Monika Bogusławska-Bączek, *Lubos Hes

University of Bielsko-Biala, Faculty of Materials and Environmental Sciences, Institute of Textile Engineering and Polymers Materials, Department of Textile Engineering and Science of Commodities,
ul. Willowa 2, 43-309 Bielsko – Biała, Poland,
E-mail: mboguslawska@ath.bielsko.pl

***Technical University of Liberec, Faculty of Textile Engineering, Department of Textile Evaluation,**
Liberec, Czech Republic

Effective Water Vapour Permeability of Wet Wool Fabric and Blended Fabrics

Abstract
The water vapour permeability of fabrics is one of the most important factors determining wearer comfort. Contrary to commonly accepted theories, outerwear is often used in a wet state, which has an influence on their properties. However, common standard measuring instruments mostly do not enable reliable measurement of wet fabrics due to the long time of measurement, during which the fabrics get dry. This paper presents the fast instrument - Permetest, which provides reliable measurement of the water vapour permeability of fabrics in a dry and wet state. By means of the instrument, the relative and effective water vapour permeability of different wool fabrics in a dry and wet state were determined and the results discussed. The main contribution of the measurement was the determination of the exact ratio between the level of heat flux density of the heat flow penetrating the wet fabric, having a cooling effect, and that of the heat flux density of the heat flow caused by moisture evaporation from the fabric surface, also having a cooling effect.

Key words: *water vapour permeability, Permetest, wet fabrics, cooling, heat flow.*

Survey of symbols used

α, - convection heat, $W{\cdot}m^{-2}K^{-1}$,
β_p - mass transfer coefficients, $kg{\cdot}m^{-2}Pa^{-1}s^{-1}$,
L - latent heat of evaporation of water, $J\ kg^{-1}$,
q_{fabw} - density of heat flux caused by convection mass transfer from the fabric surface, $W{\cdot}m^{-2}$,
$q_{fabw,sk}$ - density of heat flux causing skin cooling by evaporation from the wet fabric, $W{\cdot}m^{-2}$,
q_{skin} - density of heat flux evaporated from the skin, $W{\cdot}m^{-2}$,
q_{tot} - density of heat flux (q_{tot}) transferred through the boundary layer on the fabric surface, $W{\cdot}m^{-2}$,
q_o- density of heat flux passing through the uncovered measuring head, $W{\cdot}m^{-2}$,
$p_{sat}, p_{sat,fab}$ - saturated water vapour pressure on the skin and fabric surface in Pa, which increases with the skin and / or fabric temperature,
p_{wo} - water vapour saturate partial pressure valid for the temperature of air in the measuring laboratory, Pa,
p_{air} - water vapour pressure of outside air, Pa,
R_{eto}, R_{cgap} - evaporative resistance of the boundary layer and air gap, $Pa{\cdot}m^2W^{-1}$,
R_{et} – evaporative resistance of the fabric, $Pa{\cdot}m^2W^{-1}$,
R_{ct}, R_{gap} - thermal resistances of the fabric in an ultra-dry state and that of the air gap, $K{\cdot}m^2W^{-1}$,
R_{ctw} - thermal resistance of the fabric in a wet state, Km^2W^{-1},
D_p - diffusion coefficient related to water vapour partial pressure and heat flow, W/Pa·m,
Δt_{air} - gradient of ambient temperature q_s - heat flux passing through the measuring head covered by the sample, $W{\cdot}m^{-2}$,
U - relative mass increase of the fabric with moisture content in %, determined by weighing,
h - thickness of air gaps between the measuring surface and fabric, m,
k – experimentally determined constant characterising the decrease in thermal resistance caused by the increased moisture U of the fabric.

