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Heat transfer through a textile layer composed of hollow fibres

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Abstract Textiles are used as thermal isolating materials for technical and clothing applications. The paper generally deals with heat transfer through textile layers by conduction, convection, radiation and evaporation of humidity. This experiment evaluates heat transfer by conduction and radiation through textile layers containing hollow polyethylene terephthalate (PET) fibres. The environment created by a composite textile layer containing hollow PET fibres and air is not identical for every method of heat transfer. During heat transfer through a textile layer, we evaluate of the importance of macromorphological structure of the elementary fibres and textile layer, taking into account the thermo-physiological properties.

Keywords Heat transfer · Hollow fibres · Physiological properties

Introduction

Unaware of physical laws about heat and humidity transfer through textile layers, man started wearing clothing based on his natural needs. In spite of this fact, theories about heat transfer were primarily used in technical disciplines during the design of thermal isolating materials for building insulation, different pipings, etc. Theoretical information about the evaluation of thermal isolating properties and heat transfer through textile-clothing materials became available starting from the first half of the last century and were derived from generally known physical laws about heat [1, 2]. The effect of the composition of textile material on heat transfer as well as the effect of macro-morphological structure of elementary fibres and textile construction was scarcely analysed during that period. Only after the two decades of the last century, a big boom in new textile clothing and technical materials arrived, together with a focus on the physiological and comfort properties of these materials, which are primarily linked with heat transfer [3–6]. 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 conductivities of various materials [7–34].

Theory

Heat transfer through a textile layer depends on its properties and the environmental conditions where it takes place. The construction and macromorphological structure of elementary fibres are the main properties of the textile layer from the point of view of heat transfer. Depending on these properties, the textile layer is filled with air participating in a fibre–air composite system. Such a composite system may have perfect thermal isolating properties [34–37].

Heat transfer theory deals with the three basic methods of heat transfer—heat transfer by conduction; heat transfer by convection; and heat transfer by radiation. The physiology of clothing describes heat transfer as sweating from

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the skin's surface and evaporation of humidity. Humidity transfer through a textile layer is very important during sweating and evaporation of humidity [38–43].

According to the second thermodynamic law, heat freely spreads from the site of a higher temperature to the site of a lower temperature. All three methods of heat transfer can mutually exist in actual conditions. The total resolution of heat transfer becomes much simpler if one method of heat transfer prevails or, on the other hand, one method of heat transfer is suppressed.

Heat transfer by conduction is heat transfer taking place on the molecular and electron levels. Conduction is the gradual transfer of the kinetic energy of electrons and molecules due to temperature differences in solid, liquid and gas phases. According to kinetic theory about heat, heat transfer by conduction is a consequence of the change in energy of micro-movements of substance [2].

Fourier's law indicates the amount of heat being transferred to an arbitrary isothermal area over time due to temperature differences:

$$Q_v = \lambda\,(t_1 - t_2)\cdot A \cdot \tau / h \qquad (1)$$

where Q_v—amount of heat by conduction, [W]; λ—thermal conductivity, [W m^{-1} K^{-1}]; ($t_1 - t_2$)—temperature difference in contact interface, [K]; A—area, [m^2]; τ—time, [h]; and h—layer thickness, [m].

According to Eq. (1) the difference in temperatures on both sides of textile layers is the driving force.

Thermal conductivity in the gas phase changes with the temperature and pressure. Dependence on pressure in actual conditions in the solid and liquid phases is negligible. The dependence of thermal conductivity from the temperature is evaluated empirically according to the following equation:

$$\lambda_t = \lambda_0\left(1 \pm At \pm Bt^2 \pm \ldots\right) \qquad (2)$$

where λ_t—thermal conductivity at temperature t, [W m^{-1} K^{-1}]; λ_0—thermal conductivity at temperature t_0, [W m^{-1} K^{-1}]; and A and B are experimental coefficients.

