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Thermal transport characteristics of polypropylene fiber-based knitted fabrics

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Abstract Thermal comfort is condition of an organism, when there is no sweating and the mean skin temperature is in the range from 32 to 34 °C (Hes, Measurement of comfort, What can textile III, 2009). Thermal comfort is closely connected with the following characteristics: thermal resistivity and thermal conductivity. Related properties are: resistance against the penetration of water vapor, air permeability, and porosity. The thermal resistivity R (W^{-1} K m^2) and thermal conductivity K (W K^{-1} m^{-1}) of knitted fabrics containing PP fiber were measured. Measurements were realized on three different types of devices. The experimental results were compared with simple mechanistic model for prediction of thermal conductivity K for textile structures.

Keywords Comfort · Thermal resistance · Thermal conductivity · Air permeability · Volume porosity · Interlock structure

Introduction

Now-a-days people are more and more interested in clothing systems assuring physiological comfort. Physiological comfort is strongly connected with thermal comfort, which is defined as a state of satisfaction with the environmental thermal conditions. One of the first attempts for specification of thermal comfort was introduction of special units clo or tog dealing with thermal resistivity R. Thermal resistivity is defined as fabric thickness divided by fabric thermal conductivity K. The units clo and tog are measures of thermal resistance and include the insulation provided by any layer of trapped air between skin and clothing and insulation of clothing itself. One tog is equal to 0.1 m^2 K W^{-1} and clo is equal to 1.55 tog. One clo corresponds to the intrinsic insulation of a business suit worn by a sedentary resting male in a normally ventilated room at 21 °C and 50 % RH and an air ventilation of 0.1 m s^{-1}. These conditions represent the environmental state at which most males feel comfortable. Suitable clo values for winter outdoor and summer clothing is approximately 0.3 and 3, respectively (obviously, with decreasing thermal resistivity the ability of clothing to insulate against the environmental conditions decreases as well). Prediction of the thermal conductivity of fibrous structures is important for the purpose of designing new fabrics and prediction of their ability to provide thermal comfort. It is well known that thermal conductivity of fabric is mainly influenced by their porosity. The fabric porosity is generally a function of construction parameters and yarn fineness. The knitted fabric porosity is changed very easily by selection of suitable patterns and dimensions of loops. Thermal evaluation of transgenic cotton containing polyhydroxybutyrate is discussed in [2]. The thermal conductivity K is defined as proportionality factor in the Fourier equation describing the

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steady state one directional transport of heat through a body of cross-sectional area A and length L due to thermal difference ΔT. Thermal analysis, heat transfer, and thermal conductivity are very important properties of materials. Therefore, many authors have studied thermal analysis, heat transfer and/or thermal conductivity of various materials [3–30].

The main aim of this study is to compare some devices for measurement of thermal conductivity. Experimental measurements are compared with mechanistic models for prediction of thermal conductivity K.

Experimental

Measurement of thermal conductivity

Heat transfer was measured on three types of devices. Used devices simulated the transfer of heat between the skin–clothing–environment. The measurements were made by conditions similar to state of human body. The results of measurements were expressed as value of thermal conductivity K, and thermal resistance R for a set of knitted fabrics. The following devices were selected:

(1) *Device Alambeta* represents indirect method of measurement. It is based on the simulation of thermal contact between the skin and dry clothes in a short time period [31]. Measurements of thermal properties are realized in the transition period between unsteady and steady state. The test conditions are following: temperature of environment 20 ± 3 °C, temperature of hot head 30 ± 3 °C, pressure of head 250 Pa.

(2) *Device Togmeter* is composed of two plates located in a box with controlled condition of air flow [32, 33]. Circular samples (diameter = 330 mm) are used. The fabric thickness is measured independently. This thickness is used for adjustment of distance between hot and cold plate of Togmeter. The temperature is recorded by using three sensors $T1$, $T2$, $T3$ in conditions without the sample and with the sample located between two plates. The thermal resistance R is calculated from these temperatures readings. The test conditions are following: temperature of environment 20 ± 3 °C, air pressure 6.91 Pa, temperature of sensors from 31 to 35 °C.

(3) *Device PSM 2* is in fact skin model containing heated plate as a model human skin. It was created to simulate the processes of heat and mass transfer on the human skin [34]. The measurements can be realized in various environmental conditions combining temperature, relative humidity, velocity of air flow, and transfer of water in liquid or gaseous phase.

The thermal resistance is measured under these conditions: temperature of environment 20 °C, temperature of hot head 35 °C, air pressure 7 Pa air flow rate = 1 m s^{-1}.

