Jūratė Nadzeikienė,
***Rimvydas Milašius,**
Juvencijus Deikus,
Juozas Eičinas,
****Paulius Kerpauskas**

Evaluating Thermal Insulation Properties of Garment Packet Air Interlayer

Lithuanian University of Agriculture
Department of Occupational Safety
and Engineering Management
Studentų 15, LT-53362 Akademija, Kauno r.
Lithuania
Tel +370 37 752376
E-mail: juratele_n@yahoo.co.uk

***Kaunas University of Technology**
Department of Textile Technology
Studentų 56, LT-51424 Kaunas, Lithuania
Tel.: +370 37 300222
E-mail: rimvydas.milasius@ktu.lt

****Lithuanian University of Agriculture**
Department of Heat
and Biotechnology Engineering
Studentų 15, LT-53362 Akademija, Kauno r.
Lithuania
Tel +370 37 752317
E-mail: paulius@tech.lzuu.lt

Abstract
In this article, we present an evaluation of the heat exchange processes taking place in the garment packet air interlayers. In the quest to improve garment designs, evaluate their thermal insulation properties and create new garment materials, it is necessary to evaluate all kinds of heat transfer in the air interlayer. Heat exchange process in the air interlayer manifests itself by conductance, convection and radiation. Thermal evaluation of a garment packet with air interlayers which is based on conductance alone will be incomplete, as it is also necessary to evaluate the influence on the packet's thermal insulation of the air interlayer between the human body and the garment's internal surface . An equivalent thermal conductivity coefficient was proposed to evaluate the total heat transfer in the air interlayer. Methods for calculating a thermal conductivity coefficient for evaluating the garment packet's thermal insulation properties were developed.. It was established while evaluating the heat exchanges in the 1 to 10-mm thick air interlayer as a whole, that the equivalent thermal conductivity coefficient varies depending on the air interlayer thickness. A comparative analysis of air interlayer thermal resistance is presented, which evaluates the garment's air interlayer thermal insulation properties by its thermal conductance and by its combined conductance, convective and radiation process.

Key words: *garment, air interlayer, conductance, convection, radiation.*

Introduction

From the thermal point of view, the garment packet is a regulated thermal insulation layer. It must satisfy as fully as possible the demands of a human wearer, who has limited thermal regulation abilities. In most cases, a garment packet's heat resistance is evaluated by the thermal conductance of the garment's materials and the thickness of those materials. However, the garment packet also contains air interlayers between materials, which appear because of the garment structure's particularities and surface unevennesses, which in their turn are caused by the properties of the garment yarns used for producing the materials; their length, density, structure (spun more or less), surface particularities (for fancy yarns), as well as their material structure; thread density, and particularly their twist [1]. Cloth and other textile materials also have inter-thread channels, distinct for their complex geometry [2], which also influence their thermal insulation properties. Air interlayers are separate thermal insulation layers of the garment packet, with the best thermal insulation properties being λ=0,026 W/(m·K). They are transparent to infrared radiation, and all possible ways of heat exchange are inherent to them, namely conductance, convection and radiation.. The air interlayer's influence on the garment packet's thermal insulation properties is obvious. Nevertheless, the air interlayer's effect on a garment's heat resistance has so far been left without any thorough investigation [3-7]. The air interlayers which occur between the human body and the garment's internal surface, between separate material layers of the garment packet, have a cylindrical form. This form more clearly describes the real process and the garment wearing conditions than the plane form does. This particular form of the air interlayer, its small thickness and complex heat transfer in interlayers make assessing the air interlayer's effect on the general heat resistance of a garment packet rather complicated. The most difficult part of solving this problem includes assessing the heat transfer process through the air interlayer which is on the human body surface. This forms between skin and garment packet internal surface. After this complex problem was solved for the interlayer, the evaluation of garment packet heat transfer became more general and many-sided, including all kinds of heat transfer.

The aim of our research was to generalise the regularities of heat exchanges in the air interlayer, also including the gap between the human body and the garment's internal surface, expressing them through the equivalent thermal conductivity coefficient, and also to elucidate the advantages of the equivalent thermal conductivity coefficient for evaluating the air interlayer's heat resistance.

To achieve this aim in our article, on the basis of heat transfer process regularities, we have mathematically described the process of heat transfer, taking place in the air interlayer between the human body and the garment's internal surface. Using this equivalent thermal conductivity coefficient, we united air conductance, convection and radiation processes into one entirety. We then carried out a comparative analysis of the air interlayer heat resistance using the equivalent thermal conductivity and still-air thermal conductivity coefficients.

