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Analysis and Experimental Determination of Effective Water Vapor Permeability of Wet Woven Fabrics

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ABSTRACT

Despite the fact, that protective clothing is very often used in wet state, which reduces its thermal insulation and water vapor permeability (WVP), just few papers were published on fabric thermal comfort in wet state. Moreover, there are no standards on testing of (WVP) of fabrics in wet state available. In the paper, an analysis of effective WVP of fabrics in wet state is presented, along with related experimental results based on the measurement of relative cooling flow passing through a fabric placed on the measuring surface of the PERMETEST instrument. The difference between the direct measurement and the measurement with a foil inserted between the wet sample and the measuring surface of the tester then presents the required level of the relative cooling flow or relative WVP of fabrics in wet state. From the measurements of effective relative WVP of 30 woven fabrics differing in the used polymer and structure at 4 moisture levels follows, that the most interesting results were achieved at the 50% moisture level, which is may serve as the reference moisture level in the proposed new testing standard.

Keywords: Water vapor permeability, textile fabrics, wet state, testing standard

Introduction

Contrary to a common clothing, protective garments, due to sweat sorption or because of the effect of rainy climate are often used in wet state, which influence their thermo-physiological comfort. Sweat evaporation from the skin which passes through the garment and the direct evaporation of moisture from the fabric surface cause the cooling flow, which may contribute to the wearing comfort of the user, but in most cases reduces the effective thermal insulation of the garment. In fundamental papers on water vapor permeability (WVP) of textile fabrics such as [1,2] the authors did not take into consideration the changes in this parameter due to the absorbed moisture. This follows from the fact that current measuring instruments for the evaluation of thermo-physiological properties of fabrics usually require more than 30 minutes for full reading, thus avoiding the precise determination of fabrics humidity effect on the cooling heat flow, due to the humidity decrease during the measurement. Therefore, a detailed analysis of cooling effect accompanying wearing of wet fabrics is almost missing in the literature, as well as any standard method for determination of WVP of fabrics in wet state. One of the few instruments suitable for the WVP evaluation of wet fabrics is the fast working non-destructive PERMETEST Skin Model, which performs precise measurements within a few minutes [3,4]. In the paper the measurement of relative and effective water vapor permeability of selected woven fabrics in dry and wet state are described. The presented results are discussed with respect to the fabric structure and composition and used in the proposal of a new standard method for determination of WVP of fabrics in wet state.

1. Approach

Cooling of human body by the heat flow generated by the sweat evaporation causes heat loss. However, the effect of cooling also affects the heat flow due to moisture evaporation from the surface of fabric - see Fig. 1. This cooling effect may not cool the body sufficiently, because the heat flow caused by the temperature drop at the fabric surface is reduced by the effect of thermal resistance of fabric and thermal resistance of the air gap between the fabric and a skin – see the detailed analysis in [4,5]. In this study, the effect of the contact thermal resistance is neglected. The model of the total evaporative resistance (Pa*m^2/W) can be shown as a sum of three evaporative resistances reducing the heat flow (W/m^2), caused by the evaporation of sweat into the environment - see Fig. 2.

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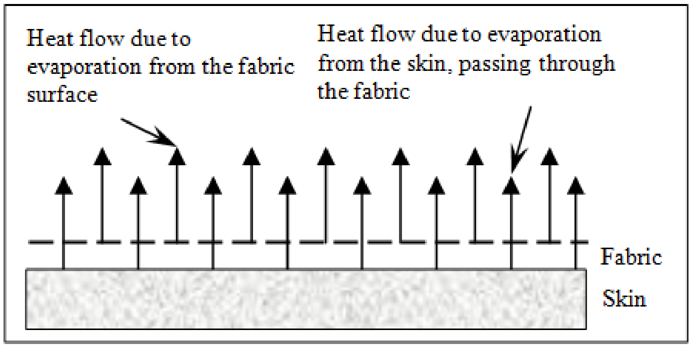


Figure 1. Heat flow generation due to sweat evaporation from the skin and heat flow released from the wet fabric surface

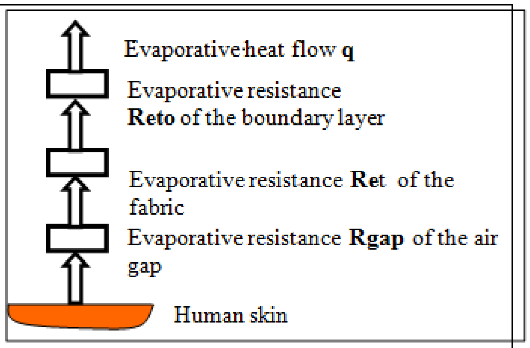


Figure 2. Model of evaporative resistances during the moisture evaporation from the skin