Introduction

Thermal comfort implies the maintenance of body temperature within relatively narrow limits. Under conditions where thermal comfort cannot be achieved by the human body's own ability (i.e. body temperature regulation), such as very cold or hot weather, clothing must be worn to support its temperature regulation by resisting or facilitating heat exchange between the human body and the environment. Together with good insulation, the garment should allow adequate transport of water vapour from the body to the external environment. Thus the final thermo-physiological comfort is given by two principal components: thermal resistance in a wet state and active cooling resulting from moisture evaporation from the skin and passing through the garment and from direct evaporation of sweat from the fabric surface [1, 2]. Fundamental papers on fabric thermal resistance and water vapour permeability have been published [3 - 5], but they did not take into consideration the aspect of changes in these parameters due to the moisture content of fabrics. In a dry state, most fabrics deliver satisfactorily permeability to water vapour (WVP), but in a wet state, a water film on the outer fabric surface is formed, which may reduce the effective permeability of the fabric [6, 7]. Meanwhile wet skin can greatly increase the cooling effect of the body, and hence, for example, a moisture content of 10 - 20% could cause a drop in thermal insulation of up to 50% compared to the dry fabric. Sweat production by the human body depends on the type and intensity of physical activity, and changes from 40 – 100 g/h (standard perspiration) to even up to 1 litre of sweat in an hour (very heavy physical work). Therefore it seems very important to investigate the water vapour permeability of fabric not only in a dry state but also in a wet state, which applies in particular to fabrics with high hygroscopicity, which wool fabrics have. Unfortunately, the permeability cannot be detected by common WVP testers because the samples during this measurement get dry as a result of too long time of measurement. The only instruments that are suitable for WVP evaluation of wet fabrics are instruments of the Skin Model Type (f.e. PERMETEST Sensora Skin Model), which allow to perform tests quickly and reliably [8].

Theoretical assumptions

The heat flux density generated due to sweat evaporation determines heat lost by the body and has a cooling effect on it. The heat flux density also has an effect on cooling due to the moisture which evaporates from the surface of the fabric (see ***Figure 1***, page 68). However, this cooling effect may not cool the body sufficiently because the heat flux density caused by the temperature drop at the fabric surface is reduced by the effect of

Bogusławska-Bączek M, Hes L. Effective Water Vapour Permeability of Wet Wool Fabric and Blended Fabrics.
FIBRES & TEXTILES in Eastern Europe 2013; 21, 1(97): 67-71.

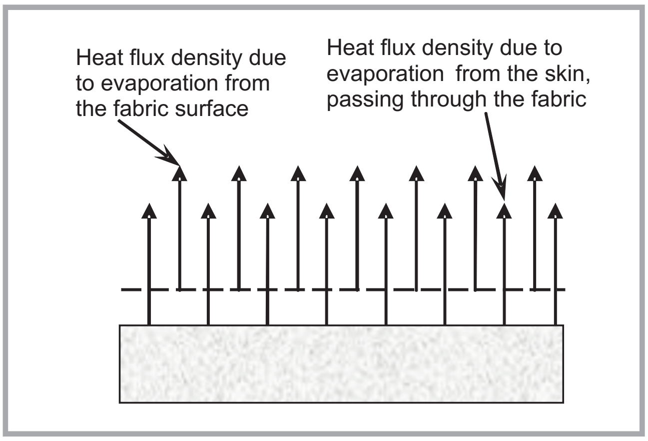

Figure 1. Heat flux density generation due to sweat evaporation from the skin surface and moisture evaporation from the fabric surface [7].