Evaluation of heat transfer in an air interlayer between the human body and the garment's internal surface

Heat transfer processes in the garment packet may be regarded as steady-state, assuming that the heat flow Q_h through the garment packet is not transient, and the heat transfer from the human body through the garment packet is maintained in a steady-state condition $dt/d\tau=0$ (where t is the temperature in °C; τ is the time, s). The heat exchange processes in the air interlayer consist of conductance, convection and radiation (Figure 1). This complex heat transfer process in the interlayer may be expressed by the following equation [8]:

$$Q_h = \frac{\pi l (t_h - t_1)}{\frac{1}{2\lambda_{air}} \ln \frac{d_1}{d_h}} + \pi l \alpha_c \frac{d_h d_1}{d_h + d_1} (t_h - t_1) + \varepsilon_r C_0 \pi l d_h \left[\left(\frac{T_h}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right]. \tag{1}$$

where:

Q_h – the heat flux released by the human body surface W;

λ_{air} – air without motion thermal conductivity, W/(m·K);
t_h, t_1 – the human skin and garment internal surface temperatures respectively, °C;
d_h, d_1 – the diameters of the internal surfaces of the human body and garment, m;
l – the length of the cylinder surface, m;
α_c – the convective heat transfer coefficient in the air interlayer, W/(m·K);
ε_s – the human body and the garment's internal surface system's relative emissivity factor;
C_0 – the blackbody radiation coefficient, C_0=5,67 W/(m^2·K^4);
T_h, T_1 – the human skin and garment's internal surface temperatures, K.

Air interlayer heat resistance can be found from the equation [8].

$$R_{air} = \frac{1}{2\lambda}\ln\frac{d_1}{d_h}, \qquad (2)$$

where:
λ – the heat conductivity coefficient of the air interlayer, W/(m·K);
R_{air} – the heat resistance of a cylinder-shaped air interlayer, m·K/W.

Rearranging equation (1) leads to a complex expression of the air interlayer's thermal conductivity coefficient with several unknown parameters, namely Q_h, α_c, ε_s, C_0. Therefore, to simplify the description of the heat transfer process and for thorough evaluation of the air interlayer heat exchanges, we have applied Hankey's method of introducing the concept of the equivalent thermal conductivity coefficient [8, 9]. This coefficient unites the three different kinds of heat transfer (conductance, convection and radiation), and enables the description of the heat transfer process in the air interlayer using Fourier's law expression to evaluate the influence of the air interlayers in the clothes packet on the total clothes packet's heat resistance.

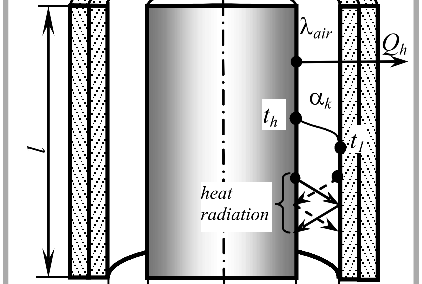

Figure 1. Scheme of heat transfer in air layer.

Equivalent thermal conductivity coefficient

An equivalent air interlayer thermal conductivity coefficient λ_{equiv} is expressed as the sum of the still air thermal conductivity coefficient λ_{air} and the equivalent heat conductivity coefficients for convection λ_c and radiation λ_r [9,10], that is:

$$\lambda_{equiv} = \lambda_{air} + \lambda_c + \lambda_r \qquad (3)$$

The coefficient λ_{equiv} is not a specific material property constant, like the material heat conductivity coefficient used to evaluate garment packet resistance. It is appropriate to discuss each equivalent heat conductivity coefficient component presented in equation (3) separately, considering the dependence and possible limit variation for the air interlayer in the garment packet discussed.

Still air heat conductivity coefficient λ_{air}. In our case, this coefficient is not constant. It directly depends on the internal surface temperatures of the human body and garment, that is, on the air interlayer's mean temperature. This dependence is described by equation [10]:

$$\lambda_{air} = \lambda_0(1 + 0.0315 t_{air}), \qquad (4)$$

where:
λ_0 – the air thermal conductivity coefficient value at 0°C, equal to 0.02442 W/(m·K) [10],
t_{air} – the air interlayer's mean temperature, °C.

