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Simplified Model for Predicting Fabric Thermal Resistance According to its Microstructural Parameters

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Abstract
This paper presents a modified model to calculate the thermal resistance of woven and knitted fabrics according to the microstructural parameters. The model was established by analysing the heat transfer process in the simplified basic unit of the fabrics. The model was modified and checked by experimental values of various fabric samples. Pearson correlation coefficients between the thermal resistance and fabric structural parameters were calculated. Results indicate that fabric thermal resistance can be predicted by the modified equation satisfactorily. The Pearson correlation coefficient from high to low follows such a sequence: fabric thickness, fabric volume density, fabric structural parameter a, fibre volume density, and fibre thermal conductivity.

Key words: *fabric model, thermal resistance, microstructure, correlation coefficient.*

Introduction

Fabric thermal resistance has an important influence on clothing comfort [1], which impacts the health of human beings [2 - 4]. Thermal resistance indicates the ability of a fabric to inhibit heat flow transferred through it. Heat transfer can occur by several mechanisms: free and forced convection, conduction through solid fibres, conduction through the air in inter-fibre spaces, and radiation [5]. The exact quantities of the above three heat transfer proportions vary with a change in the fabric microstructure, which depends on the fibre structure, yarn structure and fabric construction [6]. It is meaningful to establish a mathematic model to estimate fabric thermal resistance according to its structure and components [7], thus fabrics can be chosen more correctly for certain clothing to get the thermal comfort desired.

During the past several decades, many researchers have endeavoured to work on this in theory and experiments [8 - 13]. Martin and George [14] studied the effect of fibre structural parameters on the thermal conductivity of nonwovens, and results indicate that thermal conductivity decreases if the nonwoven is compressed, made with finer fibres or has a reflective coating on the fibre surface. However, the study did not provide a numerical relationship between thermal conductivity and the nonwoven fabric structure. Bandyopadhyay *et al* [15] reported results demonstrating that the thickness is the most important factor in determining the thermal resistance of textile materials and that there exists a linear relationship between these two parameters. Bankvall [16] investigated the mechanisms of heat transfer in fibrous insulations and presented equations for calculating thermal conductivities according to fabric structural parameters; but did not present testing methods for the key fabric structural parameters. Alibi *et al*. [17] investigated the modelling of thermal conductivity of knitted fabrics made from cotton, viscose and lycra fibres using an Artificial Neural Network (ANN). Knitted fabric structure type, yarn count, yarn composition, gauge, lycra proportion in %, lycra yarn linear density, fabric thickness, loop length and fabric areal density were used as input parameters for the ANN model. However, the application of this model is restricted to stretch knitted cotton viscose fabrics. Kou *et al*. [18] presented a fractal model of the effective thermal conductivity of porous media; but this model is based on the pore fractal dimension D_f, tortuosity fractal dimension D_t, and porosity Φ, which are not easy to be measured. Mangat et al. [19] presented a model for predicting the thermal resistance of denim fabric. The simulations agree with actual values well and the paper focuses on the prediction of thermal resistance at different moisture levels.

The novelty of this paper lies in the presentation of a simplified fabric structural model in a heat transfer field. A theoretical equation for calculating fabric thermal resistance was derived from the model. The thermal resistances predicted agree with experimental values satisfactorily. The point to highlight is that all the microstructural parameters used in this model have definite physical meanings and can be tested easily. The purpose of this paper is to introduce the establishment and modification process of the theoretical equation.

Establishment of the theoretical equation

Fabrics can be different in many aspects, such as fibre type, yarn type, yarn number, twist, fabric weaves, fabric count, patterns, etc. What are the main factors that influence thermal resistance? In other words, how to calculate fabric thermal resistance according to its structural parameters? In fact, no matter what kind of fabric it is, for the fabric in the heat transfer field, its basic unit can be divided into three parts: part I is composed of solid fibres, part II - the porosity vertical to the heat flow direction, and part III

