One-dimensional unsteady heat transfer model of three-layer thermal protective clothing

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Abstract

Thermal protective clothing is the most widely used special protective clothing, At present, the design of more thermal protective clothing focuses on the determination of thermal protection performance, the establishment of internal heat transfer models for thermal protective clothing, the development of test methods for measuring thermal protection performance, and the evaluation of experimental devices and thermal protective clothing comfort. In this paper, based on a certain ambient temperature, the whole heat conduction model of heat transfer to the dummy skin under thermal protection is studied. What needs to be solved in this problem is the heat conduction problem of the three-layer fabric thermal protective clothing. In view of the influence of the parameters of the three-layer thermal protective clothing on the protective performance of the human body during continuous exposure to high temperatures, modeling and simulation methods are used to predict the optimal thickness for safety.Firstly, for the system consisting of three layers of fabric materials including layers I, II and III, the skin of the dummy and the air layer between the three layers, the differential equations of heat transfer and the initial boundary conditions of the various layers of the system are given. Some heat transfer models for multi-layer thermal protective clothing under high temperature conditions.Then, the model is used to calculate the temperature distribution of each layer of fabric material, and the fitting function of the temperature and time finally obtained is fitted with the collected data to verify the reliability of the model.Finally, an improved model was used to predict the optimal solution of the layer II fabric at known temperatures, and the effect of air layer and fabric thickness on the protective performance of the protective clothing was analyzed.In question two, we use a single-index optimization model and a binary algorithm to find the optimal solution for the layer II fabric that satisfies the conditions. In question three, we used an optimization model with two indicators. The optimized particle swarm optimization algorithm is also called the particle swarm optimization algorithm or the flock foraging algorithm.Starting from the random solution, the optimal solution is found through iteration, and the quality of the solution is evaluated by fitness. In this way, the optimum thickness of the II and IV layers satisfying the conditions is obtained.The above operations are all done in MATLAB, the main code and source data are in the appendix.

Keywords

Heat transfer model , one-dimensional unsteady state , optimal soluti.

1. Introduction

In some special industries, such as fire protection and metal steelmaking, workers often work in high temperature environments. In this special environment, people need to wear special clothing to avoid burns. Special clothing is usually composed of three layers of fabric material, which are recorded as layers I, II and III. The layer I is in contact with the external environment. There is also a gap between the layer III and the skin. This space is recorded as the IV layer.

Questions raised:

In order to design special clothing, the dummy whose body temperature is controlled at 37℃ is placed in the high temperature environment of the laboratory to measure the temperature outside the skin of the dummy. At the same time, in order to reduce R&D costs and shorten the R&D cycle, it is necessary to establish a mathematical model to determine the temperature change outside the skin of the dummy and solve the following problems:

1. Experiment with the ambient temperature of 75℃, the thickness of the II layer of 6 ㎜, the thickness of the IV layer of 5 ㎜, and the working time of 90 minutes. The temperature outside the skin of the dummy was measured. Create a mathematical model, calculate the temperature distribution, and generate an Excel file of temperature distributions.

2. When the ambient temperature is 65℃ and the thickness of the IV layer is 5.5㎜, the optimum thickness of the II layer is determined. When the working temperature is 60 minutes, the outside temperature of the dummy's skin does not exceed 47℃, and the time exceeding 44℃ does not exceed 5 minutes.

3. When the ambient temperature is 80℃, determine the optimal thickness of the II and IV layers, and ensure that the outside temperature of the dummy does not exceed 47℃ and the time of more than 44℃ does not exceed 5 minutes when working for 30 minutes.

2. Organization of the Text

2.1 Problem analysis

2.1.1 Problem one analysis

Problem 1 requires the establishment of a mathematical model of the temperature change outside the skin of the dummy. This problem can be simplified as a study of the one-dimensional unsteady heat transfer model of the multilayer material. In addition, the simulation of the opposite heat source model can also be transformed into the study of the point heat source, ie the micro-element. After reviewing heat transfer and other related materials, we learned that the temperature transfer of the unsteady medium is closely related to the conduction distance, conduction time, specific heat, density, and thermal conductivity of air. Therefore, the key to solving the problem one is to determine the parameters related to the temperature change and the relationship between the temperature and the parameters, and establish a relationship model of the outside temperature of the dummy skin with respect to each parameter. In this way, the variation of the outside temperature of the dummy skin with respect to each parameter is analyzed, and the unknown parameters are determined according to the data obtained from the experiment in Annex 2.