We may consider that the temperature of garment internal surface varies within a range of 17 to 32°C, that is in a range of 15°C; the human body surface temperature is 32°C (according to human skin topography t_{hmin}= 28°C and t_{hmax}= 37°C). The still air thermal conductivity coefficient λ_{air} increases with the air interlayer temperature, while in the same time reducing temperature difference between the human body and the garment's internal surface, ussuming that the human body temperature remains constant (Q_h=const).

The equivalent heat conductivity coefficient in the air interlayer for heat transfer by convection λ_c. Heat transfer by convection in the air interlayer occurs because of natural convection caused by the temperature difference between human skin and garment internal layer surface. It should be remarked that this coefficient is not constant, depending on the air interlayer thickness, its air temperature, temperatures of boundary surfaces and the form and spatial orientation of the interlayer. On the grounds of Newman's principle for natural convection when $Gr \cdot Pr < 10^8$ and the similarity theory [9,10], the equivalent thermal conductivity coefficient in the case of heat transfer by convection can be expressed by the following equation:

$$\lambda_c = \lambda_{air}\frac{m(Gr \cdot Pr)^r}{(Gr \cdot Pr) + n}. \qquad (5)$$

where:
m, n, r – dimensionless constants representing air interlayer geometric form and orientation in space;
Gr, Pr – Grashof's and Prandtl's criteria.

The above-mentioned criteria Gr and Pr characterise the heat exchange process in the air interlayer. After the calculations of the equivalent heat conductivity coefficient for the convective heat transfer λ_c according to equation (5), it was established that heat transfer by means of convection in the air interlayer of up to 4 mm thickness is practically independent of the temperature (Figure 2). The sudden growth of λ_c with a further rise directly depending on temperature differences may be noticed when the thickness of the air interlayer has been increased from 4 to 10 mm. When the human body and garment internal surface temperature differences reach 15°C, λ_c is equal to 0.001416 W/(m·K). The 1.5 time decrease in the temperature difference leads to a 1.7 time decrease of λ_c ; at a 5°C temperature dif-

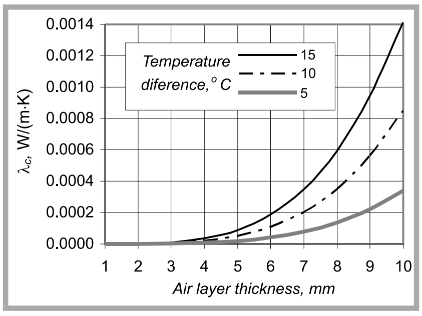

Figure 2. Dependence of the equivalent heat conductivity coefficient by means of convection λ_c on the air interlayer thickness at the corresponding temperature difference.

ference, the heat conductivity coefficient for convective transfer lessens by another 2.5 times. At a temperature difference equal to 0, with the human skin and the garment's internal surface temperatures being equal, convective heat exchanges never take place.

It follows from the analysis presented that for thin air interlayers between the human body and the garment's internal surface, heat exchanges by means of convection are negligible. At larger air interlayer thicknesses (when reaching a thickness of 10 mm), convective heat exchanges become more intense, and the coefficient mentioned above reaches a mean value of about 6.51-10^{-4} W/(m·K), which is 41.4 times greater than in an interlayer of 4 mm thickness. This data demonstrates that any increase in thickness of the air interlayer in the garment packet exceeding 4 to 5 mm is not expedient, while the best results may be obtained with an air interlayer thickness less than 3 mm (Figure 2).

Equivalent heat conductivity coefficient, evaluating heat exchanges by means of radiation λ_r. To evaluate the heat transfer radiation, we used Fourier's equation [9]:

$$Q_h = \frac{\pi l (t_h - t_1)}{\frac{1}{2\lambda_r} \ln \frac{d_1}{d_h}}. \qquad (6)$$

Dividing this equation by $\pi d_h l$ and introducing the equivalent heat conductivity coefficient for heat exchanges by radiation λ_r, we obtain the expression of this coefficient:

$$\lambda_r = \frac{q_h}{t_h - t_1} \cdot \frac{1}{2} d_h \ln \frac{d_1}{d_h}. \qquad (7)$$

The heat flow density q_h (W/m^2) through the area unit of the internal garment surface, transferred by means of radiation, according to the Stefan-Boltzmann law [9,10] may be expressed in the following way:

$$q_h = \varepsilon_r C_0 \left[\left(\frac{T_h}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right]. \qquad (8)$$

