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THERMAL CONDUCTIVITY OF WOOL/PET WEAVES

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ABSTRACT

It is well known that thermal conductivity of fabric is mainly influenced by their porosity. The fabric porosity is a function of construction parameters such as yarn fineness and set of weft and warp. The ideal volume porosity can be computed from basic fabric parameters and the structure of elementary cell. The main aim of this work is the creation of simple mechanistic model for the prediction of fabric thermal conductivity from basic fabric properties such as yarn diameters, weft and warp sett, planar weight and thickness of fabric. This model is in fact the combination of air conductivity and conductivity of fibrous phase in hierarchy fibers, yarn and fabric. The experimentally obtained thermal conductivities of 27 wool/PET plain weaves with constant sett of warp and varying sett of weft and varying yarn fineness are used for checking of the predictive ability of this model.

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INTRODUCTION

Nowadays people are more and more interested in clothing assuring physiological comfort. Physiological comfort is strongly connected with thermal comfort, which is defined as a state of satisfaction with the environmental thermal conditions. Thermal comfort can be defined as "that condition of mind which expresses satisfaction with the thermal environment" [1-3].

Thermal comfort is generally connected with sensations of hot, cold dry or cold dampness in clothes and is usually associated with environmental factors, such as moisture transport, thermal conductivity and air permeability.

One of the first attempts for specification of thermal comfort was introduction of special units *clo* or *tog* dealing with thermal resistivity *Tr*. The *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°Cand 50 % RH and an air ventilation of 0.1 m/s. These conditions represent the environmental state at which most males feel comfortable. Suitable clo values for winter and summer clothing is approximately 0.8 and 0.5, respectively (obviously, with decreasing thermal resistivity the clothing's ability to insulate against the environmental conditions decreases as well)

Thermal resistivity is defined as fabric thickness divided by fabric thermal conductivity K. Prediction of the thermal conductivity of fibrous structures is therefore important for the purposes designing of new fabrics and prediction of their ability to provide thermal comfort.

A variety of models for prediction of thermal conductivity of multiphase materials which can be used for prediction of textile fabrics thermal conductivity exists [8]. Militky [8] used the plain weave cell model for computation of volume porosity and then various two phase models for prediction of cotton type fabrics thermal conductivity. A simple linear mixture model corresponding to the parallel arrangements of phases provided the best match between experimental data and computational prediction

The present work aims at expanding the linear mixture model of [8] to accommodate blended yarns and to include yarn porosity as one step of prediction in the hierarchy: fibers, yarn and fabric. The experimentally obtained thermal conductivities of 27 wool/PET plain weaves with constant sett of warp and varying sett of weft and varying yarn fineness are used for checking of the predictive ability of the expanded model.

NOMENCLATURE

K	[W m^{-1}K^{-1}]	Thermal conductivity
Tr	[W^{-1} m^{2}K]	Thermal resistivity
Q	[W]	Heat flow
u	[ms^{-1}]	Sound velocity
R	[%]	Moisture regain
P	[-]	Porosity
D_C	[m^{-1}]	Sett of weft
D_M	[m^{-1}]	Sett of warp
d	[m^1]	Yarn diameter
T_C	[tex]	Weft yarn fineness
T_M	[tex]	Warp yarn fineness
t_l	[m]	Fabric thickness
Z	[m]	Yarn twist

Special characters

ρ	[kgm^{-3}]	fibre density
μ	[-]	fibre packing density

Subscripts

C	Weft
M	Warp
F	fibre
Y	yarn
D	Density
V	Volumes
s	Surface
P	Parallel
S	Serial
PS	Parallel serial mean
wo	wool
pe	polyester
co	cotton

THERMAL CONDUCTIVITY OF FABRICS

Thermal conductivity K is defined as proportionality factor in the Fourier equation describing the steady state one directional transport of heat through a body of cross sectional area A and length L due to thermal difference ΔT (see fig. 1).

$$Q = K * A * \frac{\Delta T}{L} \qquad (1)$$

where heat flow is generated by the temperature gradient as is shown in fig. 1.

