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Mathematical Model of Embedded Temperature Sensing Fabric Heat Transmission

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Abstract
In order to explore effect factors in the measurement of temperature sensing fabric, a heat transmission mathematical model of temperature sensing fabric was established. The concept of surface contact thermal resistance associated with the material thermal conductivity, fabric layer number and yarn linear density between the fabric and sensor was proposed in the model, whose surface contact thermal resistance was produced in the process of fabric heat transmission. Some test samples were woven to prove the rationality of the model. The results demonstrated that the value measured would be influenced by the performances of surface contact thermal resistance, which was consistent with the derivation of the theoretical model. The raw material, fabric layer number and yarn linear density of temperature sensing fabric had a great effect on the measurement value. The correlation coefficient reached more than 0.988 among the experimental and theoretical values, respectively, which proved that the heat transmission mathematical model of temperature sensing fabric could be applied in the research of this fabric.

Key words: *temperature sensing fabric, mathematical model, surface contact thermal resistance, testing system, temperature value.*

Nomenclature

Q - *heat flow*
R - *thermal resistance*
A - *area of heat transfer*
ρ - *density*
T_{skin} - *skin surface temperature*
v - *volume*
T_{inner} - *inner surface temperature*
s - *width*
R - *thermal resistance*
c - *specific heat capacity*
λ_h - *heat transfer coefficient*
λ - *thermal conductivity*
r_h - *thermal radiation coefficient*
T - *temperature value*
d_h *and* δ - *thickness*
j_F - *mass flux*
r - *distance*
ΔH_{vap} - *steam enthalpy*
t - *time*
m - *mass*
x - *distance*
q - *heat flux*
$Q(x)$ - *imported heat*
w - *quality of water vapor*
ΔT - *temperature change*
D - *water vapour diffusion coefficient*
L - *width of model*
τ - *bending ratio of fabric*
$E(i)$ - *ratio of elastic plastic fabric*
ε - *porosity of fabric*
h_j - *thermal conductivity coefficient*
K - *diffusion equilibrium constant*
a - *effective radius*
h - *distance*
H - *effective micro-hardness*
β_r - *radiation heat transmission*
P - *contact pressure coefficient*
$\Psi(\varepsilon)$ - *convergent rate*
n - *micro unit number*
k - *thermal conductivity*
τ - *bending ratio*

Introduction

The weave process, partial heat treatment process and fabric temperature measurement system of temperature sensing fabric were introduced in the first report in our team [1]. The factors of local heat treatment and raw material which effected the measurement values were discussed and some self-designed equipment was made to improve the precision and stability of temperature measurement in the temperature sensing fabric such as the partial heat treatment equipment and corresponding measurement device [2, 3]. But the specific heat transmission of temperature sensing fabric was not explored and there was not a strong theoretical basis to guide the fabric weave. Fabric heat transmission has been a major factor for functional temperature sensing fabric design. A hot plate or sweating manikin has been commonly used in the study of this fabric in heat transmission [4 - 6]. Although research of the fabric heat transmission process has been very significant, they were expensive, lacked some specific theory to guide the fabric weave, and there was not a very rigorous test criteria to analyse the fabric heat transmission process. Recently inverse problem research was applied to analyse the heat transmission of temperature sensing fabric [7, 8]. The best solution of the inverse problem research was established under knowledge of the fabric heat transfer law, finite difference method and golden section method of the inverse problem. However, it only stayed in its initial stage, lacked in-depth research, and also required systematic and further practicical research. Currently the models include the pure conducting heat model, the combination model of conducting heat and radiation, the combination model of heat and moisture resistance, the cylindrical ring system model, the two-dimensional dynamic heat transfer model between heat and moisture, the porous fabric model, the multi-media combining fabric model and so on [15 - 17]. But these models of heat transmission were not suitable for temperature sensing fabric research. Moreover the concept of surface contact resistance was not considered between two touching objects for heat transmission analysis of fabric in all models above.

In order to solve the problems mentioned above and make the measurement truly reflect the temperature of the human body surface, a mathematical model of embedded temperature sensing fabric heat transmission was established in this study. The factors which effected the measurement values, including the material thermal conductivity, fabric layer number and yarn linear density were discussed. In this paper, the heat transmission processes of temperature sensing fabric heat transmission were analysed