As shown in the Fig. 1, the total heat flow (qtot) transferred through the boundary layer on the fabric surface is given by the sum of heat flux passing from the skin through the fabric and heat flux caused by temperature gradient between the skin and fabric surface, which is cooled by evaporating of water from the fabric surface (see the details in [4,5]):

$$q_{tot} = \left[(p_{sat} - p_{air})/\left(R_{gap} + R_{et} + R_{eto}\right)\right] + \left\{ß.L(p_{sat} - p_{air})/\left[1 + \alpha.R_{ct}(1 - k.U) + \alpha.R_{cgap}\right]\right\} \quad (1)$$

where:

α, β - convection heat and mass transfer coefficients (W.m-^{2}K-1), (kg.m^{-2}Pa^{-1}s^{-1}),

k - experimentally determined constant characterizing the decrease of the fabric thermal resistance R_{ct} with moisture content U

L - latent heat of evaporation of water (J/kg),

p_{air} - water vapor pressure of the outside air (Pa),

p_{sat}, $p_{sat,fab}$ - saturated water vapor pressure on the skin and fabric surface (Pa),

R_{ct}, R_{gap} -thermal resistances of a fabric in ultra-dry state and that of air gap (K.m^{2}/W),

R_{et} – evaporative resistance of the fabric (Pa.m^{2}/W),

R_{eto}, R_{cgap} - evaporative resistance of the boundary layer and of the air gap (Pa*m^{2}/W),

q_{o}- the heat flux passing through the uncovered measuring head (W.m^{-2}),

q_{v} - the heat flux passing through the measuring head covered by the sample (W.m^{-2}),

U – content of moisture in the fabric related to the ultra-dry mass of the tested fabric (%).

This analysis was also used in this study, but this time the air gap between the fabric and the simulated skin in the testing instrument was not considered, it means the R_{gap}= 0.The measurement of the effective relative cooling flow or effective relative water vapor permeability of fabric in wet state ($P_{eff\ rel\ wvp}$) consists of several steps, as explained below.

In the regime of calibration, the used PERMETEST instrument always measures the evaporation resistance of the boundary layer Reto (no sample inserted), which then presents the relative vapor permeability $P_{rel\ wvp}$.

$$q_0 = \Delta p/R_{eto} \quad \text{where} \quad \Delta p = (p_{sat} - p_{air}) \quad (2)$$

This signal is then adjusted as $P_{rel\ wvp}$ = 100%. When dry fabric (measured under standard laboratory conditions) with evaporation resistance R_{et} is inserted, then the relative cooling flow or RWVP in dry state (with R_{et}) will be:

$$RWVP = q_s/q_0 = [\Delta p/(R_{et} + R_{eto})]/\{\Delta p/R_{eto}\} = R_{eto}/\{R_{et} + R_{eto}\} \quad (3)$$

where q_s is cooling flow with inserted sample. Now consider that instead of dry fabric, wet fabric is inserted. Relative cooling flow determined by the instrument, which arrives from the wet fabric surface only (see the theory in [4,5]) yields the relationship

$$q_{rel\ cool\ wet} = \{\beta.L.\Delta p/[1 + \alpha.R_{ct}(1 - k.U)]\}/(\Delta p/R_{eto}) = \beta.L.R_{eto}/[1 + \alpha.R_{ct}(1 - k.U)] \quad (4)$$

Total relative cooling flow measured by the PERMETEST in the first step (no separating foil placed between the measuring head and the tested sample):

$$q_{tot\ cool\ rel\ wet} = [R_{eto}/(R_{etw} + R_{eto})] + \{\beta.L.\Delta p/[1 + \alpha.R_{ct}(1 - k.U)]\}/(\Delta p/R_{eto}) \quad (5)$$

After simplification

$$q_{tot\ cool\ rel\ wet} = [R_{eto}/(R_{etw} + R_{eto})] + \beta.L.R_{eto}/[1 + \alpha.R_{ct}(1 - k.U)] \quad (6)$$

where R_{etw} is the evaporative resistance of a fabric in wet state. In the second step a thin separating foil is placed between the measuring head and the tested sample. Thus, no water vapor can penetrate through the wet fabric and just evaporation cooling flow from the wet surface is recorded. Relative cooling flow from the wet fabric surface then is as follows:

$$q_{rel\,cool\,wet\,surface} = \beta.L.R_{eto}/[1 + \alpha.R_{et}(1 - k.U)] \quad (7)$$