Results and discussion

Thermal conductivity model

There exist plenty of models for prediction of thermal conductivity of multiphase materials which can be used for prediction of textile fabric thermal conductivity [35–37]. For expression of thermal conductivity of fabric, it is simple to use two phase model composed from yarns having thermal conductivity K_v and air with thermal conductivity K_a in series (lower limit) or parallel (upper limit) arrangement. The relative portion of air phase is equal to porosity p_0 and relative portion of fibrous phase is $1 - p_0$. The parallel model (Fig. 1) was selected as suitable based on the results of previous experiments. The thermal conductivity of parallel model is expressed by relation:

$$K_p = p_0 \cdot K_a + (1 - p_0) \cdot K_v \quad (1)$$

where K_p is the thermal conductivity of the knitted fabric, p_0 (0..1) is volume porosity of knitted fabric, K_a is thermal conductivity of air, and K_v is thermal conductivity of yarns.

Direction of heat transfer

Fabrics

The fabrics were made from polypropylene multifilament yarns on an interlock knitting machine. Six types of knitted fabrics with different constructional parameters: mesh, cardigan loop, and support loop were prepared. The basic

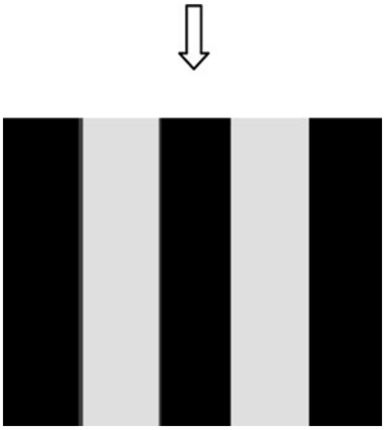

Fig. 1 Parallel model textile structure composed from yarn phase (*black*) and air phase (*white*)

Table 1 Parameters of knitted fabric

No.	H_c	h	w	T	f
1	31,500	0.85	124	11 × 2	33 × 2
2	36,464	0.77	119	5.6 × 2	43 × 2
3	35,905	0.75	115	5.5 × 2	33 × 2
4	46,200	0.78	124	5 × 2	33 × 2
5	36,960	1.02	217	5 × 1	50
6	46,800	1	187	8,4 × 2	25 × 2

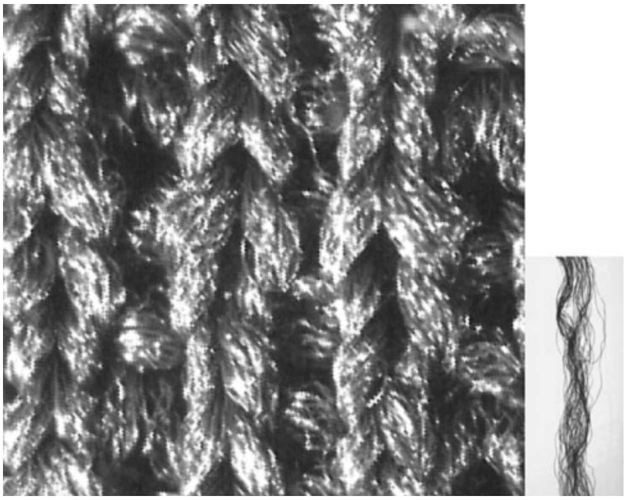

Fig. 2 Interlock knitted fabric from multifilament

Table 2 Thermal resistance R measured on Alambeta, Togmeter and PSM 2

No.	R/W^{-1} K m^2 Alambeta	R/W^{-1} K m^2 Togmeter	R/W^{-1} K m^2 PSM 2
1	0.0217	0.0341	0.054
2	0.0186	0.021	0.045
3	0.018	0.023	0.044
4	0.019	0.0286	0.053
5	0.02	0.021	0.047
6	0.0204	0.0203	0.05

Table 3 Porosity p_0, packing density z, and predicted thermal conductivity K_p (W K^{-1} m^{-1}) of knitted fabrics

No.	z	p_0	K_P
1	0.1552	0.8448	0.049
2	0.1644	0.8356	0.051
3	0.1631	0.8369	0.0499
4	0.1691	0.8309	0.0515
5	0.2263	0.7737	0.0559
6	0.1989	0.8011	0.0551

construction parameters i.e., total density of knitted fabric H_c (surface 100 × 100 mm), thickness of knitted fabric h (mm), areal weight of knitted fabric w (kg m^{-2}), multifilaments linear density T (tex) and the number of monofilaments in multifilament f were measured (Table 1).

The knitted fabric patterns were ribbing (No. 1), cardigan (No. 2, 3), jacquard (No. 5), double jersey (No. 6), interlock and integrated (No .4) knitted fabric. A common feature was the connection links of two single jersey directly in the production. The surface structure of one of the samples (multifilament, knitted fabric) is shown in Fig. 2.