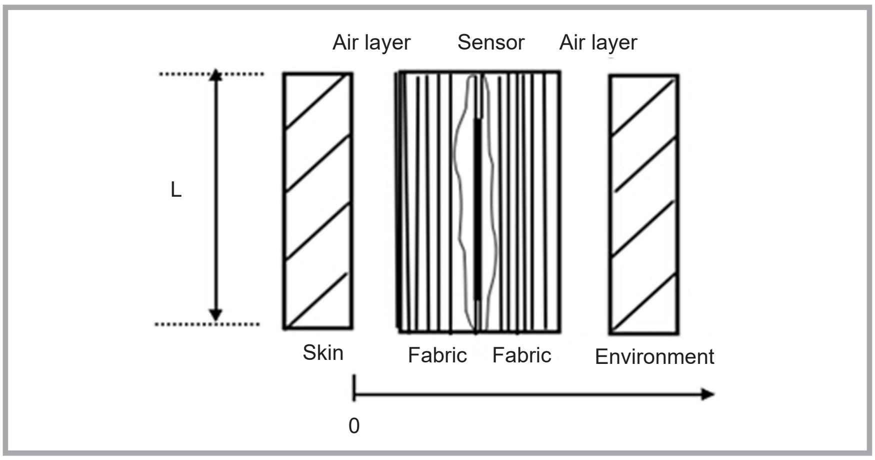


Figure 1. *Heat transfer structure diagram.* ***Note****: The sensor is located in the middle of fabric.*

on the basis of the cylindrical micro unit model and surface contact thermal resistance between two touching objects.

According to the actual application of this fabric in health care and monitoring, the temperature of skin is more than that of the external environment. Thus we can assume that the heat transmission processes were mainly from the body's skin to the external environment. The effect of surface contact thermal resistance between the fabric and small objects embedded was considered in the calculations of heat transmission. The surface contact thermal resistance had a great effect on the mathematical model of temperature sensing fabric heat transmission. The basic theoretical research would provide guidance for temperature sensing fabric.

Model of temperature sensing fabric simulation

First we analysed the process of heat transfer from the human skin to the external environment through the fabric. ***Figure 1*** shows a structure diagram of the temperature sensing fabric heat transmission. Heat was transferred from the human skin to the inner surface of the fabric and subsequently transferred from the outer surface of the fabric to the external environment. The conditions of the mathematical model of the temperature sensing fabric assumed are as follows:

1) The inner air in the microclimate is an ideal isotropic gas continuous medium, meeting the ideal gas equation. In a certain range, the pressure remains unchanged, and the distribution of pressure is even.
2) The heat transmission process is one-dimensional in the body, fabric and external environment and is stationary.
3) The main mode of thermal conduction includes thermal conduction and thermal radiation between the body and inner fabric; the main mode of thermal conduction includes thermal conduction between the upper and lower fabric, the main mode of thermal conduction - thermal convection, and thermal radiation between the outer fabric and external environment.
4) The surface contact thermal resistance was between the temperature sensor and inner surface or outer surface of the fabric. In terms of the whole fabric, the model of fabric constructed is divided into an infinite number of rectangular micro-units packed closely. The direction of heat transmission is along the thickness of the fabric from the skin of the body's surface to the outside environment. The micro temperature sensor is regarded as a micro unit in these micro units.
5) The surface temperature of the human skin and external environment both retain a constant average value in the range of a certain time. Furthermore a surface point of the skin is regarded as the coordinate origin.
6) The distance between the surface of the skin and the temperature sensor is x.
7) The diffusion of heat across a temperature gradient is from skin of body surface to outside environment.

In this paper, the heat transmission process was divided into three regions from the skin to the outside environment. The first region was from the human skin to the inner surface of the fabric, the second region - from the inner to outer surface of the fabric, and the third region was from the outer surface of the fabric to the outside environment.

Region 1. From the human skin to the inner surface of the fabric, the ways of heat transfer in this area included thermal conduction and thermal radiation. Then the heat transfer expression in this region [15] was obtained:

$$Q_1 = \frac{A(T_{skin} - T_{inner})}{R_{A1}} \tag{1}$$

In the equation, Q_1 represents the transmitted heat flow from the surface of the human skin to the inner surface of the temperature sensing fabric, A - the effective area of heat transfer, T_{skin} - the skin surface temperature of the human body, T_{inner} - the inner surface temperature of the fabric, and R_{A1} - the thermal resistance from the skin to the inner surface of the fabric during heat transmission. In the region, the thermal conduction and thermal radiation were the main ways of heat transmission. The thermal resistance R_{A1} could be represented as:

$$R_{A1} = \frac{1}{r_h + \frac{\lambda_h}{d_h}} \tag{2}$$

In the equation, λ_h represents the heat transfer coefficient from the human skin surface to the inner surface of the fabric [15], r_h - the thermal radiation coefficient from the human skin surface to the inner surface of the fabric, and d_h - the thickness from the human skin surface to the inner surface of the fabric.

Region 2. From the inner to outer surface of the fabric, the way of heat transfer in this area was thermal conduction. Thermal contact resistance existed between the micro fabric unit and temperature sensor [16, 17], assuming that the distance between the skin surface and temperature sensor was x. The fabric was divided into n micro units, with the temperature sensor regarded as one, assuming that the instantaneous temperature of the front micro unit of the fabric connected with the temperature sensor was T_1. The part of the fabric between the inner surface of the fabric and the temperature sensor was in accordance with the single flat wall model. The temperature of any parallel section between them was:

$$T_r = T_{inner} - (T_{inner}\ T_1)\frac{r}{\delta_1} \tag{3}$$

In the equation, δ_1 represents the thickness from the skin surface to the front micro unit of the fabric connected with the temperature sensor, *r* - the distance from any point between them to the inner surface of the fabric, and T_r is the temperature of any point.