2.1.2 Problem two analysis

The second problem is to determine the optimal thickness of the II layer when the ambient temperature is 65℃ and the thickness of the IV layer is 5.5㎜. When the working temperature is 60 minutes, the outside temperature of the dummy skin does not exceed 47℃, and the time exceeding 44℃ does not exceed 5 minutes. . Because the thicker the fabric material, the better the heat insulation effect is, the problem is naturally converted into a solution, so that when the work is 60 minutes, the outside temperature of the dummy skin does not exceed 47℃, and the layer II woven fabric exceeds 44℃ for less than 5 minutes. thickness of. We used a single-index optimization model to find the thickness of the layer II fabric that meets the conditional accuracy by a binary algorithm.

2.1.3 Problem three analysis

Problem 3 is similar to Problem 2, and it is also the problem of solving the optimal solution. It is to find the layer II when the ambient temperature is 80℃, when the working temperature is 30 minutes, the outside temperature of the dummy skin does not exceed 47℃, and the time exceeds 44℃ for 5 minutes. And the thickness of the IV layer. In this case, we use a two-index optimization model, which is also called particle swarm optimization algorithm or bird flocking algorithm by optimizing particle swarm optimization algorithm. Starting from the random solution, iteratively finds the optimal solution.

2.2 Symbol Description

Symbol	Meaning
C^{A}	Heat Capacity ($kJ \cdot m^{-3} \cdot K$)
T	Temperature (K)
c_p	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
ρ	density ($kJ \cdot m^{-3}$)
$F_L(x,\ t)$	Radiation to the left ($kJ \cdot m^{-2} \cdot s^{-1}$)
$F_R(x,\ t)$	Radiation to the left ($kJ \cdot m^{-2} \cdot s^{-1}$)
k	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
L	thickness(m)
β	Air expansion coefficient (K^{-1})
σ	Stephen Boltzmann constant ($5.670 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$)
ξ	Emissivity ($W \cdot s^{-1} \cdot m^{-2}$)
q	Heat flux density ($W \cdot m^{-2}$)
$h_{c,fl}$	Thermal convection coefficient between the external environment and fabric material I
$h_{c,\mathrm{I}\Lambda}$	Convective heat transfer coefficient of air conduction and natural convection
q_{conv}	Thermal convection density from the external environment to fabric material I
q_{rad}	Thermal radiation density from the external environment to fabric material I
$q_{\mathrm{IV},rad}$	*Thermal radiation density of the air layer*
t	*time*(s)
I, II, III, IV	*Fabric material I, II, III and air*
sum	*Fabric layer*
Nu	*Nutt number, value 1*
x	*Abscissa*
$skin$	*Dummy skin*

2.3 Problem hypothesis

- The fabric is isotropic;
- Heat transfer is carried out perpendicular to the skin, so it can be considered as one-dimensional;

- The structure of the fabric is almost constant during heat transfer, where the tortuosity coefficient is considered constant;
- The thickness of the air layer does not exceed 6.4 mm, and the effect of heat convection is small, so heat convection is not considered;
- Because it is a dummy, it ignores the thermophysiological regulation of the human body and considers all changes in temperature as the role of the material;
- System heat transfer only considers the heat transfer of heat radiation and heat conduction, ignoring the effects of water vapor and sweat, ie not considering wet transfer;
- The temperature distribution between the fabric layers, between the fabric and the air layer, and between the air layer and the skin is continuously variable, but the temperature gradient is hopping.

2.4 Model establishment and solution

2.4.1 The establishment and solution of the problem one model

At high temperatures, there are two main modes of heat transfer. One is heat transfer. Heat transfer occurs when there is a temperature difference between a medium or two media. This heat transfer is called heat transfer. The phenomenon of heat conduction does not involve the macroscopic migration of matter, also known as thermal diffusion, which is a property that describes the thermal conductivity of a material. The second is thermal radiation. Radiation is the way in which an object transmits energy through electromagnetic waves. Electromagnetic waves generated by heat are called thermal radiation. The total effect of transmitting energy and momentum between waves in the form of waves is called radiative heat transfer. Thermal convection is inevitable when heat radiation is generated, and thermal convection density is an important parameter reflecting the convection intensity.