Effective relative cooling flow or effective relative water vapor permeability of a fabric in wet state then results from the difference of the above equations(6) and (7):

$$q_{rel\,cool\,wet\,fab} = R_{eto}/(R_{etw} + R_{eto}) \quad (8)$$

2. Experimental

In this research, 30 various woven fabrics with plain, satin and twill structure at 3 different weft setts were investigated. Their square mass ranged from 170 to 220 g/m^2 and they consisted of cotton (co), viscose (VI), polyester (PE) and polypropylene (PP) fibers – see the Tab. 1. The temperature of measurement was 21-23ºC and their relative moisture related to the ultra-dry state was 25%, 50% and 75 %. Each sample was measured 5 times. The experiment consisted of measuring the RWVP and R_{et} of dry and wet fabrics. In the first series of measurement, the relative cooling flow was measured on fabrics directly placed on the measuring surface of the PERMETEST instrument, and in the second step, and impermeable foil was inserted between the wet sample and the measuring surface of the tester. The difference between the direct measurements and the measurement with a foil then presents the required level of the relative cooling flow or RWVP of fabrics in wet state. The Tab. 2 then presents an example of big volume of the executed measurements, as it refers to the samples made of polypropylene and cotton only. The full data can be found in [6].

Table 1. Samples characteristics

Material	Structure	Density a,b,c [warp/weft /cm]			Square mass a,b,c [g/m^2]		
PP	Satin 5/1	36/11	36/14	36/17	270	260	300
PP	Plain	18/11	18/13	18/15	175	195	200
PP	Twill 3/1	27/9	27/12	27/15	185	225	230
VI	Satin 5/1	36/16	36/19	36/22	230	250	270
VI	Plain	18/13	18/15	18/17	170	170	170
VI	Twill 3/1	27/14	27/17	27/20	195	230	240
PES	Satin 5/1	36/13	36/16	36/19	280	285	300
PES	Plain	18/12	18/14	18/16	175	190	195
PES	Twill 3/1	27/11	27/14	27/17	220	240	250
CO	Plain	30/25	20/18	18/15	175	185	180

Table 2. Results of measurements

Moisture [%]	Fabric/ Structure	q_{tot} /$q_{fab\ surf.}$ [%]	CV [%]	Moisture [%]	Fabric/ Structure	q_{tot} /$q_{fab\ surf.}$ [%]	CV [%]
Dry state	PP 27/15 t	52,4	0,5	Dry state	PP 18/11 pl	57,4	0,8
25%	PP 27/15 t	77,0	1,6	25%	PP 18/11 pl	78,4	1,9