The heat conservation law was applied to the heat transmission of the temperature sensor. The heat conservation law is expressed as follows: the imported heat is equal to the sum of the exported heat, internal energy increase and heat of water vapor vaporization.

Assuming that heat flowing into a micro unit of the temperature sensor was $Q_{(X)}$, then:

$$Q_{(X)} = -\lambda \frac{\partial T}{\partial x} A - \frac{\partial(\frac{\Delta T_1}{R_1})}{\partial x} = \\ = -\lambda L \frac{\partial T}{\partial x} x - \frac{\partial(\frac{\Delta T_1}{R_1})}{\partial x} \quad (4)$$

In a very short period of time *dt*, the heat flowing into a micro unit of the temperature sensor was $d_{Q_{(x)}}$ along the radial direction of the fabric. The heat flow expression was obtained as follows:

$$d_{Q_{(x)}} = -\lambda L^2 \frac{\partial T}{\partial x} xdt - \frac{\partial(\frac{\Delta T_1}{R_1})}{\partial x} xdt \quad (5)$$

In the equation, λ represents the specific heat capacity of materials, which includes a small part of the fabric temperature sensor micro unit and temperature sensor specific heat capacity, *T* the temperature sensor measurement value, *x* - the horizontal distance from the surface of the skin to a micro unit of the temperature sensor, ΔT_1 - the temperature change value of the temperature sensor when in contact with the front a micro unit of the fabric connected with the temperature sensor, R_1 - the touch thermal resistance between the micro unit of the temperature sensor and front micro unit of the fabric in contact with the temperature sensor, *L* - the width of the fabric taken only for system analysis, and *t* represents the elapsed time in which heat flows into the micro unit of the temperature sensor.

Because the micro-element body consists of two parts: a small portion of the fabric wrapped temperature sensor and the temperature sensor, the surface of the contact thermal resistance was composed of two parts. The equation of thermal resistance R_1 is as follows:

$$R_1 = R_{1S} + R_{1F} \quad (6)$$

In the equation, R_{1S} representd the thermal resistance between the other micro unit of the fabric and a small portion of the fabric wrapped temperature sensor in the process of touching, and R_{1F} - the thermal resistance between the other micro unit of the fabric and the micro unit of the temperature sensor.

According to numerous studies on the surface contact thermal resistance, it was found that the thermal properties, elastic-plastic, heat flow direction, surface hardness, surface shape, the value of the contact force and other factors were associated with the contact thermal resistance value. Furthermore a corresponding relationship existed between the surface contact thermal resistance and thermal conductivity. The theory of the surface contact thermal resistance was as follows [18, 19]:

$$\frac{1}{h_j} = \frac{\pi}{4} a(\frac{H}{P})[\frac{\psi_{(\varepsilon)}}{k_\alpha} + \frac{\psi_{(\varepsilon)}}{k_\beta}] \quad (7)$$

In the equation, h_j represents the thermal conductivity coefficient of the touching surfaces between the other micro unit of the fabric and the whole micro unit of the temperature sensor connected to each other, *a* - the effective radius between the other micro unit of the fabric and the whole micro unit of the temperature sensor connected to each other, *H* - the effective micro-hardness of the two contacting objects, *P* - the contact pressure between the other micro unit of the fabric and the whole micro unit of the temperature sensor connected to each other, $\Psi(\varepsilon)$ - the convergent rate of the contact point between the other micro unit of the fabric and the whole micro unit of the temperature sensor connected to each other, and k_α & k_β represent, respectively, the thermal conductivity of two objects in contact with each other. A relationship exists between the contact material convergent rate $\Psi(\varepsilon)$, material micro hardness *H* and contact pressure *P* [20].The equation was as follows:

$$\Psi(\varepsilon) = 0.76(\frac{P}{H})^{-0.027} \quad (8)$$

The relationship between the surface contact resistance *R* and thermal conductivity h_j was as follows:

$$R = \frac{\Delta T}{h_j} \quad (9)$$

Summing up ***Equations 6***, ***7***, ***8***, ***9*** and the temperature sensing fabric performance parameters, it shows that the touch thermal resistance R_1 between the micro unit of the fabric and the micro unit of the temperature sensor was related to the thermal conductivity h_j of the fabric yarn and temperature sensor material k(*i*), the ratio of elastic plastic fabric *E*(*i*), which was related to the convergent rate $\Psi(\varepsilon)$; the hardness *H*(*i*) and the shape of touching objects, and the fabric layer number, which was related to contact pressure, and so on.