The median value of thermal conductivity in a temperature range $t_1 > t_2$ is expressed according to the following equation:

$$\lambda = \sum_{t2}^{t1} \lambda_t / (t_1 - t_2) \qquad (3)$$

where λ—median thermal conductivity, [W m^{-1} K^{-1}]; λ_t—thermal conductivity at temperature t, [W m^{-1} K^{-1}]; and ($t_1 - t_2$)—temperature range, [K].

The area resistance of heat conduction is a function of thermal conductivity and the layer thickness [m] through which heat is conducted and is expressed as follows:

$$r = h/\lambda \qquad (4)$$

where r—area resistance of heat conduction, [W^{-1} K m^2]; h—thickness of layer, [m]; and λ—thermal conductivity, [W m^{-1} K^{-1}].

Thermal absorption is defined as follows:

$$b = \sqrt{\lambda} \cdot \rho \cdot c \qquad (5)$$

where b—thermal absorption, [W m^{-2}s$^{1/2}$K^{-1}]; λ—thermal conductivity, [W m^{-1} K^{-1}]; ρ—fabric density, [kg m^{-3}]; and c—unit thermal capacity, [J kg^{-1}K^{-1}].

Equation (1) can be modified for a composite textile layer composed of i—textile simple layers and i—air layers as follows:

$$Q_v = (t_1 - t_2)\,A\,\tau / R \qquad (6)$$

where R—the area resistance of heat conduction through the composite textile layer, [W^{-1} K m^2].

It is calculated according to the following equation:

$$R = \sum (h_i/\lambda_i)_{\mathrm{tex}} + \sum (h_i/\lambda_i)_{\mathrm{air}} \qquad (7)$$

or

$$R = \sum (r_i)_{\mathrm{tex}} + \sum (r_i)_{\mathrm{air}} \qquad (8)$$

where r_{tex}—area resistance of the heat conduction of the textile layer, [W^{-1} K m^2]; and r_{air}—the area resistance of the heat conduction of the air layer, [W^{-1} K m^2].

When it comes to compression of a textile layer in real conditions, the R values of the experimental and calculated according to Eq. (7) show the difference depending on the deformability of the textile material due to the change in environment to the heat transfer [41].

Heat transfer by convection is heat transfer caused by macro-movements of particles in a liquid or gas phase. Newton's law expresses heat transfer by convection:

$$Q_p = \alpha \cdot A(t_1 - t_2) \qquad (9)$$

where Q_p—amount of heat by convection, [W]; α—coefficient of heat transfer by convection, [W m^{-2} K^{-1}]; (t_1 − t_2)—difference in temperature, [K]; and A—area, [m^2].

The coefficient of heat change by convection through an arbitrary layer is dependent on the layer's properties such as temperature and pressure, the shape of the surface area and air movement. Heat change by convection is more intensive during air movement. Heat transfer by convection based on temperature differences is called natural and compulsory if the convection is caused by an external mechanic shuffle.

Heat transfer by convection supports heat transfer by conduction. On the contrary, heat transfer by convection through a layer can be suppressed by heat transfer by conduction.

Natural convection in an air portion is considerably suppressed in fibre–air textile composite materials. Fibres in a textile layer create a barrier to air movement. Heat change by convection generally occurs on the interface of a textile layer with the environment.

It is complicated to set out the coefficient of heat transfer by convection in a system due to the many number of variables that influence it.

The following semi-empirical equation by Büttner calculates the coefficient of heat transfer by convection on a skin surface:

$$\alpha = 0.02(0.04 + 0.01v \cdot d \cdot p/p_0)^{0.54} \quad (10)$$

where α—coefficient of heat transfer by convection, [W m^{-2} K^{-1}]; v—air movement, [m s^{-1}]; d—body surface property, [m]; p—pressure of vapours on skin surface, [mbar]; and p_0—normal barometric pressure, [mbar].

Other semi-empiric equations [22] express dependency α from the temperature or the velocity of air movement:

$$\alpha = 3^4\sqrt{(t_1 - t_{air})} \quad (11)$$

where $(t_1 - t_{air})$ temperature difference, [K] or

$$\alpha = 11.2\sqrt{v} \quad (12)$$

where v is the air velocity, [m s^{-1}].