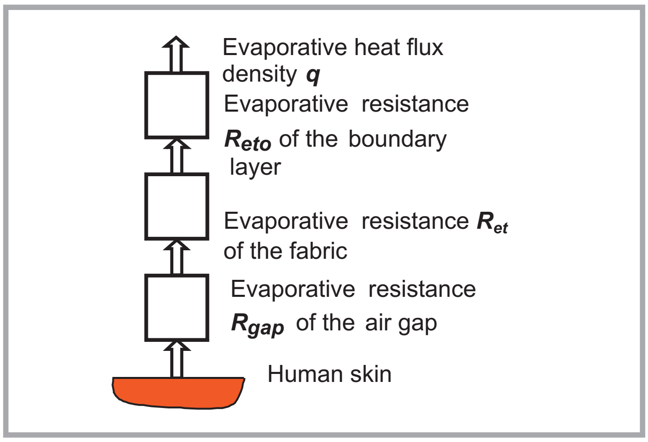

Figure 2. Evaporative resistances (connected in series) during evaporative heat flux from the skin through the garment [7].

thermal resistance of the fabric and by that of the air gap between the fabric and skin [9, 10]. In this study the effect of the contact thermal resistance is neglected. ***Figure 2*** shows all the evaporation resistances R_{et} in Pa·m^2/W encountered during the passage of heat flux density caused by the evaporation of sweat to the environment.

At first, the effect of skin cooling caused by the evaporation of moisture from the fabric surface was analysed. Despite the assumption of isothermal conditions, the wet fabric becomes cooler than the surrounding air because the fabric surface, due to the effect of a certain fabric thermal resistance, is not kept at the temperature of the instrument's (Skin Model) measuring surface. The heat flux density, caused by convection mass transfer from the fabric surface (q_{fabw}), can be described by ***Equation 1***, on condition that the fabric surface is covered by a continuous water film [7]:

$$q_{fabw} = L\,\beta_p(p_{sat,\,fab} - p_{air}) \qquad (1)$$

The force which causes water vapour transfer can be expressed as the difference in partial pressures of water vapour, or as the difference in water vapour concentrations. In the Ergonomic Sciences, the use of partial pressures of water vapour (***Equation 1***) is more common [1, 6]. Except for dry and very dry fabric states, a continuous water film is present at any level of fabric moisture - it is called the period of constant drying velocity and constant fabric surface temperature. During this period, the partial pressure of water vapour at the skin surface reaches saturation. The heat flux density q_{fabw} must be in equilibrium with thermal losses by convection to the outside air and heat conduction towards the skin:

$$L\,\beta_p\,(p_{sat,fab} - p_{air}) = \\ = \alpha\,\Delta t_{air} + \Delta t_{air}/(R_{ctw} + R_{gap}) \qquad (2)$$

The thermal resistance of the fabric in a wet state R_{ctw} can be in the first approximation expressed as a linear function of the relative moisture of the fabric U:

$$R_{ctw} = R_{ct}\,(1 - kU) \qquad (3)$$

The heat flux density causing skin cooling then follows from the equations:

$$q_{fabw{\cdot}sk} = \Delta t_{air}/(R_{ctw} + R_{gap}) \qquad (4)$$

Table 1. Specifications of wool fabrics tested.

No	Fibre content	Square mass G, g/m^2	Thickness h, mm	Density of threads d, dm^{-1}	
				warp	weft
1	100% wool	150	0.38	250	220
2	100% wool	180	0.42	320	250
3	100% wool	200	0.45	380	320
4	100% wool	210	0.47	400	360
5	100% wool	240	0.48	420	380
6	45% wool/55% viscose	180	0.38	330	240
7	45% wool/55% viscose	210	0.45	380	340
8	45% wool/55% PES	180	0.42	300	240
9	45% wool/55% PES	210	0.48	400	380

$$q_{fabw,sk} = \\ = \frac{\beta_p(p_{satfab} - p_{air})}{1 + \alpha R_{ct}(1 - kU) + \alpha R_{gap}} \qquad (5)$$