In a very short period of time dt, the process of heat transmission has no internal heat. The exported heat equation of the whole micro unit of the temperature sensor $Q_{(x+dx)}$ is as follows:

$$d_{Q_{(x+dx)}} = Q_{(x+dx)}\, Ldt + \frac{\partial(\frac{\Delta T_2}{R_2})}{\partial x} xdt \quad (10)$$

T_2 represents the temperature value of the temperature sensor when it touches the back micro unit of fabric connected to each other, ΔT_2 - the temperature change value of the temperature sensor when it touches the back micro unit of fabric connected to each other, and R_2 represents the touch thermal resistance between the micro unit of the temperature sensor and the back micro unit of fabric connected with the temperature sensor. The equation of Q_{x+dx} is as follows:

$$Q_{x+dx} = Q_x + \frac{\partial Q_x}{\partial x} dx + \frac{\partial(\frac{\Delta T_2}{R_2})}{\partial x} xdt \\ = -\lambda Lx \frac{\partial T}{\partial x} + \frac{\partial(-\lambda Lx \frac{\partial T}{\partial x})}{\partial x} dx + \frac{\partial(\frac{\Delta T_2}{R_2})}{\partial x} xdt \\ = -\lambda Lx \frac{\partial T}{\partial x} - \lambda L \frac{\partial T}{\partial x} dx - \frac{\partial \lambda_{(x,t)}}{\partial x} Lx \frac{\partial T}{\partial x} dx \\ - \lambda x \frac{\partial^2 T}{\partial x^2} dx + \frac{\partial(\frac{\Delta T_2}{R_2})}{\partial x} xdt \quad (11)$$

According to the above ***Equations 10*** and ***11***, the expression $d_{Q_{x+dx}}$ was as follows:

$$d_{Q_{x+dx}} = -\lambda Lx \frac{\partial T}{\partial x} - \lambda L \frac{\partial T}{\partial x} dx \\ - \frac{\partial \lambda_{(x,t)}}{\partial x} Lx \frac{\partial T}{\partial x} dx + \frac{\partial(\frac{\Delta T_2}{R_2})}{\partial x} xdt \quad (12)$$

In the equation, $\lambda(x, t)$ represented the thermal conductivity, which was related to time (*t*) and distance (*x*).

In a very short period of time *dt*, the heat increase of the whole micro unit of the fabric temperature sensor could be divided into two parts: the heat increase of the temperature sensor and the heat increase of a small portion of the fabric wrapping the temperature sensor.

The whole micro unit of the fabric temperature sensor $d_{Q_{inner}}$ can be shown as below:

$$d_{Q_{inner}} = c\rho \frac{\partial \Delta T}{\partial x} dvdt = c\rho \frac{\partial \Delta T}{\partial x} sdxdt \quad (13)$$

$$= cm \frac{\partial \Delta T}{\partial x} dt = c_1 m_1 \frac{\partial \Delta T_1}{\partial x} dt + c_2 m_2 \frac{\partial \Delta T_2}{\partial x} dt$$

In the equation, represents the density of the temperature sensor micro unit, v - the volume of the temperature sensor micro unit, s - the width of the temperature sensor micro unit, c_1 & c_2 - the specific heat capacity of the temperature sensor and a small portion of the fabric wrapping the temperature sensor, respectively, and m_1 & m_2 represent the mass of the temperature sensor and a small portion of the fabric wrapping the temperature sensor, respectively [21, 22].

Heat loss exists during the heat transfer of the fabric. Partial heat was lost by evaporation through a small portion of the fabric wrapping the temperature sensor. The equation below is obtained:

$$d_q = j_F d_{H_{vap}} = j_F \Delta H_{vap} dx \quad (14)$$

In the equation, j_F represents the mass flux through the temperature sensor micro unit, ΔH_{vap} - steam enthalpy through the temperature sensor micro unit, and q represents the evaporation heat through the temperature sensor micro unit. According to the mass diffusion theory and other relevant knowledge [23, 24], equation j_F can be written as:

$$j_F = -D_1 \frac{dw}{dx} \quad (15)$$

In the equation, D_1 represents the combination of the water vapour diffusion coefficient of the temperature sensor micro unit and that of a small portion of the fabric wrapping the temperature sensor, and w - the quality of the water vapour micro unit.

According to the diffusion theory of an object [25], the equation for D_1 can be obtained:

$$D_1 = (D_2 \frac{\varepsilon}{\tau} + KD_3) \quad (16)$$

$$D_1 \frac{d^2 w}{dx^2} = 0 \quad (17)$$

In the equation, D_2 represents the diffusion coefficient of water vapour, D_3 - the diffusion coefficient of the fabric surface, K - the diffusion equilibrium constant, w - the mass fraction of water vapor, ε - the porosity of the fabric, and τ represents the bending ratio of the fabric.

$$c_1\rho_1 Ls \frac{\partial T_1}{\partial x} + c_2\rho_2 Ls \frac{\partial T_2}{\partial x} - j_F \Delta H_{vap} + \frac{\partial(\frac{\Delta T_1}{R_1})}{\partial x} + \frac{\partial(\frac{\Delta T_2}{R_2})}{\partial x} x$$
$$= L\lambda x \frac{\partial T}{\partial x} + \lambda L(1-L)\frac{\partial T}{\partial x} + L\frac{\partial \lambda(x,t)}{\partial x} x \frac{\partial T}{\partial x} + L\lambda x \frac{\partial^2 T}{\partial x^2} \quad (19)$$

Equation 19.