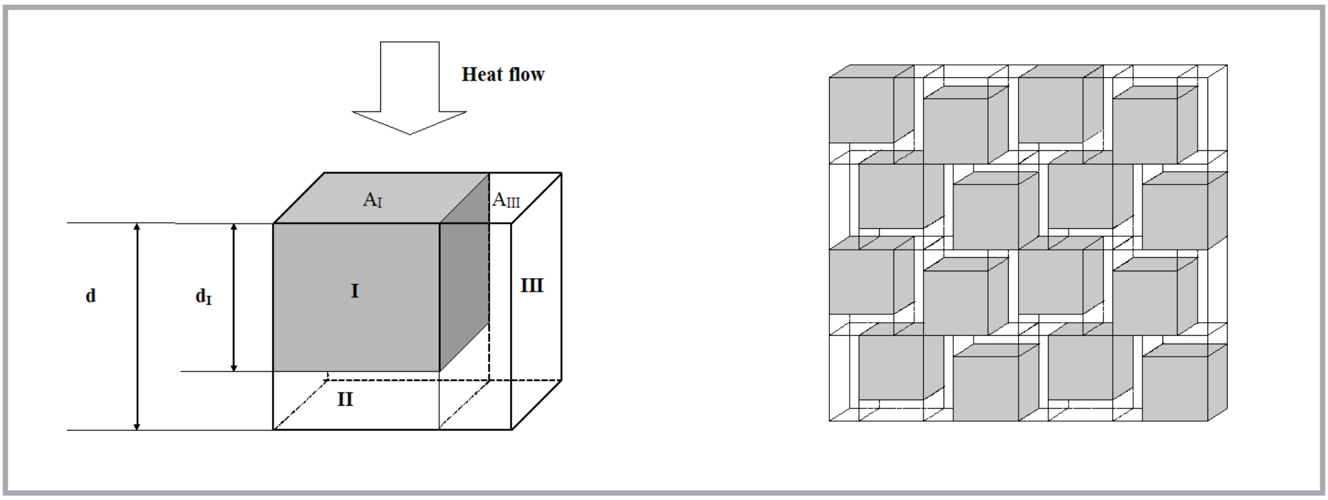

Figure 1. Simplified microstructure of the fabric; a) illustration of the basic unit, b) illustration of the fabric structure.

is the porosity parallel to the heat flow direction, as shown as ***Figure 1***. Fabric thermal resistance depends largely on the heat transfer process in the basic unit.

As shown in ***Figure 1.a)***, the heat transfer area and thermal resistance of the three parts are A_I, A_{II}, A_{III} and R_I, R_{II} & R_{III}, respectively. The thickness of part I is d_I in m, the volume density of the fabric - ρ_{fabric} in kg/m^3, the volume density of the fibre ρ_{fibre} in kg/m^3, the thermal conductivity of the fibre λ_{fibre} in W/(m·K), and the thermal conductivity of the porosity is λ_{air} in W/(m·K). The thermal resistance of the basic unit is R in m^2·K/W. The temperature difference between two sides of the basic unit is Δt in K, the thickness of the fabric D in m, and the thermal resistance is R_{fabric} in m^2·K/W.

Heat flow in the basic unit shown in ***Figure 1*** is as follows

$$Q = Q_{I\text{-}II} + Q_{III} \qquad (1)$$

According to the relationship between the heat flow and thermal resistance, ***Eqation 1*** can be written as follows

$$\frac{(A_I + A_{III})\Delta t}{R} = \frac{A_I \Delta t}{R_I + R_{II}} + \frac{A_{III}\Delta t}{R_{III}} \qquad (2)$$

The relationship between thermal resistance and thermal conductivity is as follows:

$$R = d/\lambda \qquad (3)$$

Thus, ***Equation 2*** becomes:

$$\frac{A_I + A_{III}}{R} = \frac{A_I}{\frac{d_I}{\lambda_{fiber}} + \frac{d - d_I}{\lambda_{air}}} + \frac{A_{III}}{\frac{d}{\lambda_{air}}} \qquad (4)$$

The mass of the basic unit is equal to that of part I, hence we have the following relationship.

$$(A_I + A_{III}) d \rho_{fabric} = A_I d_I \rho_{fibre} \qquad (5)$$

According to ***Equation 5***, ***Equation 4*** can be written:

$$\frac{1}{R} = \frac{\lambda_{air}}{d_{I-1}\rho_{fiber}}\left[\frac{\lambda_{fiber}\rho_{fabric}}{\lambda_{fiber} - \frac{d_{I-1}}{d}(\lambda_{fiber} - \lambda_{air})} + \frac{d_{I-1}}{d}\rho_{fiber} - \rho_{fabric}\right] \qquad (6)$$