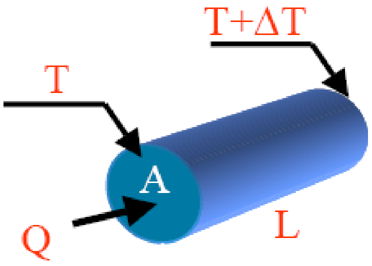

Fig. 1 Thermal transport through solid body

Thermal conductivity of solid matter is about 1 - 5 [W m^{-1}K^{-1}], e.g. water K = 0.6 [W m^{-1}K^{-1}], ice K = 2.24 [W m^{-1}K^{-1}] and air K = 0.024 [W m^{-1}K^{-1}].

No adequate theory exists which may be used to predict the thermal transport in the polymeric systems accurately. A simple phonon model of thermal conductivity is described by Van Krevelen [6]. In crystalline solids the thermal conductivity is enlarged by a concerted action of the molecules.

The thermal conductivity of textile fabrics is based on the thermal conductivity of fibres, yarns and on the construction of fabrics responsible for major part of fabric porosity.

Fibre conductivity

For polymeric fibres the semi empirical expression for prediction of the thermal conductivity based on the Debye equation exists.

$$K = C_p \; \rho \; u \; L \qquad (2)$$

where ρ is the density, u is the velocity of the elastic waves (sound velocity), C_p is the specific heat capacity and L represents the average free path length (distance between molecules in adjacent layers). In [6] all constants enabling to use eqn. (2) for prediction of polymeric fibres thermal conductivity at room temperature are published.

Semi crystalline polymers exhibit higher thermal conductivity than amorphous ones. For typical PET with 40 % crystallinity K_{pe} = 0.272 [W m^{-1}K^{-1}]. This value is used for the prediction of the thermal conductivity of polyester fibres.

The thermal conductivity of textile fibres generally depends on their chemical composition, porosity and content of water. Haghi [7] published thermal conductivity for some typical fibres. For practically nonporous polypropylene fibre he found K = 0.518 [W m^{-1}K^{-1}] and for porous acrylic fibre K = 0.288 [W m^{-1}K^{-1}]. In hydrophilic fibres the thermal conductivity depends on the moisture content characterized by regain R [%] (percentage of water in structure). The following relation describes the dependence of K on R for wool fibres [7]

$$K_{wo} = 10^{-3}\left((38.49 - 0.72\frac{R}{100} + 0.113\left(\frac{R}{100}\right)^2 - 0.002\left(\frac{R}{100}\right)^3\right)$$

Empirical relation between K and R for cotton fibre was found to be [7]

$$K_{co} = 10^{-3}\left(44.1 + 63\frac{R}{100}\right)$$

In case when the two fibres A and B are blended (blending ratio i.e. proportion of fibre A in blend is equal to b_r) their conductivity K_{AB} is estimated as upper limit defined as

$$K_{AB} = b_r K_A + (1 - b_r) K_B \qquad (3)$$

The mean density of blended fibre ρ_{AB} is

$$\rho_{AB} = \frac{\rho_A \; \rho_B}{b_r \rho_B + (1 - b_b)\rho_A} \qquad (4)$$

Yarn conductivity

Fabric is composed from weft and warp mutually interlaced yarns. Input characteristic of yarn is fineness of weft yarn T_C and fineness of warp yarn T_M.

For **idealized circular yarn** with constant packing density the yarn diameter may be computed using the following relations

$$d_C = \frac{2\sqrt{T_C}}{\sqrt{10^6 \pi \rho_C}} \tag{5}$$

$$d_M = \frac{2\sqrt{T_M}}{\sqrt{10^6 \pi \rho_M}} \tag{6}$$

Here ρ_C and ρ_M are unknown densities of weft and warp yarns. These densities are combinations of densities of fibres ρ_F and air $\rho_A = 1\ 000$ [kg m^{-3}] according to the packing of fibres in yarns. For known packing density μ_M is $\rho_M = \mu_M\ \rho_F$ and the same relation is valid for a weft yarn. The values ρ_C and ρ_M are therefore functions of twist and the method used for yarn spinning. For moderate levels of twist it has been empirically found that $\rho_C / \rho_F = \mu_C \approx 0.525$. This correction can be imposed to the relations for computation of d_C or d_M. Yarn porosity P_Y is

$$P_Y = 1 - \mu_C \tag{7}$$

Neckar [9] derived equations for prediction of mean packing density of yarn as a function of twist Z, fineness and type of material (constant M)

$$\frac{\left(\frac{\mu}{\mu_m}\right)^{5/2}}{\left[1-\left(\frac{\mu}{\mu_m}\right)^3\right]^3} = \frac{M\sqrt{\pi}}{2\mu_m^{5/2}\sqrt{\rho}}\left(ZT^{1/4}\right)^2 \tag{8}$$