The heat conservation law was introduced in the analysis of heat transmission of the temperature sensor. The heat conservation law can be expressed as follows: the imported heat $d_{Q(x)}$ = the exported heat $d_{Q_{x+dx}}$ + the internal energy increase $d_{Q_{inner}}$ + the heat of water vapour vaporisation d_q.

$$d_{Q(x)} = d_{Q_{x+dx}} + d_{Q_{inner}} + d_q \quad (18)$$

The above ***Equations 11***, ***13***, ***14***, ***15*** respectively was introduced into the ***Equation 18***, the following ***Equation 19*** could be obtained and analyzed.

In ***Equation 19***, the parameters c, s & L were all constant, and variables ρ, j_F, ΔH_{vap}, R_1, R_2 & λ all had a corresponding relationship with the distance (x) and time (t). Partial differential ***Equation 19*** could be established from the temperature T, time (t) and axis (x).

The fabric between the outer surface of the fabric and the temperature sensor could be regarded as a single flat wall model. The temperature of any parallel section between them was:

$$\mathrm{T_h} = \mathrm{T_2} - (\mathrm{T_2} - \mathrm{T_{out}}) \frac{h}{\delta_2} \quad (20)$$

In the ***Equation 20***, δ_2 represents the thickness from the back micro unit of fabric connected to the temperature sensor to the outer surface of the fabric, h - the distance from any point between them to the back micro unit of fabric connected to the temperature sensor, and T_h represents the temperature of any point.

Region 3. From the outer surface of the fabric to the external environment, the ways of heat transmission in this area were thermal convection and thermal radiation. The heat transmission equation is as follows:

$$Q_2 = \frac{A(T_{out} - T_{environment})}{R_{A2}} \quad (21)$$

In the ***Equation 21***, Q_2 represents the heat transmission from the outer surface of the fabric to the external environment, T_{out} - the outer surface temperature of the fabric, $T_{environment}$ - the temperature of the outside environment, and R_{A2} - the touch thermal resistance between the outer surface of the fabric and the outside environment. The expression R_{A2} is related to the heat radiation coefficient and heat convection coefficient, which is expressed as follows:

$$R_{A2} = \frac{1}{\beta_r + \beta_c} \quad (22)$$

In the equation, β_r represents the radiation heat transmission coefficient, and β_c the convective heat transfer coefficient.

The generalization of the formulas in the temperature sensing fabric mathematical model of heat transmission.

The above equation could be applied to describe the commonly established mathematical model of the temperature sensing fabric. The essential problem of heat transmission was to solve the partial differential equations. To get specific temperature values, some additional conditions must be given. Initial and boundary conditions must be obtained for analysis of specific heat transmission problems. The most complete mathematical description of the specific heat problems is as below [26, 27].

1) Initial conditions:
In the initial time, the temperature of human skin was T_{skin}; the ambient temperature was $T_{environment}$.

2) Boundary conditions:
According to the assumptions above, the fabric was divided into (n - 1) micro units, and the temperature sensor was embedded in the fabric, whose distance to the human skin was x in the vertical direction. The boundary conditions could be divided into two cases: the inner boundary conditions and the outer boundary conditions.

The inner boundary conditions of temperature sensing fabric:

$$-\lambda x \frac{\partial T}{\partial x} + c_1\rho_1 \frac{dv}{A} \frac{\partial T}{\partial t} = \quad (23)$$
$$= q_{\text{thermal conduction}} + \mathrm{q}_{\text{thermal radiation}}$$

The outer boundary conditions of temperature sensing fabric:

$$-\lambda x\frac{\partial T}{\partial x}+c_n\rho_n\frac{dv}{A}\frac{\partial T}{\partial t}= \tag{24}$$
$$=q_{\text{thermal convection}}+q_{\text{thermal radiation}}$$

The conditions of the inner and outer boundary could be transformed using the relationship between the thermal resistance and heat transfer:

$$q_{inner}=\frac{\Delta T}{R_{air1}}=\frac{T_{skin}-T_{inner}}{R_{air1}} \tag{25}$$

$$q_{out}=\frac{\Delta T}{R_{air2}}=\frac{T_{out}-T_{environment}}{R_{air2}} \tag{26}$$

In the ***Equations 25*** & ***26***, q_{inner} represents the true heat from the skin surface to the inner surface of the fabric, T_{skin} - the temperature value of human skin, T_{inner} - the temperature value of the inner surface of the fabric, R_{air1} - the thermal resistance between human skin and the inner surface of the fabric, T_{out} - the temperature value of the outer surface of the fabric, $T_{environment}$ - the external environment temperature value, and R_{air2} represents the thermal resistance between the outer surface of the fabric and the external environment.