Structural parameter *a is* defined as

$$a = d_{I\text{-}I}/d \qquad (7)$$

Substituting ***Equation 7*** into ***Equation 6***, we obtain the equation for calculating the thermal resistance of the basic unit as follows

$$R = \frac{d}{\lambda_{air}}\left[\frac{\lambda_{fiber} - a(\lambda_{fiber} - \lambda_{air})}{\lambda_{fiber} - (\lambda_{fiber} - \lambda_{air})(a - \frac{\rho_{fabric}}{\rho_{fiber}})}\right] \qquad (8)$$

To calculate the thermal resistance of the fabric, some assumptions are necessary. Suppose that the fabric is composed of a series of units that has the same structural parameters, just as shown in ***Figure 1.b)***, then we obtain the following relationships

$$D = nd \qquad (9)$$

$$R_{fabric} = nR \qquad (10)$$

Substituting ***Equation 8*** and ***Equation 9*** into ***Equation 10***, we obtain the thermal resistance of the woven and knitted fabrics as follows

$$R_{fabric} = \frac{D}{\lambda_{air}}\left[\frac{\lambda_{fiber} - a(\lambda_{fiber} - \lambda_{air})}{\lambda_{fiber} - (\lambda_{fiber} - \lambda_{air})(a - \frac{\rho_{fabric}}{\rho_{fiber}})}\right] \qquad (11)$$

Experimental details

Materials

Woven and knitted fabrics of cotton, ramie, wool and polyester were used. Cotton fabrics were provided by Changzhou Xilaiwei Textile Technology Company in China. Ramie fabrics were provided by Suzhou Xinsheng Textile and Garment Company in China. Wool fabrics were provided by the Second Woolen Mill of Chifeng in China. Polyester fabrics were provided by Wujiang Huacheng Textile Company in China.

Fabric thickness test

Fabric thickness D was tested by a YG141L thickness instrument, which was produced by Laizhou Electron Instrument Co. LTD. (China); the diameter of the presser is 50.48×10^{-6} m^2; the pressure on the presser was chosen according to fabric thickness test standard GB/T3820. The press time was 30 seconds, and every physical parameter were tested three times to get the mean value.

Fabric structural parameter test

The compressed fabric thickness $D_{compressed}$ was tested by the YG141L thickness instrument, where the pressure exerted on the presser was 1000 cN. Fabric structural parameter *a* is calculated according to ***Equation 12***.

$$a = \frac{d_I}{d} = \frac{D_{compressed}}{D} \qquad (12)$$

Fabric volume density test

Square fabrics of precisely 0.04 m^2 were cut and weighted to calculate their volume densities according to ***Equation 13***

$$\rho_{fabric} = \frac{M}{A \cdot D} \quad (13)$$

ρ_{fabric} - fabric volume density in kg/m^3
M - mass of fabric tested in kg
A - area of fabric tested in m^2
D - thickness of fabric tested in m.

Experimental fabric thermal resistance test

Thermal resistances of the fabric samples were tested by KES-F7 thermal Lab II apparatus, which was produced by KES KAT Technology Company in Japan. The fabric area was 0.01×0.01 m^2, temperature of the BT box (Heat plate) 30 °C, and the basic temperature was 20 °C. The integral time was 60 seconds. All the experiments were carried out under 20 ± 1 °C, 65 ± 1% RH standard conditions. All samples had reached equilibrium in standard conditions for 24 hours before the test.

Results and discussion

Modification of the model

To investigate the validity of ***Equation 1***, the thermal resistance and structural parameters of 35 slips of fabrics were tested. Fundamental parameters of the fabrics are shown in ***Table 1***.

Thermal resistance and fabric structural parameters are shown in ***Table 2***.

Table 2 shows that the thermal resistances calculated from ***Equation 11*** agree with the experimental values quite well for thin fabrics, but with an increase in fabric thickness, the deviation increased. This deviation was caused by heat convection and radiation, thus a modification coefficient was introduced. The coefficient is determined according to the experimental testing results. The modified equation is as follows:

$$R_{fabric} = \frac{D1.043e^{-0.16D}}{\lambda_{air}} \left[\frac{\lambda_{fiber} - a(\lambda_{fiber} - \lambda_{air})}{\lambda_{fiber} - (\lambda_{fiber} - \lambda_{air})(a - \frac{\rho_{fabric}}{\rho_{fiber}})} \right] \quad (14)$$

Table 2 shows that thermal resistances calculated from ***Equation 14*** agree with the experimental values better than ***Equation 11***.