Symbol μ_m [-] denotes practical limit packing density. The packing densities of cotton yarns computed from eqn (8) vary in the range of 0.42 to 0.60.

For computation of a yarns thermal conductivity K_Y a model based on the combination of thermal conductivities of air and fibres accounting fibres orientation is proposed.

$$K_Y = K_F + \frac{K_a - K_F}{1 + \frac{1-P_Y}{P_Y}\left[1 + z\ \frac{K_a - K_F}{K_a + K_F}\right]} \tag{9}$$

where $z = 1$ when all fibres are perpendicular to the direction of heat flow, $z = 2/3$ for random fibre orientation and $z = 5/6$ for half of fibres being random and the other half being normal to the direction of heat flow. Based on the preliminary testing the best choice is $z = 1$

Fabric conductivity

Classical parameters of fabrics are sett (texture) of weft D_C [1/m], sett of warp D_M [1/m], planar weight W_P [kg m^{-2}] and thickness of fabric t_W [m].

The volume porosity is computed from the idealized fabric surface structure projection shown in the fig.2.

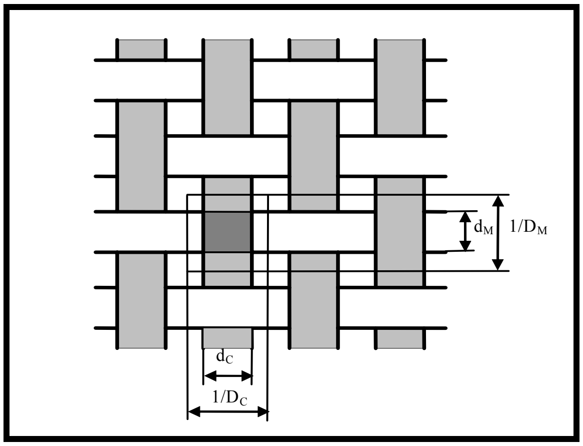

Fig. 2 Idealized surface of fabrics projection (solid lines bound the unit cell)

The unit cell (element of structure) contains a part of curved weft and warp yarns portions. Volumes and lengths of these portions are computed from an equation derived by Militký [10]. Corrected volume porosity is then defined as

$$P_V = 1 - \frac{\pi\left[d_C^2 D_C \sqrt{1.16\ d_C^2 D_C^2 + 1} + d_M^2 D_M \sqrt{1.16\ d_M^2 D_M^2 + 1}\right]}{4(d_M + d_C)}$$

For expression of thermal conductivity of fabric is then simple to use two phase model from yarns (moist) having thermal conductivity KY and air with thermal conductivity Ka in serial (lower limit) or parallel (upper limit) arrangements as is shown on the fig. 3. The relative portion of air phase is equal to porosity PV and relative portion of fibrous phase is 1 - PV.

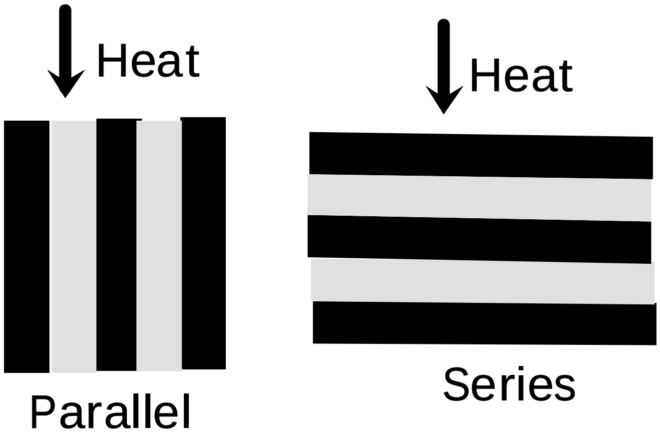

Fig. 3 Limit arrangement of yarns (black) and air (white) in conductivity model

The thermal conductivities for parallel and serial arrangements K_P and K_S, respectively, are equal to