Equations 25 & ***26*** were introduced into ***Equations 23*** & ***24*** and the equation of the inner and outer boundary are as follows:

$$-\lambda x\frac{\partial T}{\partial x}+c_1\rho_1Ls\frac{dx}{A}\frac{\partial T}{\partial t}= \tag{27}$$
$$=\frac{T_{inner}-T_{environment}}{R_{fab}}$$

$$-\lambda x\frac{\partial T}{\partial x}+c_n\rho_nLs\frac{dx}{A}\frac{\partial T}{\partial t}=$$
$$=\frac{T_{inner}-T_{environment}}{R_{fab}} \tag{28}$$

In the end, the complete mathematical model of the embedded temperature sensing fabric heat transmission is as follows:

$$\begin{cases} Q_1=\dfrac{A(T_{skin}-T_{inner})}{R_{A1}} \\[2ex] \mathrm{T_r}=\mathrm{T_{inner}}-(\mathrm{T_{inner}}-\mathrm{T_1})\dfrac{\mathrm{r}}{\delta_1} \\[2ex] c_1\rho_1 sL\dfrac{\partial T_1}{\partial x}+c_2\rho_2 sL\dfrac{\partial T_2}{\partial x}-j_F\Delta H_{vap}+\dfrac{\partial(\frac{\Delta T_1}{R_1})}{\partial x}+\dfrac{\partial(\frac{\Delta T_2}{R_2})}{\partial x}x \\ =L\lambda x\dfrac{\partial T}{\partial x}+\lambda L(1-L)\dfrac{\partial T}{\partial x}+L\dfrac{\partial\lambda(x,t)}{\partial x}x\dfrac{\partial T}{\partial x}+L\lambda x\dfrac{\partial^2 T}{\partial x^2} \\[2ex] \mathrm{T_h}=\mathrm{T_2}-(\mathrm{T_2}-\mathrm{T_{out}})\dfrac{\mathrm{h}}{\delta_2} \\[2ex] Q_2=\dfrac{A(T_{out}-T_{environment})}{R_{A2}} \end{cases} \tag{29}$$

Summing up ***Equations 27, 28*** & ***29***, a complete description of the temperature sensing fabric could be formulated in the end. If some parameters give specified values, we can calculate the theoretical the temperature value of the body's surface. From ***Equations 29*** we can see that the raw material, fabric layer number and yarn linear density of the temperature sensing fabric, whose parameters are related to the material thermal conductivity, elasticity, density, porosity, bending and contact interface pressure between the fabric and sensor, greatly affected the measurement value.

Experimental

In order to study the effects of the temperature sensing fabric performances on the temperature detected, cotton yarn and polyester yarn were selected as raw material of the fabric weave, and the different thicknesses of the temperature sensing fabric were woven. In the study, the fabric performances which affected the measurement were investigated using the temperature sensing fabric model. ***Table 1*** shows the physical properties of some temperature sensing fabrics. The temperature measurement system included a circuit system and simulation temperature device. The temperature measurement equipment included an amplifier circuit, data acquisition card, a constant temperature vessel (copper heat sink fixed on a small cube), a computer, and so on. The principle of the test was that when the temperature of the fabric sensing changed, its resistance varied. The change signal would be collected by the computer.

Results and discussion

Effect of raw material on the values of temperature sensing fabric measured

Yarn of cotton, polyester, ramine and acrylic were selected as raw material of the fabric weave. ***Table 2*** shows the relevant parameters of some temperature sensing fabrics. The difference values between the sample measurement value and actual temperature value were compared, the results of which are shown in ***Figure 2***. The influence of the raw material on temperature measurement precision and stability was investigated by comparing No. 1 to No. 4. The sequential order was close to the degree of the true value: No. 4 > No. 3 > No. 2 > No. 1. The maximum measurement difference value reached 57.1%, the main reasons for which could be attributed to the following:

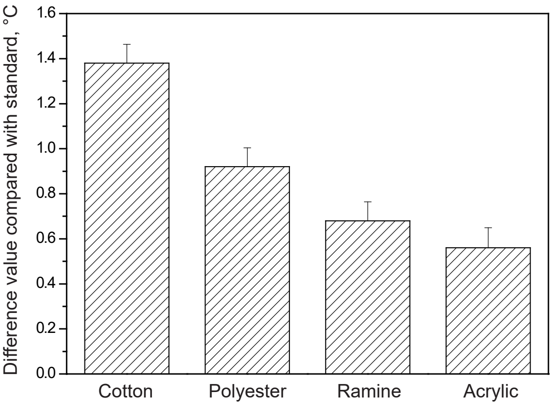
1). When the material thermal conductivity coefficient became larger, heat transmission through the fibrous products became more. In a short time, the more heat the fibrous products had,