Equation 5 confirms that with increasing fabric moisture, fabric thermal resistance decreases, which causes an increase in the cooling effect by conducting the heat flux away from the skin. This explanation can be simplified - the increase in moisture of the fabric will also probably be followed by an increase in the mass transfer area, at least to some extent. The heat flux density evaporated from the skin (q_{skin}) can be then described by ***Equation 6***, provided that the partial pressure of water vapour at the skin surface reaches the saturated level (this assumption is used by many researchers [1, 6]):

$$q_{skin} = \frac{p_{sat} - p_{air}}{R_{gap} + R_{et} + R_{eto}} \qquad (6)$$

The evaporative resistance of the relatively narrow air layer (R_{gap}) without the contribution of free convection [11] can be described as:

$$R_{gap} = h/D_p \qquad (7)$$

The evaporative resistance of the boundary layer (R_{eto}) yields the next equation:

$$R_{eto} = 1/\,\beta_p \qquad (8)$$

Thus the flux density of the total heat flux (q_{tot}) transferred through the boundary layer on the fabric surface is obtained (with some simplifying assumptions like neglecting the heat transfer by radiation) from the sum of heat flux densities of heat flux passing from the skin through the permeable fabric and the heat flux caused by the temperature gradient between the skin and fabric surface, which is cooled by the evaporation of water from the fabric surface, as follows:

$$q_{tot} = \frac{p_{sat} - p_{air}}{R_{gap} + R_{et} + R_{eto}} + \qquad (9)$$
$$+ \frac{\beta_p (p_{satfab} - p_{air})}{1 + \alpha R_{ct}(1 - kU) + \alpha R_{gap}}$$

Experimental materials

The research material used was weave 2/1 twill fabrics in different combinations of the percentage of wool fibres and square mass (***Table 1***). They were measured in a laboratory at a temperature of 21 ± 0.5 °C and 55 ± 1% relative humidity.

Research program

The researches were conducted with PERMETEST apparatus, which measured the amount of heat passing through the thermal model of human skin (***Figure 3***).

The fabric sample was placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1 m/s. The measurements were carried out under isothermal conditions (23.0 ± 0.5 °C). A computer connected to the apparatus determined the evaporative resistance, Ret, and thermal resistance, R_{ct} and *RWVP,* of the textile fabrics according to the standard ISO 11092, which did not refer to the fabric surface temperature when there was an air gap between the skin model surface and test fabric (***Equation 8***). These values served to reflect the thermophysiological properties of the textile fabrics and garments. The higher the *RWVP*, the lower the R_{et}, and the better the thermal comfort of the garment.

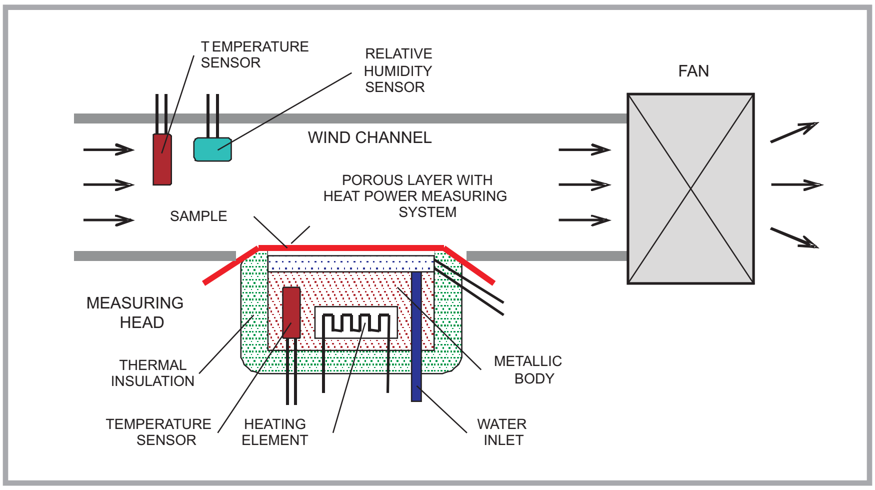

Figure 3. *PERMETEST skin model [8].*

The relative water vapour permeability, *RWVP* in %, was calculated from the relationship:

$$RWVP = q_s / q_o \times 100\% \qquad (10)$$

The samples were first dried in an air conditioner at 105.0 ± 0.5 °C in order to get rid of all moisture. The samples were subsequently soaked with water to their full volume to increase their humidity. The water used for soaking contained a surfactant to lower the surface tension. During the measurement procedure, each sample was stepwise mechanically dried and weighed. When the results of the measurement should be expressed in terms of water vapour resistance R_{et} in Pa·m²/W according to the ISO 11092 standard [11], then the following relationship was applied:

$$R_{et} = (p_{wsat} - p_{wo}) \, [(1/q_s) - (1/q_o)] = \\ = C\,(100 - \varphi)\,[(1/q_s) - (1/q_o)] \qquad (11)$$

Here, q_s and q_o mean the heat flux density lost by the moist measuring head and p_{wo} in ***Equation 11*** represents the water vapour saturate partial pressure valid for the temperature of air in the measuring laboratory (21.0 ± 0.5 °C), and the partial water vapour pressure in the laboratory air. Constant *C* was determined by the calibration procedure. For this purpose special hydrophobic polypropylene reference fabric was delivered with the instrument.

All fabrics were tested in various states of moisture content: 1 – normal state, 2 – 'ultra-dry' and 3 – various wet states. The experiment consisted of measuring the *RWVP* and R_{et} of dry and wet fabrics without an air layer (*h* = 0 mm).

Results and discussion

From the experimental results obtained from PERMETEST measurement it was seen that with the increasing square mass of wool fabrics in a dry state, the relative

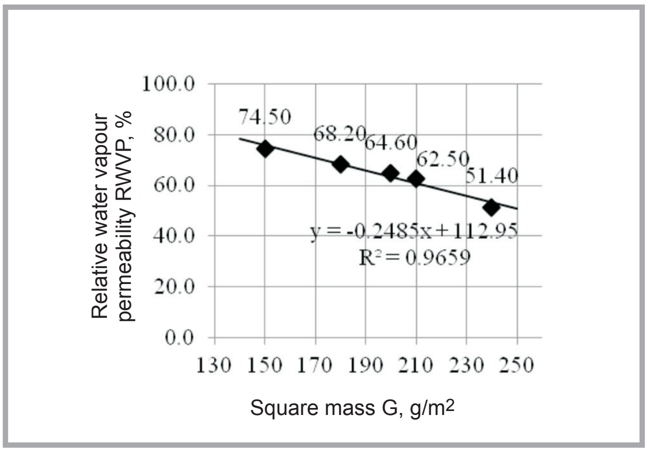

Figure 4. *Square mass effect on relative water vapour permeability RWVP of dry 100% wool fabrics.*

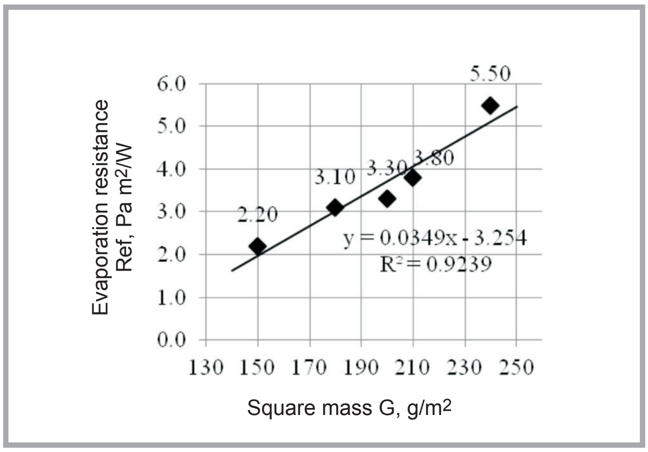

Figure 5. *Square mass effect on water evaporation resistance R_{et} of dry 100% wool fabrics.*