It can be known from the hypothesis that the heat transfer problem of multi-layer woven fabric in problem one can be transformed into one-dimensional heat transfer problem for multi-layer unsteady medium, and heat conduction and heat radiation and heat convection need to be considered at the same time. We only consider the thermal radiation and thermal convection of the surface of the fabric I and the air, while the thermal radiation and thermal convection inside the fabric are neglected, so as to reduce the difficulty of solving the partial differential equation. Also, the adiabatic conditions between the I and II layers are ignored and the error is reduced.

The solution to the problem is to solve the three layers of fabric materials separately, and solve them one layer at a time, and use the result of the previous layer as the boundary condition of the latter layer. In this way, a solution function is obtained for each layer of woven material, and the temperature distribution of each layer is obtained.The established mathematical model is then verified by fitting the temperature-to-time relationship between the heat transfer of the three layers of woven and air layers to the collected data.

2.4.1.1 Establishment of Unsteady Heat Transfer Model of Multilayer Yarn

Based on the above assumptions, an unsteady heat transfer model of the multilayer fabric material is established. There are two main modes of heat transfer, one is the heat transfer between the fabrics, and the other is the thermal radiation and thermal convection on the surface of the I layer.

Solve the first layer as follows:

Fabric material I layer thermal conduction differential equation:

$$C_{\mathrm{I}}^{A}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_{\mathrm{I}}\frac{\partial T}{\partial x}),x\in(0,L_{\mathrm{I}}) \tag{5.1}$$