From equations (7) and (8), we obtain an expression for the equivalent heat conductivity coefficient by means of radiation [8, 10]:

$$\lambda_r = \frac{\varepsilon_r C_0 \left[\left(\frac{T_h}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right]}{t_h - t_1} \times \frac{1}{2} d_h \ln \frac{d_1}{d_h}, \qquad (9)$$

or

$$\lambda_r = \frac{1}{2} d_h C' b \ln \frac{d_1}{d_h}, \qquad (10)$$

where:

b – the temperature coefficient, found from the following formula:

$$b = \frac{\left[\left(\frac{T_h}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right]}{t_h - t_1}; \qquad (11)$$

C' – the radiation coefficient of interacting bodies (human skin and garment internal surface), which according to Nusselt is equal to [10]:

$$C' = \frac{1}{\frac{1}{C_h} + \frac{d_h}{d_1}\left(\frac{1}{C_1} - \frac{1}{C_0} \right)}, \qquad (12)$$

where:

C_h, C_1 – the heat emissivity of the human body and the garment's internal surface respectively, W/(m^2·K^4).

The equivalent thermal conductivity coefficient of heat transfer by radiation λ_r increases rapidly with the air interlayer thickness, that is, in direct dependence on its thickness (Figure 3). With the air interlayer thickness increased 10 times, λ_r increases 9.81 times. At a garment internal surface temperature lower than human body temperature, λ_r has a smaller value. The temperature differences between the human body and the garment's internal surface (and, correspondingly, the interlayer temperature) causes less change in the coefficient λ_r as its thickness.

A summation of λ_{air}, λ_c and λ_r coefficients gives the total air interlayer equivalent thermal conductivity coefficient λ_{equiv}:

$$\lambda_{equiv} = \lambda_{air} \left(1 + \frac{m (Gr \cdot Pr)^{\gamma}}{(Gr \cdot Pr) + n} \right) + \frac{1}{2} d_h C' b \ln \frac{d_1}{d_h}. \qquad (13)$$

The equivalent thermal conductivity coefficient λ_{equiv} increases with the air interlayer thickness (Figure 4). For an interlayer thickness of 1 mm, its mean value reaches 0.032 W/(m·K), while for 10 mm –it is 0.08 W/(m·K). It is safe to assume that this variation of this coefficient is linear, and depends mostly on the thermal radiation factor.

The summary equivalent thermal conductivity coefficient λ_{equiv} includes all three ways of heat transfer, and noticeably increases with the air interlayer thickness. The still air heat conductivity coefficient λ_{air} which is usually used is constant in the whole air interlayer, and depends only on the mean temperature therein. A comparison of air interlayer heat resistances calculated according to equation (2) using the thermal conductivity coefficients mentioned above is presented in Figure 5.

Upon calculating the air interlayer's heat resistance by using the still air heat conductivity coefficient, we obtain a linear

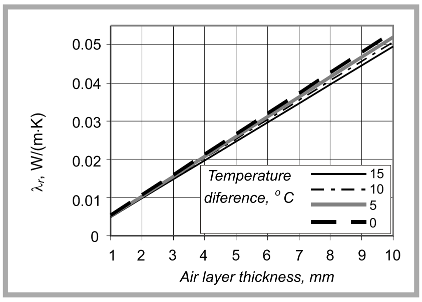

Figure 3. *Dependence of equivalent heat conductance coefficient for heat transfer by means of radiation λ_r on air interlayer thickness at difference of corresponding temperatures.*

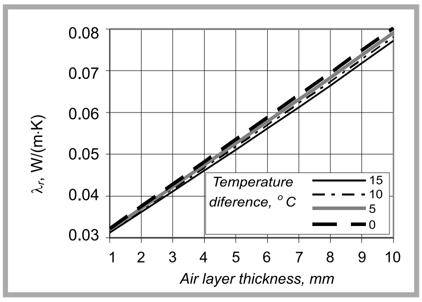

Figure 4. *Dependence of the equivalent thermal conductivity coefficient λ_{equiv} upon air layer thickness at particular temperature differences.*