Equation (12) is valid for $v = 0.2$–5 m s^{-1}.

Heat transfer by radiation is heat transfer occurs as a result of the electromagnetic radiation of a certain wave length. Planck's theory of radiation says that every entity radiates heat in the area of wave lengths of the electromagnetic spectrum between 280 nm and 1 mm. In general, thermal radiation coming to an entity is partially absorbed, partially reflected and partially released through the entity. The radiation energy saving law is as follows:

$$E = E_a + E_r + E_t \quad (13)$$

where E—incoming radiation, [W]; E_a—absorbed radiation, [W]; E_r—reflected radiation, [W]; E_t—released radiation, [W].

The Stefan–Bolzmann's equation expresses the thermal flow of radiation:

$$E = c \cdot (T/100)^4 \cdot A \quad (14)$$

where E—thermal flow of radiation, [W]; T—temperature of radiator, [K]; c—radiation coefficient of the real entity, [W m^{-2} K^{-4}]; and A—area [m^2].

Lambert's law expresses the density of a radiating flow:

$$e = E/4\pi R^2 \quad (15)$$

where R is the distance from the source, [m].

Any given thermal source can serve as a thermal radiator. Under specific conditions, dry human skin is an ideal thermal radiator. The human body's radiation is characterized by a wave length of $\lambda = 5$–40 µm, and the skin absorbs IR by a wave length of $\lambda = 3$ µm. If an environment's temperature is lower compared to the skin's temperature, then the thermal radiation is negative, and the skin cools down. A positive change occurs when the skin absorbs radiation heat from the environment [42].

Stefan–Bolzmann's law expresses heat transfer by radiation from the skin's surface through a textile layer:

$$Q_r = c \cdot A\left[((273 + t_1)/100)^4 - ((273 + t_2)/100)^4\right] \quad (16)$$

where Q_r—amount of heat from radiation, [W]; c—radiation coefficient, [W m^{-2} K^{-1}]; t_1, t_2—temperatures of radiating surfaces, [K]; and A—area, [m^2].

The driving force according to Eq. (16) is the difference in temperature and their fourth square.

For dry skin, $c = 4.56$, and for an absolutely black entity, $c_o = 4.96$.

The interaction of the skin–textile–climate–physical work of man during heat transfer requires a complex evaluation of heat leaving the skin's surface by sweating and sweat transport through a textile layer and evaporation.

The following equation expresses the amount released by sweating skin:

$$Q_e = \alpha_e \cdot wA(p_k - p_{air}) \quad (17)$$

where Q_e—amount of heat derived from sweat evaporation, [W]; α_e—coefficient of heat transfer by sweat evaporation, [W m^{-2} mbar]; wA—skin surface area covered by sweat, [m^2]; p_k—partial pressure of water vapour over skin surface, [mbar]; and p_{air}—partial pressure of water vapour in surrounding air, [mbar].

The driving force according to Eq. (17) is the difference in partial pressures on both sides of a textile layer.

The total amount of heat coming from a thermal source through a textile layer to the surrounding environment is expressed as follows:

$$Q_t = Q_v + Q_p + Q_r \quad (18)$$

where Q_t—total heat transfer, [W]; Q_v—heat transfer by conduction, [W]; Q_p—heat transfer by convection, [W]; and Q_r—heat transfer by radiation, [W].

The total amount of heat increases in portion to Q_e in the case of a textile layer insulating sweating skin:

$$Q_t = Q_v + Q_p + Q_r + Q_e \quad (19)$$

where Q_e—amount of heat by sweat evaporation, [W].

Not every element will be equally represented during an evaluation of heat transfer through a textile layer. A number of factors will determine which method of heat transfer will prevail or be suppressed.