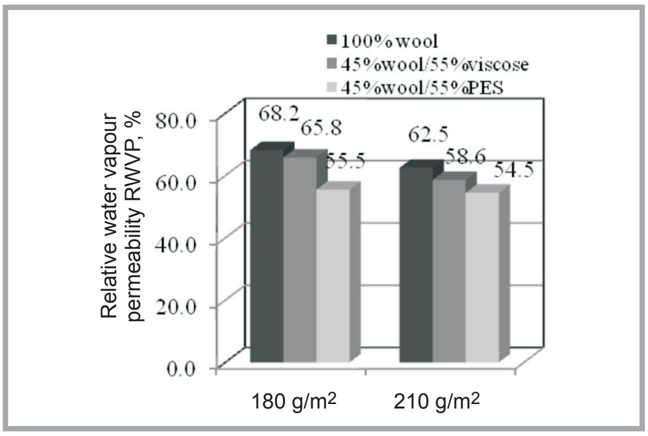

Figure 6. Effect of fibre content on the relative water vapour permeability RWVP of dry fabrics.

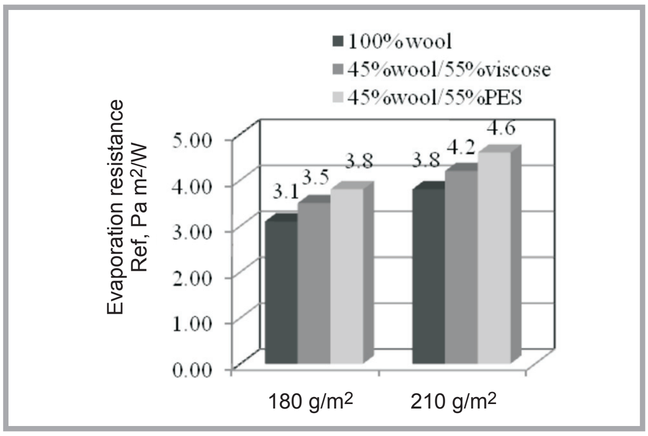

Figure 7. Effect of fibre content on the evaporation resistance R_{et} of dry fabrics.

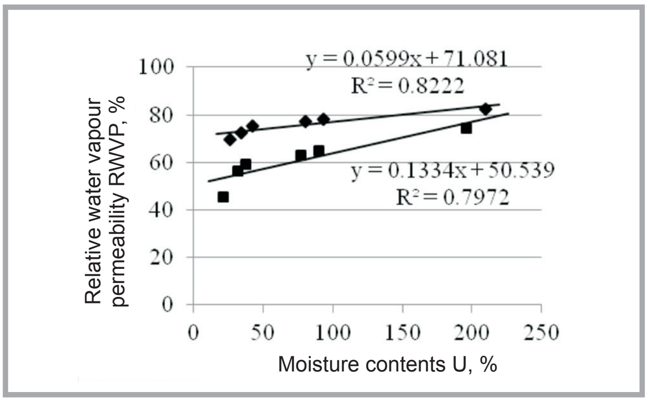

Figure 8. Relative WVP of wet 100% wool fabric (sample No. 2): the lower line is the cooling heat flux from the fabric surface, and the upper line is the total cooling heat flux.

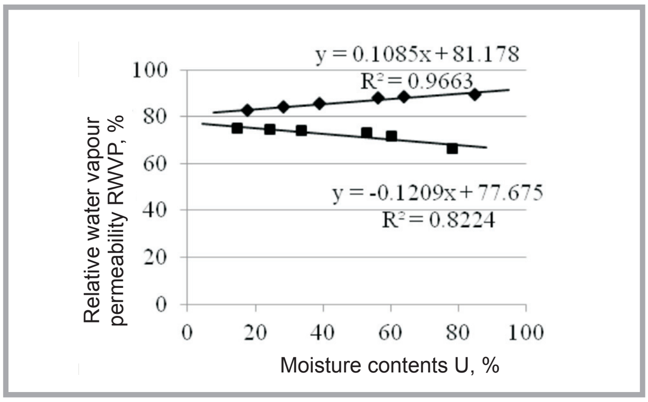

Figure 9. Relative WVP of wet 45%wool/ 55%viscose fabric (sample No. 6): the lower line is the cooling heat flux from the fabric surface, and the upper line is the total cooling heat flux.

