface is constantly rising during heat transfer, it can be converted into computational constraints [17-21]:

$$\begin{cases} T_S \leq 47^\circ\text{C}, t = 30\text{min}, \\ T_S \leq 44^\circ\text{C}, t = 25\text{min}. \end{cases} \quad (15)$$

4.3.4 Reduction of Dimension

The above two-objective model is difficult to solve directly, so it is necessary to transform the two-objective problem into a single goal by reducing the dimension. The reduction steps are as follows:

- Step1: The values of H and M in different cases are calculated respectively;
- Step2: Standardization of H and M to their respective standardized \tilde{H} and \tilde{M} ;
- Step3: The standardized values are added to different weight p and 1-p to form a single objective function:

$$Y_{\min} = \tilde{H} + \tilde{M}.$$

4.3.5 Solution of the Model

However, due to the large number of feasible solutions, the BP neural network algorithm improved by genetic algorithm is needed to calculate. BP neural network algorithm has the advantages of large-scale parallel processing, self-learning and adaptive ability, fault tolerance and robustness, but it is easy to fall into local minima. Therefore, we use genetic algorithm to optimize the weights and thresholds of BP neural networks, then assign these optimization values to BP networks to obtain optimized BP neural networks, and finally use MATLAB to optimize the nonlinear thickness function.

The BP neural network flow based on genetic algorithm optimization is as follows [22–32]: 1) Create BP neural networks; 2) Adaptability function: the reciprocal of the system error of neural network is taken as the fitness function of genetic algorithm, and the optimal weight and threshold can be obtained by using the powerful search performance of genetic algorithm; 3) Selection operation: this paper chooses roulette method to select genetic operator; 4) Cross operation: using real number cross method; 5) Mutation operation: mutation of each individual gene; 6) Assignment, optimization, BP neural network: the optimal chromosome obtained by genetic algorithm is decomposed into the initial weights and thresholds of the BP neural network, and assigned to the BP neural network for training. when the required accuracy or the number of learning is reached, the network training ends.

4.4 Results Analysis

Genetic algorithm is used to solve the weights and thresholds of BP neural networks, Because the results of each operation are different and easy to fall into the local optimal solution, So we use the results of running 50 times as the weights and thresholds of the neural network. Let the genetic algorithm have 50 iterations, Population size 25, Cross probability 0.4, Variance probability 0.2, Encoded in real numbers, Individual length 2, The optimal value of neural network based on genetic algorithm optimization is 0.692. The error is 0.2, The error percentage is 9.03%, The error is large but within 10%. The results show that the optimum thickness of the air layer is 12.1 mm, and the optimum thickness of the insulation layer is 6.7 mm.

5 MODEL EXTENSION

The neural network BP genetic algorithm optimization is divided into three parts: BP neural network structure determination, genetic algorithm optimization and BP neural network prediction. The BP neural network structure is determined by the number of input and output parameters BP the fitting function, so the number of optimization parameters of genetic algorithm can be determined, and the coding length of individual genetic algorithm can be determined. Because the parameters of genetic algorithm optimization are the initial weights and thresholds of the BP neural network, the number of weights and thresholds is known as long as the structure of the network is known. Genetic algorithm is used to optimize the BP neural network to calculate the optimal thickness of fabric more accurately.

6 CONCLUSION

In high temperature working environment, the performance of thermal protective clothing mainly depends on its resistance temperature. This paper introduces the heat transfer model of thermal protective clothing based on heat transfer theory, and calculates the temperature distribution of fabric layer and skin layer with time. Based on the determination of its chemical materials, the improved BP neural network can be used to calculate the optimal thickness parameters of fabric layer and air layer, so as to improve the performance of thermal protective clothing. The algorithm has fast convergence speed and high accuracy, and can be widely used in the problem of finding parameter extremum. However, this paper lacks the consideration of clothing comfort and aesthetics, and needs to be further improved in future research.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

FX is the first author, L-YM is the second author, HC is the third author, and J-MZ is the fourth author. Correspondence should be addressed to Jia-Ming Zhu: zhujm1973@163.com.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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