A textile layer, a carrier of thermal isolating properties, considerably affects total heat transfer. It is mainly the

Table 1 Basic geometric properties of PET fibres

Fibre profile[a]				
Number of hollows	0	1	4	10
Total hollow area/µm^2	0	60	85	160
Fibre fineness/dtex	7.2	8.8	8.8	9.7
Specific weight/g cm	0.023	0.027	0.026	0.027
Thickness of fibre/µm	22	30	25	43

[a] Cross-sectional profile of fibres with different numbers of hollows according to microscopic method using light microscope Olympus HB 2 and transfer through camera to PC. Total hollow area was evaluated by picture analysis. The textile layers were constructed of nonwoven fabrics 25 mm thick. These were made by carding machines by fibrous webs superposition

macromorphological structure of a textile layer and the elementary fibres that are present in it [2, 43].

Experimental

Materials

Textile layers were composed of polyethylenetherephthalate (PET) fibres that were 30 mm long. The basic geometric properties of PET fibres creating the textile layer's construction are stated in Table 1.

Experimental methods

Heat transfer by conduction and radiation through a textile layer was monitored under laboratory conditions at an air temperature of 22 °C and a relative air humidity of 55 %.

In order to measure the thermal properties of the heat transfer by conduction, we used a contact method on Alambeta machine. The difference in the temperatures between the upper and lower sides of the textile layer was 40 °C, and the pressure of the contact heating plate to the upper side of the textile layer was 200 kPa. We set the thermal conductivity λ, [W m^{-1} K^{-1}] and the thermal resistance r, [K m^2 W^{-1}] with an experimental error at a maximum of 2.5 %.

The heat transfer by radiation was measured by the non-contact method using a thermovision camera. We used thermovision camera Agema medical with computer program to analyse thermogram. The distance between the scanning of the radiating skin surface and the camera was 1 m. We used a computer program to acquire thermograms. The heat transfer by radiation was monitored from the dry skin surface of a volunteer standing still in a closed room without a draught in its interaction with a textile layer.

Results and discussion

In order to evaluate the heat transfer through the textile layer, we used nonwoven fabrics with a high value of thermal-isolating properties to evaluate the effect of the macromorphological structure of the elementary fibres on the heat transfer by conduction and radiation. The same technology for preparing the textile layer was used to achieve the goal. The differences in the macromorphological structure of the elementary PET fibres were given by the number and size of the hollows in the volume of the fibres as well as their disposition and fibre fineness. Textile layers composed of different hollow numbers in fibres created different environments for the spread of the heat.

Table 2 Thermal properties of PET fibres with hollows of different numbers measured by the contact method during heat transfer by conduction, $\Delta t = 40$ °C, $p = 200$ kPa

Composition of textile layers	$\lambda \cdot 10^3$/W m^{-1} K^{-1}	$r \cdot 10^3$/K m^2 W^{-1}
Non-hollow fibre	47.8	39.5
One-hollow fibre	47.0	36.9
Four-hollow fibre	46.8	40.8
Ten-hollow fibre	46.6	38.0

λ thermal conductivity, r thermal resistance

Table 3 Temperature of a skin surface without a textile layer (t_0) and with the textile layers of hollow PET fibres (t), analysis of thermograms (Fig. 1)

Nonwoven fabrics composition	Surface temperature t/°C	Temperature difference $t_0 - t$/°C
Naked skin	$t_0 = 34.0$	0
Non-hollow fibre	31.0	3.0
One-hollow fibre	30.5	3.5
Four-hollow fibre	29.5	4.5
Ten-hollow fibre	28.5	5.5