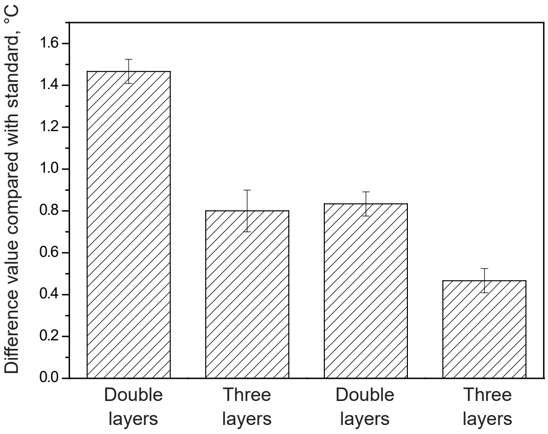
Table 1. *The physical properties of the fabric.*

Proporeties of fabric	Cotton	Ployeseter	Ramine	Acrylic
Fiber densityρ,kg/m^3	1350	1220	1550	1170
Fabric thermal conductivity K, mW/mk	29.45+27W	40.4+23W	50.2+21W	59.8+23W
Fabric volumetric heat capacity,C_p,J/kg K	1380	1255	1350	1510
Fabric tortuosity,	2.21±0.05	1.5±0.08	2.01±0.08	2.23±0.07
Fabric porosity	0.591±0.02	0.707±0.03	0.683±0.06	0.436±0.03
Fiber elastic recovery ratio in 1% elongation ε,%	91	98	60	92

Table 2. *The fabric yarns and related parameters.*

Sample number	Warp material	Thickness, mm	Warp and weft density, number/10 cm warp × weft	Multi-layered fabric organizational structure and layers
No. 1	36 tex cotton	1.63	291 × 256	plain (double layers)
No. 2	36 tex polyester	1.63	291 × 257	
No. 3	36 tex ramine	1.64	290 × 256	
No. 4	36 tex acrylic	1.61	291 × 257	
No. 5	30 tex cotton	1.19	290 × 253	
No. 6	20 tex cotton	1.09	293 × 257	
No. 7	16 tex cotton	1.06	298 × 251	
No. 8	36 tex cotton	2.12	298 × 254	plain (three layers)
No. 9	36 tex acrylic	2.04	297 × 252	





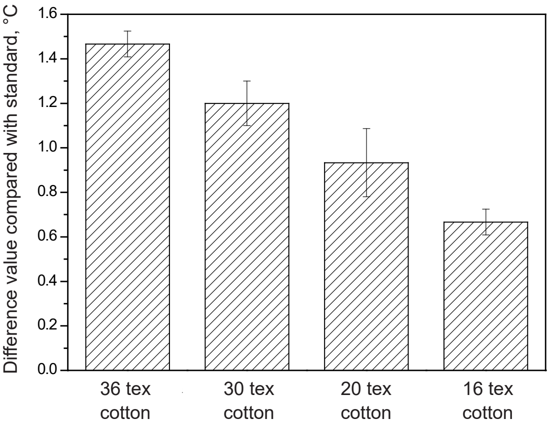


Figure 2. *Effect of raw material on fabric values measured.*

Figure 3. *Effect of fabric thickness on fabric values measured.*

Figure 4. *Effect of yarn linear density on fabric values measured.*

the higher the temperature was. Hence the results were closer to the true value.

2). When the raw materials of the fabric were different, the material's elastic-plastic was different, which led the surface touching shape of the two objects to be different, which, in turn, made the thermal contact resistance also change. However the heat transmission efficiency was closely related to the thermal contact resistance. In the model, the specific heat capacity c_1& c_2, the material density ρ_1 & ρ_2, and the thermal conductivity coefficient λ influenced the efficiency of heat transmission. And these factors were reflected in the mathematical model of the embedded temperature sensing fabric.

Effect of fabric thickness on the values of temperature sensing fabric measured

The effect of fabric thickness on temperature measurement precision was investigated by comparing No. 1 & No. 8 and No. 4 & No. 9. As can be seen from ***Figure 3***, the measurement values of No. 8 and No. 9 were more accurate than those of No. 1 and No. 4 comparing with the actual value, and the maximum difference of measurement results reached 45.6%. The main reasons for which can be attributed to the following: The efficiency of heat transmission varied with changes in fabric thickness, and therefore the measurement values changed as compared with the true values. In the model, the thermal resistance R was different when the touch pressure P changed between the two objects, which influenced the efficiency of heat transmission. Moreover these factors were reflected in the mathematical model of the embedded temperature sensing fabric.