$$K_P = P_V * K_Y + (1 - P_V) * K_a \tag{10}$$

$$K_s = \frac{K_a * K_Y}{P_V * K_a + (1-P_V) * K_Y} \tag{11}$$

Actual composition of fibres and air phases can be presented by linear combination of parallel and series structures of its constituents' thermal resistance [5]. The compromise is to compute the mean thermal conductivity K_{PS} as arithmetic mean between upper and lower limit.

$$K_{Ps} = \frac{K_P + K_S}{2} \tag{12}$$

This might not give an accurate prediction of the fabrics thermal conductivity due to the specific orientations the fibres take within the yarns as well as the distribution, shape, and size of the pores. However, the parallel/series structure gives a first hand prediction and would give reasonable prediction accuracy for practical applications due to its simplicity.

EXPERIMENTAL PART

The 27-wool/PET plain weaves with constant sett of warp D_C and varying sett of weft D_M and varying yarn fineness T_C, T_M were created in pilot plant scale. Yarns from mixture of wool fiber (45%) and PET fibers (55%) were used. From these parameters the porosity characteristics *Ps* and *Pv* were computed. From individual textiles the 10 samples 10x10 cm were randomly selected. The experimental thermal conductivity K_{ex} [W $m^{-1}K^{-1}$] was measured by means of the ALAMBETA device. For computation of fabric heat conductivity limits K_S, K_P and K_{PS} according to the above described methodology a program CONDUCT in MATLAB language was developed. Outputs from this program are volume porosities P_V and computed heat conductivities K_S, K_P and K_{PS} in comparison wit experimental heat conductivities $K_{ex.}$

RESULTS AND DISCUSSION

The dependence of thermal conductivity K_{ex} [W $m^{-1}K^{-1}$] on the volume porosity is shown on the fig. 4. The maximum relative errors of measurements was up to 2.5 %

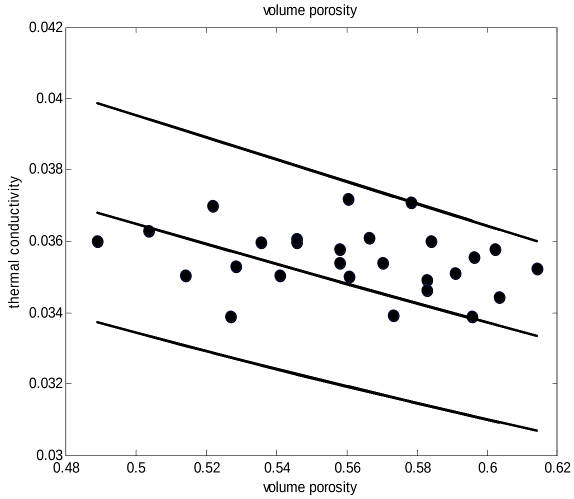

Fig. 4 Experimental and predicted thermal conductivities dependent on volume porosity P_V

The upper curve on the fig. 4 corresponds to the upper limit K_P, the lower curve on the fig. 4 corresponds to the lower limit K_S and middle curve is arithmetic mean K_{PS}.

The experimental thermal conductivities (black points) are practically fully covered by computed limits of heat conductivity. These results are surprisingly good because no measured characteristics were used for computations. Fabric parameters are used for computation of the volume porosity only.

CONCLUSION

On the basis of the conducted investigations the thermal conductivity of wool PES blended woven fabrics can be predicted from volume porosity P_V and combined model of parallel and serial arrangements $K_{PS.}$. For heat conductivity prediction the presented approach delivers sufficiently accurate results for the purpose of prediction of thermal comfort as well as for the design of fabrics. This methodology is prepared as part of a complex system for fabric design LIBTEX. LIBTEX system offers a computer based method for the virtual design of fabrics and computation of their properties

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