Evaluation of thermal resistance

The results of thermal resistance R measurements are presented in the Table 2. The results from three types of devices are different and have different trends. The reasons for no comparable results are the different principles involved in the measurement devices.

Prediction of thermal conductivity

It is necessary to calculate their ideal porosity for prediction of thermal conductivity of knitted structures. Theoretical volume porosity of knitted fabric is defined as [38]:

$$P_0 = 1 - z \tag{2}$$

where z is packing density of knitted fabric. Packing density of knitted fabric z was calculated from the relation 3 and presented in Table 3.

$$\int z = \frac{\rho_{\mathrm{pl}}}{\rho_{vl}} = \frac{\frac{w}{h}}{\rho_{vl}} \tag{3}$$

where ρ_{pl} (kg m^{-3}) is density of knitted fabric (Table 1) and ρ_{vl} (kg m^{-3}) is density of fibers. Calculated packing densities and porosities are shown in the Table 3. The theoretical values of thermal conductivity of polypropylene and air are $K_P = 0.0261$ W m^{-1} K^{-1} and $K_a = 0.172$ W m^{-1} K^{-1}. The predicted thermal conductivities of individual knitted fabric K_p calculated from the parallel model are given in the Table 3.

Comparison of experimental and predicted thermal conductivities

To compare experimental and theoretical values it was necessary to calculate from experimental values of thermal resistances corresponding thermal conductivities K_p by using the following definition:

$$K_p = h/R \tag{4}$$

where h is thickness of knitted fabric. Calculated thermal conductivities are given in the Table 4.

The dependence between experimental and predicted thermal conductivities were characterized by the simple

Table 4 The thermal conductivities K_p (W K^{-1} m^{-1}) of knitted fabrics calculated from Eq. (4)

No.	K_p Alambeta	K_p Togmeter	K_p PSM 2
1	0.0392	0.00249	0.0157
2	0.0414	0.0367	0.0171
3	0.0417	0.0352	0.017
4	0.0411	0.0273	0.0147
5	0.051	0.0495	0.0217
6	0.049	0.0493	0.02

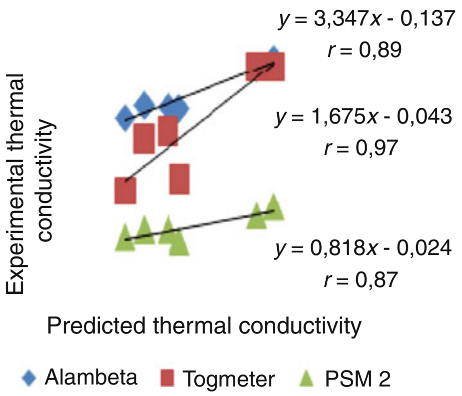

Fig. 3 The dependence between experimental and predicted thermal conductivities of knitted fabric

linear regression. The predicted thermal conductivity was selected as independent variable. The parameters of regression lines were calculated by using least squares method. Regression lines and individual points are collected in the Fig. 3. It is interesting that highest correlation between measured and predicted thermal conductivities are for the device Togmeter. Between the theoretical and experimental values of thermal conductivity measured on three types of devices, there is high degree of linear association (see correlation coefficients r).

Discussion

The results of thermal conductivity measurements on various devices have relatively high differences. One cannot uniquely decide which of the devices is the most suitable for measuring. Measurement of thermal resistance on device PSM 2 is based on the present ISO standard. The results show that this device give maximum values of thermal resistance R in comparison with other devices. Device Alambeta, which is used since a long time, is generally suitable for thermal comfort prediction. The measurements are simple and repeatable. The results from device Togmeter are similar with Alambeta device. The main disadvantage of this device is relatively difficult and long time of measurement. The measurement of thermal resistance shows high level of variability and it was necessary to do a theoretical calculation of thermal conductivity according to the chosen model. The parallel model for thermal conductivity prediction is sufficient for practical use. The relatively good linear associations between measured and predicted thermal conductivities were found.

Conclusions

From the results obtained the following conclusions can be drawn:

(1) The measured values of thermal conductivity are strictly dependent on the device used. Each of the devices has positive and negative aspects.
(2) For selected knitted fabrics with different structures the parallel model for calculation of predicted thermal conductivities is applicable.
(3) The basic parameters of knitted fabrics and fibers (density of fibers, fabrics areal weight, and thickness of knitted fabric) are used for prediction of their thermal conductivities
(4) Structure of sample no. 1 was selected as the most suitable for heat insulation. Main reason is probably more air pores between fibers in low areal density fabric. It has been proved that the heat loss is higher in structures as cardigan and support loop.

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