Table 1. *Fundamental parameters of the fabric samples [20]; λ_{air} is 0.026 W/(m·K).*

Material	λ_{fibre}, W/(m·K)	ρ_{fibre}, 10^3· kg/m^3
Wool	0.1610	1.32
Cotton	0.1598	1.54
Ramie	0.2062	1.54
Polyester	0.1921	1.38

Table 2. *Thermal resistance calculated from Eq. (11) and experimental results*

Material	Fabric texture	Fabric thickness D, 10^{-3}m	a	ρ_{fabric}, 10^3·kg/m^3	Calculated (Eq. 11), 10^{-3}·m^2·K/W	Calculated (Eq. 14), 10^{-3}·m^2·K/W	Experimental, 10^{-3}·m^2·K/W
Cotton	Plain weave	0.241	0.70	0.658	4.98	4.99	5.64
Polyester		0.270	0.70	0.410	6.29	6.28	6.48
Cotton		0.276	0.74	0.441	6.51	6.49	6.25
Cotton		0.284	0.74	0.411	6.85	6.83	6.27
Cotton		0.318	0.77	0.381	7.73	7.66	7.91
Cotton	Jersey stitch	0.353	0.73	0.322	9.37	9.24	7.79
Polyester	Plain weave	0.360	0.70	0.381	8.63	8.49	8.85
Ramie		0.376	0.85	0.395	7.73	7.59	8.20
Cotton	Twill weave	0.389	0.72	0.378	9.86	9.67	7.70
Polyester		0.412	0.81	0.474	7.96	7.17	8.04
Ramie	Plain weave	0.429	0.89	0.381	8.36	8.14	8.33
Cotton	Twill weave	0.507	0.86	0.391	11.09	10.67	10.95
Cotton		0.528	0.72	0.263	14.94	14.32	14.96
Cotton		0.553	0.98	0.383	10.71	9.40	9.63
Wool		0.566	0.91	0.495	9.85	8.91	10.03
Polyester		0.574	0.83	0.323	12.86	12.24	12.69
Cotton		0.593	1.00	0.405	9.70	9.20	9.15
Ramie	Plain weave	0.612	0.88	0.353	12.60	11.91	11.74
Cotton	Twill weave	0.623	0.75	0.260	17.42	16.44	13.50
Polyester		0.651	0.89	0.293	13.93	13.09	13.59
Cotton		0.674	0.99	0.462	10.50	9.83	10.25
Ramie	Plain weave	0.700	0.89	0.323	14.75	13.75	13.48
Polyester	Twill weave	0.723	0.88	0.245	16.39	14.41	16.08
Polyester	Plain weave	0.803	0.92	0.315	15.71	16.68	14.88
Cotton		0.949	1.00	0.300	18.23	16.33	17.21
Ramie	Twill weave	1.052	0.89	0.238	25.16	22.18	21.10
Cotton	Terry pile	1.360	0.67	0.153	43.99	36.91	38.60
Ramie	Brighton weave	1.451	0.95	0.156	36.69	30.06	28.90
Polyester	Ribbed kitting	1.538	0.95	0.245	31.80	25.94	24.51
Wool	Twill weave	2.007	0.63	0.241	58.14	43.99	45.65
Wool		2.015	0.70	0.253	55.82	42.18	43.29
Cotton	Terry pile	2.170	0.64	0.136	72.11	53.15	50.50
Cotton	Jersey stitch	2.288	0.74	0.188	69.51	50.27	46.95
Wool		2.472	0.65	0.136	79.78	56.03	57.53
Wool		2.701	0.75	0.188	78.74	53.30	54.96

Correlation coefficient of fabric structural parameters for R_{fabric}

In order to analysis the influence of fabric structural parameters on R_{fabric}, Pearson correlation coefficient $R_{pearson}$ was calculated according to the values listed in ***Table 2***. Results indicate that fabric thickness has the biggest impact on fabric thermal resistance. The $R_{pearson}$ of fabric thickness is 0.982, the fabric volume density -0.778, fabric structural parameter *a* -0.409, the fibre volume density -0.359, and the fibre thermal conductivity is -0.240. The larger the absolute value of $R_{pearson}$, the bigger the influence of the structural parameter on R_{fabric}. A positive $R_{pearson}$ indicates that R_{fabric} increases with an increase in fabric structural parameters, while a negative $R_{pearson}$ indicates the opposite trend.