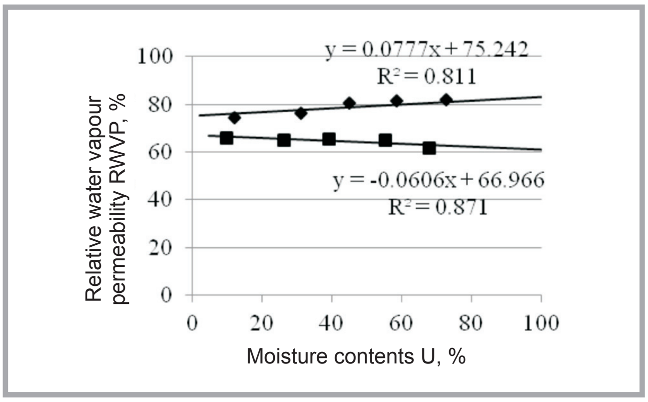

Figure 10. Relative WVP of wet 45%wool/ 55%PES fabric (sample No. 8): the lower line is the cooling heat flux from the fabric surface, and the upper line is the total cooling heat flux.

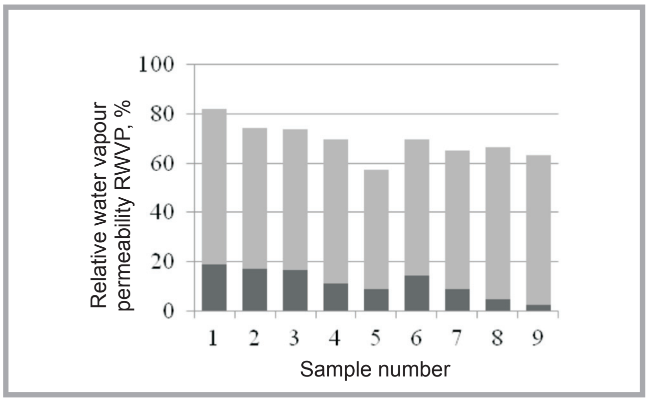

Figure 11. Relative WVP of all test samples at 50% fabric moisture content, consisting of real vapour transfer through the wet fabric (bottom level) and evaporation from the fabric surface (upper level).

water vapour permeability decreased, as has been plotted in ***Figure 4***. At the same time it can be seen that the vapour resistance of wool fabrics in a dry state increased when the square mass of the fabric increased (***Figure 5***). The research also showed that with a reduction in the percentage of wool fibres, the ability to transmit water vapour decreased. This phenomenon was more noticeable for polyester fibres than for viscose fibres (***Figures 6** and **7***).

The strategy of the wet study was as follows: if liquid water in the wet fabric structure creates a partially continuous film, then the transfer of water vapour should be limited. The results of the measurement of *RWVP* through wet fabrics shown on the diagrams (examples ***Figure 8 - 10***) confirmed that with increasing fabric moisture, the *RWVP* also increased. In all fabrics tested these dependences were linear, which confirmed the measurement reliability. In ***Figures 8, 9*** and ***10*** the lower line shows the cooling heat flux from the fabric surface, and the upper line - the total cooling heat flux. The experimental results also show that for the high hygroscopicity fabric the difference between the total heat flux density, which caused a cooling effect, and the heat flux density from the fabric surface, which also influenced the cooling effect, decreased with an increase in moisture content. Whereas in the case of the blended fabric with artificial or synthetic fibres, these differences increased with a rising moisture content in the fabric. This was dictated by the fact that in the fabrics with hydrophilic fibres most of the moisture absorbed was 'jammed' by the fibres, whereas in the case of blended hydrophilic fabrics with hydrophobic fibres the moisture was 'jammed' into the structure of the fabric, creating a partially continuous film on the surface of the wet fabrics.