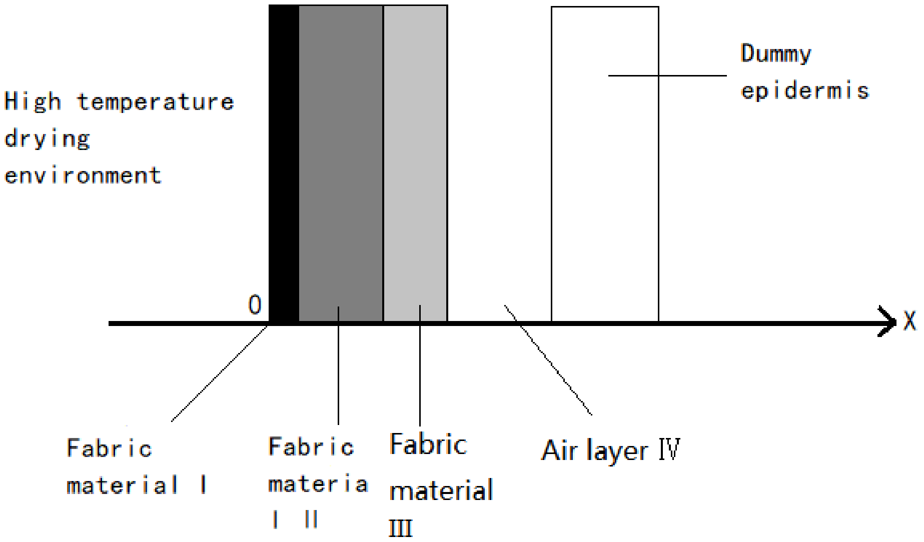

Fig. 1: ”Environment - Clothing - Human Body ”System Schematic

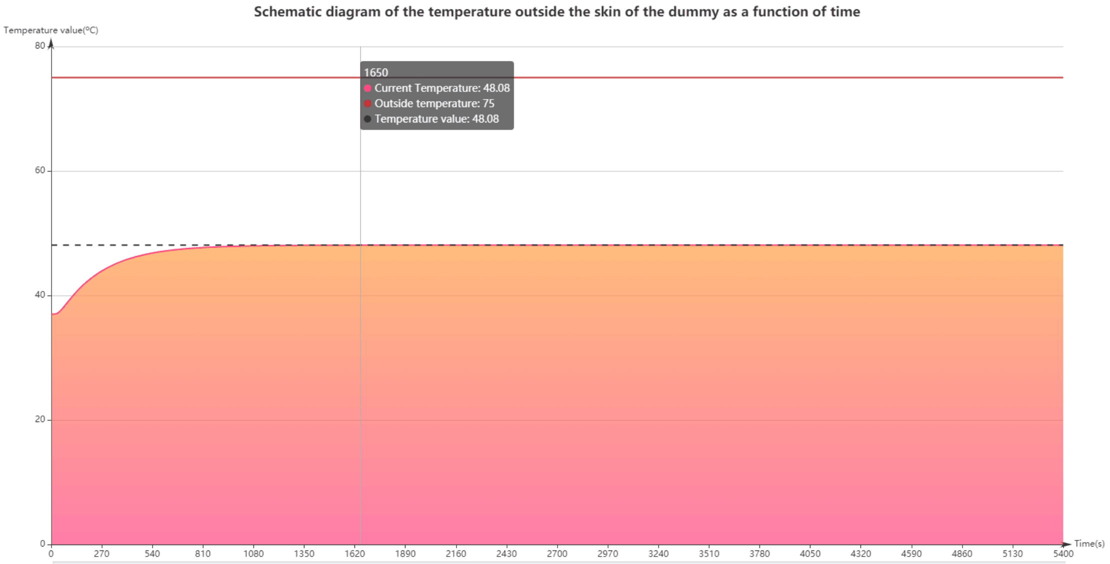

Fig. 2:Skin temperature versus time fit diagram

Initial conditions of the fabric layer:

$$T(x,0)=T_{\mathrm{I}}(x), x\in(0,L_{sum}) \tag{5.2}$$

Where TI(x) is a constant and satisfies:

$$T_{\mathrm{I}}(x)=\begin{cases} 26°C, x\in(0,L_{sum}) \\ 37°C, x\in(L_{sum},L_{sum}+L_{\mathrm{IV}}) \end{cases}$$

The boundary condition of the weave layer I is:

Related to heat flux density:

$$-k_{\mathrm{I}}\frac{\partial T}{\partial x}\Big|_{x=0}=\xi_{IV}\sigma(T_g^4-T^4(0,t))+h_{c,fl}(T_g-T(0,t))$$

Ignore the adiabatic conditions between layers I and II:

$$\frac{\partial T}{\partial x}\Big|_{x=\infty}=0$$

In the unsteady heat transfer model of multilayer fabrics, the sensible heat capacity method is used to describe the specific heat change of the fabric. The calculation formula of sensible heat capacity is:

$$C^A=\rho c_p$$

$$c_p=1300+1.6(T-300)$$

Solve the second layer as follows:

Fabric material II layer thermal conduction differential equation:

$$C^A_{\mathrm{II}}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_{\mathrm{II}}\frac{\partial T}{\partial x}),x\in(L_{\mathrm{I}},L_{\mathrm{I}}+L_{\mathrm{II}})$$

Solve the third layer as follows:

Fabric material III layer thermal conduction differential equation:

$$C^A_{\mathrm{III}}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_{\mathrm{III}}\frac{\partial T}{\partial x}),x\in(L_{\mathrm{I}}+L_{\mathrm{II}},L_{sum})$$

In the formula： L_{sum} is the total thickness of the fabric layer， C^A, C^A, C^A is the sensible heat capacity of I, II, III layers of woven fabric.

$$-k_{\mathrm{I}}\frac{\partial T}{\partial x}\Big|_{x=0}=(q_{conv}+q_{rad})\Big|_{x=0}=h_{c,fl}(T_g-T_{\mathrm{I}})$$

$$-k_{\mathrm{III}}\frac{\partial T}{\partial x}\Big|_{x=L_{sum}}=(q_{\mathrm{IV},rad}-k_{\mathrm{IV}}\frac{\partial T}{\partial x})\Big|_{x=L_{sum}}$$

The contact surface between the layers II and III of the fabric material meets:

$$T_{\mathrm{II}}\Big|_{x=L_{\mathrm{I}}+L_{\mathrm{II}}}=T_{\mathrm{III}}\Big|_{x=L_{\mathrm{I}}+L_{\mathrm{II}}}$$

$$-k_{\mathrm{III}}\frac{\partial T}{\partial x}\Big|_{x=L_{\mathrm{I}}+L_{\mathrm{II}}}=-k_{\mathrm{II}}\frac{\partial T}{\partial x}\Big|_{x=L_{\mathrm{I}}+L_{\mathrm{II}}}$$