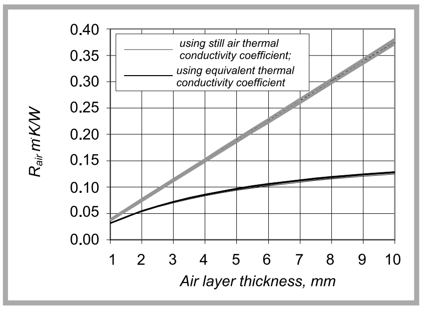

Figure 5. *Dependence of air interlayer heat resistance calculated, using the still air heat conductivity coefficient and the equivalent thermal conductivity coefficient λ_{equiv}, on air interlayer thickness.*

dependence between air interlayer thickness and its heat resistance (Figure 5). From these calculations, it follows that the greater is the layer thickness increment, the better is the thermal insulation obtained. However, such an evaluation is neither complete nor accurate. Taking into consideration all the component parts of the complex heat transfer process, that is, calculating the heat resistance in the air interlayer according to the equivalent thermal conductivity coefficient, the air interlayer heat resistance's dependence (which has an entirely different character) on the air interlayer thickness may be obtained (Figure 5). A comparison of both calculated air interlayer heat resistance variants shows that in the case of a normal calculation with the heat radiation process excluded, a heat resistance for an air interlayer width which is 10 times greater should itself also increase 10 times. However, evaluating the radiation and convection influences, the heat resistance only increases up to four times. There is no linear dependence between air interlayer thickness and heat resistance. The heat resistance increases more intensely when the air interlayer thickness is 2-3 mm (Figure 5).

In the example calculated (Figure 5), a logarithmic dependence exists between the air interlayer heat resistance R_{air} and its thickness δ (mm):

$$R_{air} = 0.0419 \ln(\delta) + 0.027, \qquad (14)$$

where:

R_{air} – the heat resistance of the air interlayer, m·K/W;

δ – the thickness of the air interlayer, mm.

On the basis of the analysis carried out of heat transfer in the air interlayer, we can say with confidence that the heat flux crossing the air interlayer may be expressed using the equivalent thermal conductivity introduced above by Fourier's law. Description of this complex heat transfer process ongoing in the air interlayer enables us to evaluate the influence of conductance, convection and radiation, to accurately calculate the interlayer heat resistance and to model the necessary properties of the garment packet's thermal insulation.

Comparing the methods of evaluating thermal insulation indicates that when air interlayer thickness increases, its heat resistance varies logarithmically. If still air heat conductivity was taken into account alone, errors may reach up to 250% depending on the air interlayer thickness.

The method presented was checked experimentally. The preliminary investigations with cotton and wool fabrics showed a slight variance (no higher 5 %) between the experimental results and the values calculated by the presented method. A more detailed discussion of the experimental results obtained by us and their conformability with the theoretical calculations presented in this paper will be the subject of further articles prepared for publishing in 'Fibres & Textiles in Eastern Europe'.

Conclusions

1. Complex heat exchanges take place in a garment packet's air interlayers by conduction, convection and radiation, a complex evaluation of which must be carried out when considering garment thermal insulation properties.
2. Heat transfer by conductance and radiation prevails in the garment packet's air interlayer. Convective heat exchanges become perceptible only in air interlayer widths exceeding 5 mm.
3. The combined evaluation of the air interlayers in a garment packet allows the conclusion that it is expedient to introduce several 2-3 mm wide air gaps into the garment packet, in order to improve its thermal insulation properties.

References

1. *N. Uçar, T. Yilmaz. Fibres & Textiles in Eastern Europe, 12(3), (2004), p. 34-38.*
2. *J. Szosland. Fibres & Textiles in Eastern Europe, 7(2), (1999), p. 41-45.*
3. *H. Sari, X. Berger. International Journal of Thermal Sciences, 39(7), (2000), p. 684-692.*
4. *H. Sari, X. Berger. International Journal of Thermal Sciences, 39(7), (2000), p. 673-683.*
5. *P. Bishop, D. Gu, A. Clapp. International Journal of Industrial Ergonomics, 25(3), (2000), p. 233-238*
6. *I. Frydrych, G. Dziworska, J. Bilska. Fibres. Fibres & Textiles in Eastern Europe, 12(2), (2002), p. 40-44.*
7. *M. Zimniewska, M. Michalak, I. Krucinska, B. Wieck. Fibres. Fibres & Textiles in Eastern Europe, 12(4), (2003), p. 55-57.*
8. *Nadzeikeinė J. Influence of Environmental Factors on Thermal Comfort of Working Person. Doctoral dissertation, 2005. 116 p.*
9. *Kreith F., Bohn M.S. Principles of Heat Transfer.- Harper and Row Publishers Inc., (1986),700 p.*
10. *Incropera F.P., DeWitt D.P. Fundamentals of Heat and Mass Transfer, 5th Edition. Hardcover (2001), 1008 p.*

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