Unfortunately the research found that for all fabrics investigated the effective water vapour permeability of wet fabrics is quite low and equals about 20% of total *WVP* for 100% wool fabrics, about 16% of the total *WVP* for wool/ viscose blended fabrics and only about 5% of the total *WVP* for wool/PES blended fabrics (***Figure 11***).

Conclusions

- From the results presented it follows that the square mass and addition of hydrophobic fibres affect the ability of wool fabrics to transport water vapour. With an increase in the square mass, there is a decrease in the relative water vapour permeability and increase in the water vapour resistance of wool fabrics. At the same time, if the fibres of blended fabrics were more hydrophobic, the worse their water vapour permeability was.
- The investigation showed that an increasing moisture content in fabrics significantly worsens their ability to transport water vapour. For wool fabrics and wool/viscose blended fabric the value decreases by over 70 - 80%. However, in the case of the addition of polyester fibres, the effective permeability of water vapour almost disappears, which is caused by substituting the air in pores by water with higher thermal conductivity. This means also that the physiological properties of the fabric, which is becoming increasingly wet as a result of use, are subject to sudden changes, which significantly affects the quality of the apparel. Knowledge of these phenomena is very important in clothing design and technology, especially for outer garments used in extreme weather conditions with high humidity
- The work presented has proved that the PERMETEST instrument enables simulation of the complex thermal feeling of a wearer of a wet garment. Using this apparatus, a new method of assessing the effective water vapour permeability of wet fabrics was developed. Moreover it was shown that the standard methods hitherto used have given erroneous results, because when the fabrics are wet, the total relative heat flux density consists not only of the flow transferred through the fabrics, but also the heat flux density caused by moisture evaporation from the fabric surface.

References

1. Gibson PW. Factors influencing steady-state heat and water-vapour transfer measure for clothing materials. *Textile Research Journal* 1993; 63, 12: 749-764.
2. Frydrych I, Dziworska G, Bilska J. Comparative analysis of the thermal insulation properties of fabrics made of nature and man – made cellulose fibres. *FIBRES & TEXTILES in Easter Europe* 2002; 10, 4(39): 40-44.
3. Bivainyte A, Mikučioniene D. Investigation on the Air and Water Vapour Permeability of Double Layered Weft Knitted Fabrics. *FIBRES & TEXTILES in Eastern Europe* 2011; 19, 3 (86): 69-73.
4. Gulbiniene A, Jankauskaite V, Kondratas A. Investigation of the Water Vapour Transfer Properties of Textile Laminates for Footwear Linings. *FIBRES & TEXTILES in Eastern Europe* 2011; 19, 3 (86): 78-81.
5. Petrulyte S, Baltakyte R. Liquid Sorption and Transport in Woven Structures. *FIBRES & TEXTILES in Eastern Europe* 2009; 17, 2 (73): 39-45.
6. Ren Y, Ruckman JE. Water vapour transfer in wet waterproof breathable fabrics. *Journal of Industrial Textiles* 2003; 32, 3: 165-175.
7. Hes L, Araujo I. Simulation of the effect of air gaps between the skin and a wet fabric on resulting cooling flow. *Textile Research Journal* 2010; 80 (14): 1488–1490.
8. Hes L, Dolezal I. A new portable computer-controlled skin model for fast determination of water vapour and thermal resistance of fabrics. In: *Asian Textile Conference* (ATC 7), New Delhi, 2003.
9. Bogusławska – Bączek M, Hes L. The effect of moisture on thermal resistance and water vapour permeability of Nomex fabrics. *Journal of Materials Science and Engineering* 2011; 1, 3: 358-366.
10. ISO 11092 Standard "Textiles – Physiological effects - Measurement of the thermal and water vapour resistance.

Received 17.11.2011 Reviewed 16.07.2012