The heat flux from the external environment to the radiation and convection of the fabric material in Equation (5.7) can be described as:

$$(q_{conv}+q_{rad})|_{x=0}=h_{c,fl}(T_g-T_{\mathrm{I}}|_{x=0})$$

The previous one is for the heat transfer model of the fabric. The following study of the heat transfer in the air is based on the assumption that the heat transfer model of the air layer can be obtained:

$$(\rho c_p)_{\mathrm{IV}}\frac{\partial T}{\partial x}=\frac{\partial}{\partial x}(k_{\mathrm{IV}}\frac{\partial T}{\partial x})-\frac{\partial q_{\mathrm{IV},rad}}{\partial x},x\in(L_{sum},L_{sum}+L_{\mathrm{IV}})$$

Due to the narrow thickness of the air layer, it can be regarded as a rectangular closed cavity. Taking advantage of the conduction/convection heat transfer principle in a limited space, considering the conduction/convection and fabric radiation in the air, it is assumed that the conduction of the air layer is steady state. Radiation can be seen as a surface phenomenon; therefore, the above air layer model can be decoupled into the following model:

$$-k_{\mathrm{IV}}\frac{\partial T_{\mathrm{IV}}}{\partial x}\Big|_{x=L_{sum}}=-k_{\mathrm{IV}}\frac{\partial T_{\mathrm{IV}}}{\partial x}\Big|_{x=L_{sum}+L_{\mathrm{IV}}}=h_{c,\mathrm{IV}}(T_{\mathrm{III}}\Big|_{x=L_{sum}}-T_{skin}\Big|_{x=L_{sum}+L_{\mathrm{IV}}})$$

$$q_{\mathrm{IV},rad}\Big|_{x=L_{sum}}=q_{\mathrm{IV},rad}\Big|_{x=L_{sum}+L_{\mathrm{IV}}}=\frac{\sigma(T^4_{\mathrm{III}}\Big|_{x=L_{sum}}-T^4_{skin}\Big|_{x=L_{sum}+L_{\mathrm{IV}}})}{\frac{1}{\varepsilon_{\mathrm{III}}}+\frac{1}{\varepsilon_{skin}}-1}$$

$$h_{c,\mathrm{I}\Lambda}=Nu\frac{k_{\mathrm{I}\Lambda}}{L_{\mathrm{I}\Lambda}}$$

In the formula：Nu is a Nusselt number,and Nu=1;

2.4.1.2 Solution of One-Dimensional Unsteady Heat Transfer Model of Multilayer Yarn

Solving the problem one:

Solving the first layer temperature distribution: Convert the fabric material I layer thermal conduction differential equation (5.1) into a standard form that conforms to the matlab PDE solver:

$$C_{\mathrm{I}}^{A}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_{\mathrm{I}}\frac{\partial T}{\partial x})+\frac{\partial F_L}{\partial x}-\frac{\partial F_R}{\partial x},x\in(0,L_{\mathrm{I}})$$

At the initial time t = 0, the solution components satisfy the initial conditions (5.2) for all x.At x=0, for all t, the boundary conditions for converting all into a solution component that meet the standard form are:

$$k_{\mathrm{I}}\frac{\partial T}{\partial x}\Big|_{x=0}+\xi_{\mathrm{IV}}\sigma(T_g^4-T^4(0,t))+h_{c,fl}(T_g-T(0,t))=0$$

Then, use the matlab PDE solver pdepe to solve the initial boundary values of the PDE equations using a spatial variable x and time t. It can be seen from Fig. 2 that the temperature tends to be stable around 1200s, so the temperature distribution of the position and time of the first layer from 0 to 1500s is as follows:

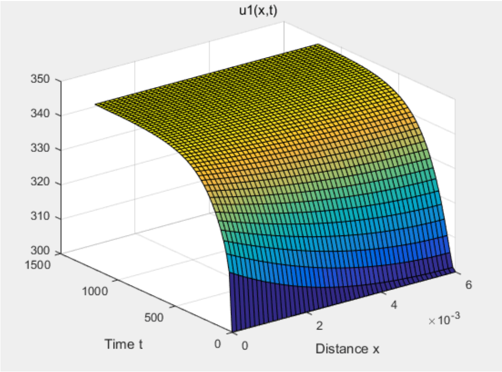

Fig. 3:Position time temperature distribution from 0 to 1500s

Time temperature profile from 0 to 1500s after cutting along x

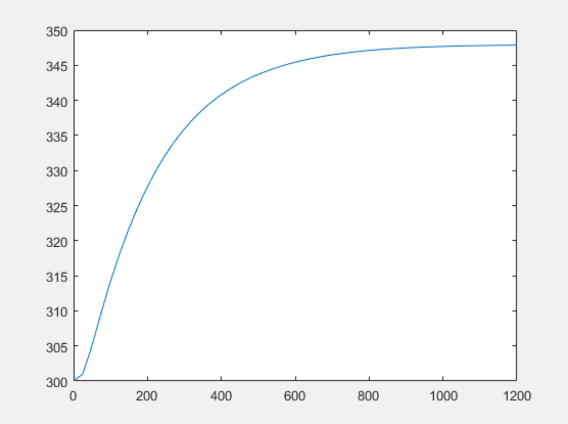

Fig.4:Time temperature distribution curve from 0 to 1500s

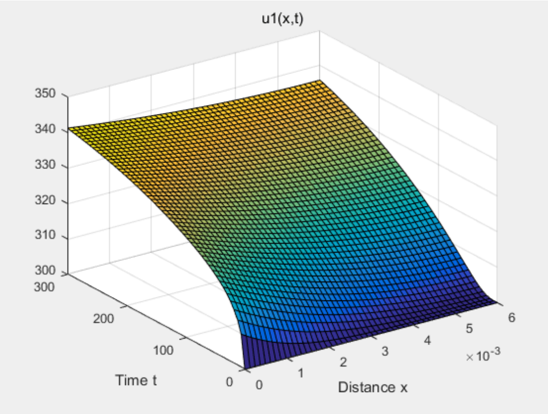

Fig. 5:Position and time temperature distribution from 0 to 300 s

At 0 to 300 s, the temperature changes greatly, so it is displayed separately: Time-temperature profile of 0 to 300 s after cutting along x

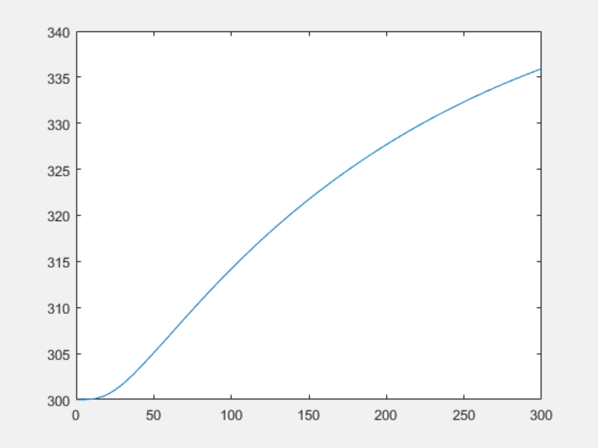

Fig. 6:Time temperature distribution curve from 0 to 300 s

Solve the fit graph as shown below:

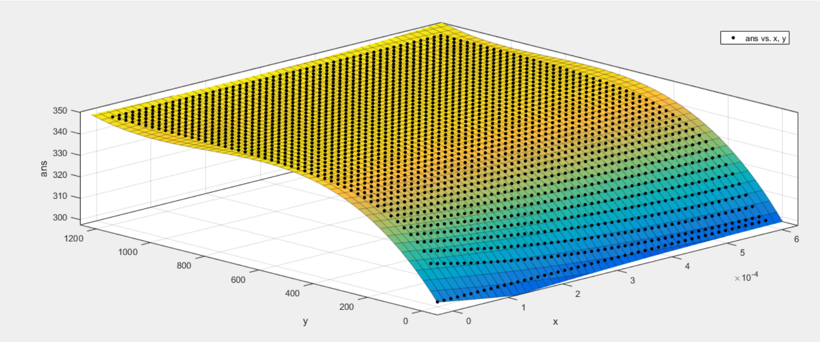

Fig. 7:"Environment - Clothing - Human Body" System Schematic

2.4.2 Establishment and Solution of Problem Two Single Index Optimization Model

The second problem is to determine the thickness of the II layer when the ambient temperature is 65℃ and the thickness of the IV layer is 5.5 ㎜, so that the outside temperature of the dummy's skin does not exceed 47℃ and the time exceeds 44℃ for less than 5 minutes. According to the idea of the first problem, the temperature distribution of each layer can be obtained, and the layer can be solved by the partial differential heat conduction equation to obtain the temperature distribution of the surface layer of the dummy. This problem is actually a question of data trial. The method we use is a dichotomy method for numerical experiments. First, select half of the range given by layer II to bring in the temperature distribution of the surface layer of the dummy. If the outside temperature of the dummy skin exceeds 47℃, If the time exceeds 44℃ for more than 5 minutes, it means that the thickness is too small, then the second half of the range given by the layer II is solved again by the dichotomy method until the accuracy of the problem is reached.