Inspection of the validity of the modified equation

To further investigate the validity of ***Equation 14***, we tested another 25 slips of fabrics. Thermal resistance calculated from ***Equation 14*** and experimental values are shown in ***Table 3*** (see page 60).

Table 3 shows that the thermal resistance of the experimental value agrees with the value calculated quite well, with 88% of experimental value deviation being

Table 3. *Thermal resistance of fabric samples outside the specimen.*

Material	Fabric texture	Fabric thickness D, 10^{-3}m	a	ρ_{fabric}, 10^3·kg/m^3	Calculated (Equation 14), 10^{-3}·m^2·K/W	Experimental, 10^{-3}·m^2·K/W	Deviation, %
Cotton	Plain weave	0.255	0.75	0.397	6.19	5.89	5.09
Ramie	Twill weave	0.271	0.78	0.465	5.69	6.68	-14.82
Cotton	Plain weave	0.281	0.78	0.315	7.21	7.15	0.84
Cotton	Jersey stitch	0.288	0.75	0.394	7.00	6.54	7.03
Cotton	Twill weave	0.310	0.88	0.441	6.23	6.22	0.16
Cotton		0.333	0.80	0.386	7.77	6.63	17.19
Cotton		0.360	0.88	0.412	7.36	7.41	-0.67
Cotton		0.384	0.83	0.425	8.24	8.28	-0.48
Cotton		0.436	0.80	0.433	9.52	7.89	20.66
Cotton		0.438	0.89	0.498	8.01	8.10	-1.11
Cotton	Terry pile	0.503	0.66	0.203	14.95	12.46	19.98
Wool	Twill weave	0.508	0.89	0.344	10.12	11.83	-14.45
Cotton		0.518	0.91	0.512	8.82	8.99	-1.89
Cotton		0.535	0.95	0.532	8.16	8.34	-2.16
Cotton		0.536	0.82	0.531	10.25	9.10	-12.64
Cotton		0.558	0.87	0.378	11.65	12.11	-3.80
Cotton		0.603	0.87	0.390	12.34	11.61	6.29
Ramie	Plain weave	0.573	0.92	0.327	10.78	10.59	1.79
Polyester	Satin weave	0.605	0.93	0.319	11.02	11.44	-3.67
Polyester	Jersey stitch	0.614	0.91	0.241	12.65	12.56	0.72
Cotton	Twill weave	0.648	0.90	0.444	11.84	11.42	3.68
Polyester		0.764	0.93	0.317	13.46	13.93	-3.37
Cotton	Basket weave	2.170	0.64	0.127	53.61	55.69	-3.73
Wool	Plain weave	2.699	0.69	0.188	54.87	55.18	-0.83

lower than 15%. ***Equation 14*** is derived based on the assumption that the fabric is composed of repeated basic units, but the sizes of the porosities in the actual fabrics distribute in a range; thus it is natural that the experimental R_{fabric} fluctuates around the value calculated from ***Equation 14***.

Conclusions

The heat transfer of fabrics in a gradient temperature field involves complex physical phenomenon, and fabrics may have various structures. To establish a mathematical model for predicting fabric thermal resistance, this paper presented a simplified fabric structural model in a heat transfer field. The model assumes that fabrics are composed of repeated basic units and are uniform. A theoretical equation for calculating fabric thermal resistance was derived by analyzing the heat transfer process in the basic unit. The equation was modified and checked by experimental values of various fabric samples. Results show that the thermal resistance of woven and knitted fabrics can be predicted satisfactorily by the theoretical equation according to fabric thickness, fabric density, fabric structural parameter a, fibre volume density, fibre thermal conductivity etc. Future work should focus on the application of the modified model to other fabrics, such as nonwoven, multilayered, and coated fabrics.

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