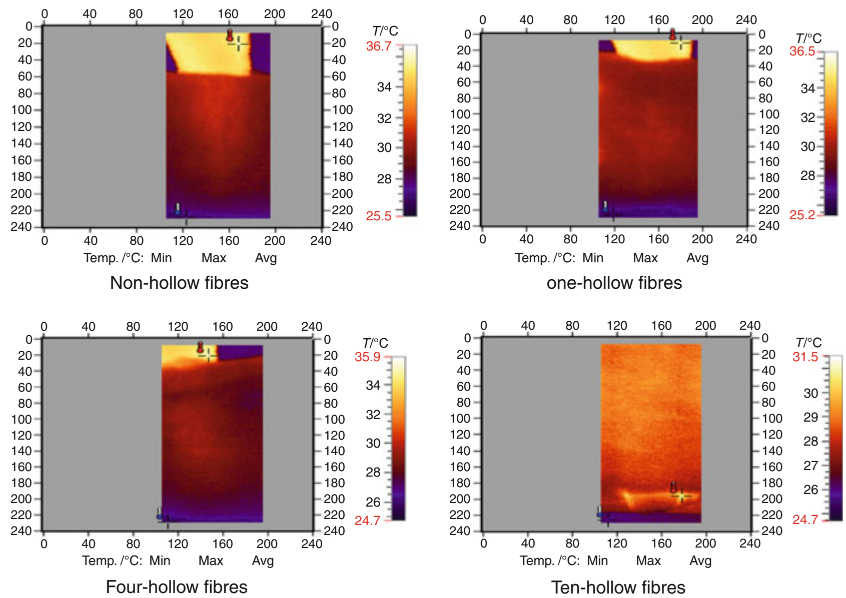

Fig. 1 Heat transfer by radiation skin–textile layer thermograms

Heat transfer by conduction is fundamentally different from heat transfer by radiation, and so are the methods for their determination. We take into consideration both methods to examine the thermal-isolating properties of the textile material. The thermal conductivity and thermal resistance of the PET fibres depending on the number of hollows in the fibre volume are given in Table 2.

The thermal conductivity of a textile layer composed of non-hollow PET fibres records the highest thermal conductivity but decreases with the number of hollows. Equation (4) proves the higher the thermal conductivity, the lower the thermal resistance. This correlation is not linear amongst the evaluated samples. The deformability of a textile layer subjected to pressure is very important, and it is different for fibres with various numbers of hollows. The air in a textile layer creates a composite fraction with a high thermal isolation. The air ratio in a textile layer decreases during the pressure of a heating plate during the contact method. Pressure during the measurement of the thermal properties was constant, although the varying deformability of the hollow fibres and the textile layer which is composed of them caused various changes in the thickness and changes in the air ratio in the textile layer. The air is permanently maintained in the hollows of the fibres except for air kept in the macromorphological structure of the textile layer. If the hollow size in the air volume is higher, then the ratio of the permanently maintained air is higher. If the thermal-isolating properties of the textile layer are evaluated while under its pressure (e.g. during wearing), then the thermal resistance does not correspond linearly with the thermal conductivity. According to the measured values of thermal resistance in the sample of the textile layers evaluated, listed in Table 2, the textile layer composed of four-hollow fibres records the highest thermal resistance. When interpreting the degree of deformability, they are the least compressible in comparison to the three other fibre profiles. The temperature differences that explain the thermal-isolating properties during heat transfer by radiation are presented in Table 3.

When analysing the thermograms, we determined the average temperature on an equal area of a naked skin's surface and one covered by textile layers from various hollow fibres. We set the temperature difference by comparing the temperatures on the textile layer's surface and the reference surface—naked skin. This difference in temperature corresponds to the permeability of radiating energy through a textile layer. The higher the difference set by the thermo-vision non-contact method between the experimental textile layer and the reference surface the higher the thermal isolation of the textile layer. The highest difference in temperature reports a textile layer of non-woven fabrics composed of ten-hollow fibres. This textile layer is the least permeable to radiating energy from a skin surface. A difference in temperature of 5.5 °C is the highest amongst the fibres evaluated and corresponds with the highest degree of thermal isolation. The difference in temperature set by the thermovision method corresponds non-proportionally with the thermal conductivity. Heat transfer by conduction and radiation was set at stationary conditions. As mentioned earlier in the article, the heat transfer by convection was negligible at such conditions of measuring.

Conclusions

The environment created by a textile layer for heat transfer depends on the macromorphological structure of the fibres creating the textile layers. The monitoring of heat transfer via radiation through textile layers using the thermovision method enables the setting of temperature differences in a less complicated way as a criterion for thermal isolation directly in the interaction between man–clothing–climate. Both methods used in this article for determining thermal isolation between them complement each other mutually

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