2.4.3 Establishment and Solution of the Problem Three-Double Index Optimization Model

This is a two-index optimization problem in order to find the optimal thickness of the II and IV layers that satisfy the conditions given in the question. We use the particle swarm optimization algorithm, also known as particle swarm optimization algorithm or Particle Swarm Optimization (PSO), which is a new evolutionary algorithm developed by J. Kennedy and RC Eberhart in recent years (Evolutionary Algorithm - EA). The PSO algorithm is a kind of evolutionary algorithm. It is similar to the simulated annealing algorithm. It also starts from the random solution and finds the optimal solution through iteration. It also evaluates the quality of the solution by fitness, but it is simpler than the rules of genetic algorithm. It does not have the "crossover" and "mutation" operations of the genetic algorithm, which seeks global optimality by following the current searched optimal values. This algorithm has attracted the attention of the academic community because of its advantages of easy implementation, high precision, and fast convergence, and it has demonstrated its superiority in solving practical problems. Particle swarm optimization is a parallel algorithm.

2.5 Page Numbers

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3. Model analysis and optimization

3.1 Analysis of the problem one model

In the one-dimensional unsteady heat transfer model of multi-layer woven fabric we established, in order to facilitate the calculation of the thermal differential partial differential equation, the thermal radiation and thermal convection inside the fabric are neglected, and the parameters are reduced to increase the error. And the three layers of fabric materials are solved separately, and solved layer by layer, so that the error accumulates at the boundary, and the error is increased again.

All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper. As show in Fig. 1 and Table 1, three scheme comparing.

References are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

3.2 Optimization of the problem one model

Considering the thermal radiation and thermal convection inside the fabric: the differential equation of the heat conduction of the fabric material I layer is:

$$C_{\mathrm{I}}^{A}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_{\mathrm{I}}\frac{\partial T}{\partial x})+\frac{\partial F_L}{\partial x}-\frac{\partial F_R}{\partial x},x\in(0,L_{\mathrm{I}})$$

The left heat radiation equation satisfies:

$$\frac{\partial F_L(x,t)}{\partial x}=\beta F_L(x,t)-\beta\sigma T^4(x,t),x\in(0,L_{\mathrm{I}})$$

The right heat radiation equation satisfies:

$$\frac{\partial F_R(x,t)}{\partial x} = \beta F_R(x,t) + \beta\sigma T^4(x,t), x \in (0, L_{\mathrm{I}})$$

Fabric material The contact surface between layer I and layer II meets:

$$T_{\mathrm{II}}|_{x=L_{\mathrm{I}}} = T_{\mathrm{I}}|_{x=L_{\mathrm{I}}}$$

$$-k_{\mathrm{II}} \frac{\partial T}{\partial x}\Big|_{x=L_{\mathrm{I}}} = -k_{\mathrm{I}} \frac{\partial T}{\partial x}\Big|_{x=L_{\mathrm{I}}}$$

$$(1-\xi_{\mathrm{II}})F_L(L_{\mathrm{I}},t) + \xi_{\mathrm{II}}\sigma T^4(L_{\mathrm{I}},t) = F_R(L_{\mathrm{I}},t)$$

The boundary conditions that are met at this time are:

$$(1-\xi_{\mathrm{I}})F_L(0,t) + \xi_{\mathrm{I}}\sigma T^4(0,t) = F_R(0,t)$$

References

[1] YanFeng Liu, ZhengYang Gao, XiuJun Liang, Heat transfer, Beijing,2015.

[2] Hao Liu, Jin Han, MATLAB R2016a completely self-study one pass , Beijing, 2016.

[3] HaiYang Liu, Getting started with LATEX,Beijing,2013