Effect of yarn linear density on the values of temperature sensing fabric measured

The effect of yarn linear density on temperature measurement precision was investigated by comparing No. 1 & No. 5 and No. 6 & No. 7. As can be seen form ***Figure 4***, the measurement value of No. 7 was more accurate than those of the other samples comparing with the actual values, and the maximum difference of measurement results reached 54.7%. The main reasons can be attributed to the following:

1) The linear density of the yarn affected the density of the yarn assembly. When the other conditions were the same, the smaller the yarn linear density, the greater the density of the fabric. When the material density was larger than 0.4 $g{\cdot}cm^{-3}$, the material thermal conductivity increased along with the material density. However, the density of fabric was more than 0.4 $g{\cdot}cm^{-3}$, and hence when the thermal conductivity of the fabric's raw material was greater, the measurement value of the temperature sensing fabric was closer to its real value for the testing temperature;
2) The greater the density of the fabric, the better the sensor was covered, which could also shorten the time to reach a stable value. It made the measurement value closer to the body temperature value. In the model, the yarn linear density was different and hence porosity and curvature of the fabric

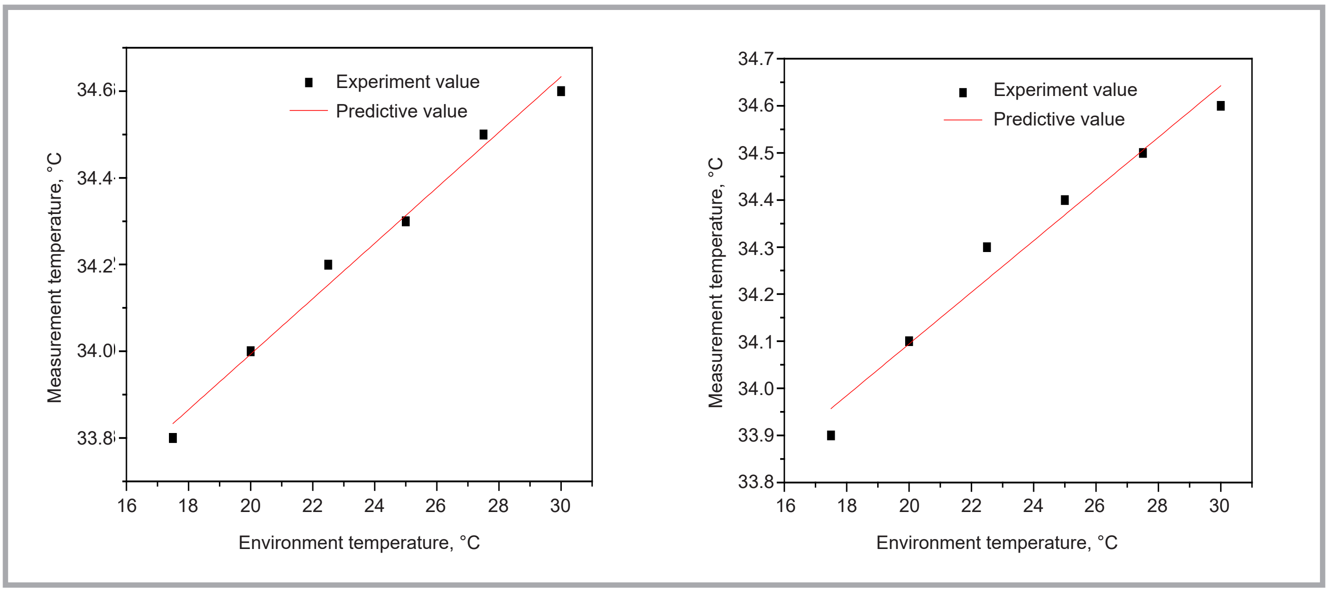


Figure 5. *Comparisoin of experimental and theoretical values.*

were different. All these factors affected the surface contact resistance of the two contacting substances and the heat transmission efficiency. These factors were reflected in the mathematical model of the embedded temperature sensing fabric.

Comparison of the experimental and theoretical values

Through the mathematical model of embedded temperature sensing fabric heat transmission above, the relationship between the measurement temperature of the temperature sensing fabric and the external temperature is linear. Some samples were measured to verify the error of the model. As can be seen form ***Figure 5***, the correlation coefficient reached more than 0.988 between the experimental and theoretical values, illustrating that the correlation was highly satisfactory between them.

Summary and conclusions

In the study a heat transfer mathematical model was established. The model included the whole heat transmission process from the human skin to the outside environment. We established the physical structure of the model for the temperature of the fabric. The effects of raw material, yarn linear density and fabric thickness on temperature measurement precision were investigated. The maximum difference in the measurement results reached 57.1%, 54.7% and 45.6%, respectively. The degree of fit was over 98.8% between measurement and theoretical values. This showed the following parameters: the material thermal conductivity, elasticity, density, porosity of the fabric, bending ratio and pressure in touching the interface affected temperature measurement values. The inference was consistent with the mathematical model of embedded temperature sensing fabric heat transmission.

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