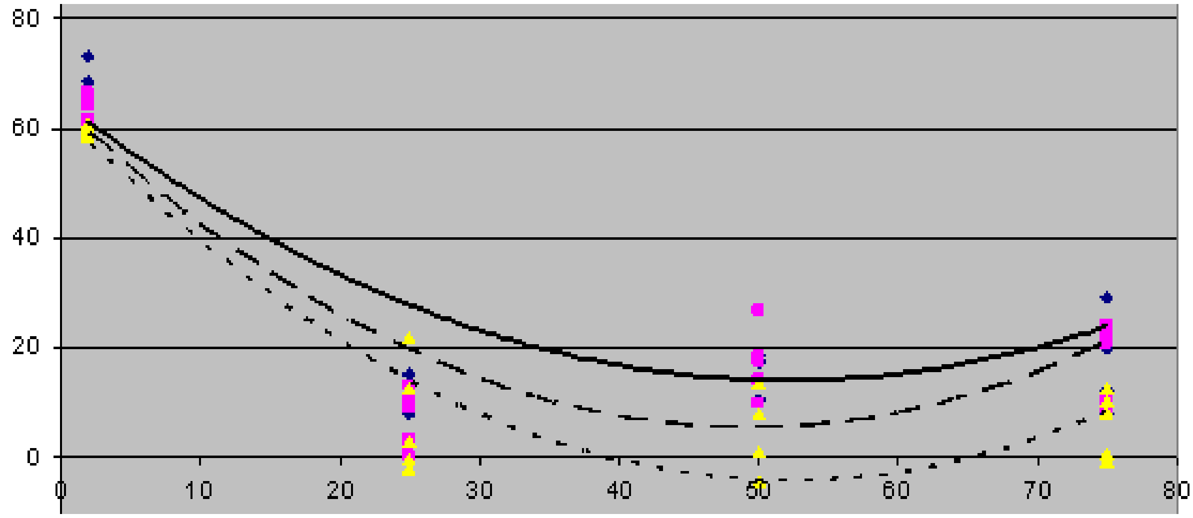
	FS	59,3	4,2		FS	57,9	4,8
50%	PP 27/15 t	76,5	1,9	50%	PP 18/11 pl	75,2	1,5
	FS	58,3	4,2		FS	55,1	2,5
75%	PP 27/15 t	78,0	1,2	75%	PP 18/11 pl	77,3	1,7
	FS	59,4	2,2		FS	57,5	2,5
Dry state	PP 27/12 t	53,4	0,2	Dry state	PP 18/13 pl	59,1	3,8
25%	PP 27/12 t	76,7	3,4	25%	PP 18/13 pl	77,5	0,6
	FS	62,6	5,1		FS	59,5	4,2
50%	PP 27/12 t	79,3	2,2	50%	PP 18/13 pl	77,7	2,5
	FS	65,2	5,0		FS	66,2	2,6
75%	PP 27/12 t	80,6	1,6	75%	PP 18/13 pl	79,5	2,1
	FS	63,2	3,2		FS	62,2	1,7
Dry state	PP 27/9 t	54,7	2,5	Dry state	PP 18/15 pl	55,8	1,8
25%	PP 27/9 t	76,1	3,2	25%	PP 18/15 pl	80,5	1,8
	FS	57,9	3,9		FS	61,3	0,6
50%	PP 27/9 t	72,4	4,1	50%	PP 18/15 pl	81,0	2,4
	FS	59,0	3,5		FS	61,0	2,0
75%	PP 27/9 t	75,5	0,9	75%	PP 18/15 pl	82,3	1,7
	FS	57,7	3,9		FS	62,8	3,0
Dry state	PP 36/14 s	49,7	2,6	Dry state	Co 30/25 pl	64,4	1,7
25%	PP 36/14 s	73,7	1,3	25%	Co 30/25 pl	90,0	5,2
	FS	56,9	6,7		FS	83,1	9,2
50%	PP 36/14 s	74,8	2,2	50%	Co 30/25 pl	90,6	2,9
	FS	51,7	3,3		FS	87,9	8,1
75%	PP 36/14 s	69,8	1,2	75%	Co 30/25 pl	92,5	2,7
	FS	51,0	7,4			86,4	4,5
Dry state	PP 36/17 s	47,6	2,2	Dry state	Co 20/18 pl	73,0	4,0
25%	PP 36/17 s	76,0	1,2	25%	Co 20/18 pl	90,8	4,2
	FS	60,5	3,3		FS	82,1	5,7
50%	PP 36/17 s	77,1	1,2	50%	Co 20/18 pl	94,5	2,6
	FS	59,3	2,6		FS	77,7	5,1
75%	PP 36/17	77,4	1,7	75%	Co 20/18 pl	95,8	1,8

	s						
	FS	59,3	4,3		FS	77,9	9,0
Dry state	PP 36/11s	47,5	1,1	Dry state	Co 25/20 pl	68,3	3,6
25%	PP 36/11s	75,5	2,0	25%	Co 25/20 pl	89,2	2,6
	FS	58,1	6,7		FS	82,0	6,0
50%	PP 36/11s	74,2	1,7	50%	Co 25/20 pl	92,7	0,4
	FS	56,4	4,2		FS	75,3	8,3
75%	PP 36/11s	73,5	1,7	75%	Co 25/20 pl	95,1	1,1
	FS	56,3	1,6		FS	77,8	8,0

Note: The code FS presents the relative cooling flow from the fabric surface only, and the abbreviations characterize the weave structures: t = twill, s = satin, pl = plain, CV – coefficient of variation

An example of the above results in the form of diagram for the cotton plain weave are displayed on the Fig. 3. The results for next 29 studied fabrics exhibit very similar dependencies.

Effective relative water vapor permeability [%]



Relative moisture content [%]

Figure 3. The effect of the relative moisture content on the effective relative water vapor permeability (RWVP) of the cotton plain weave

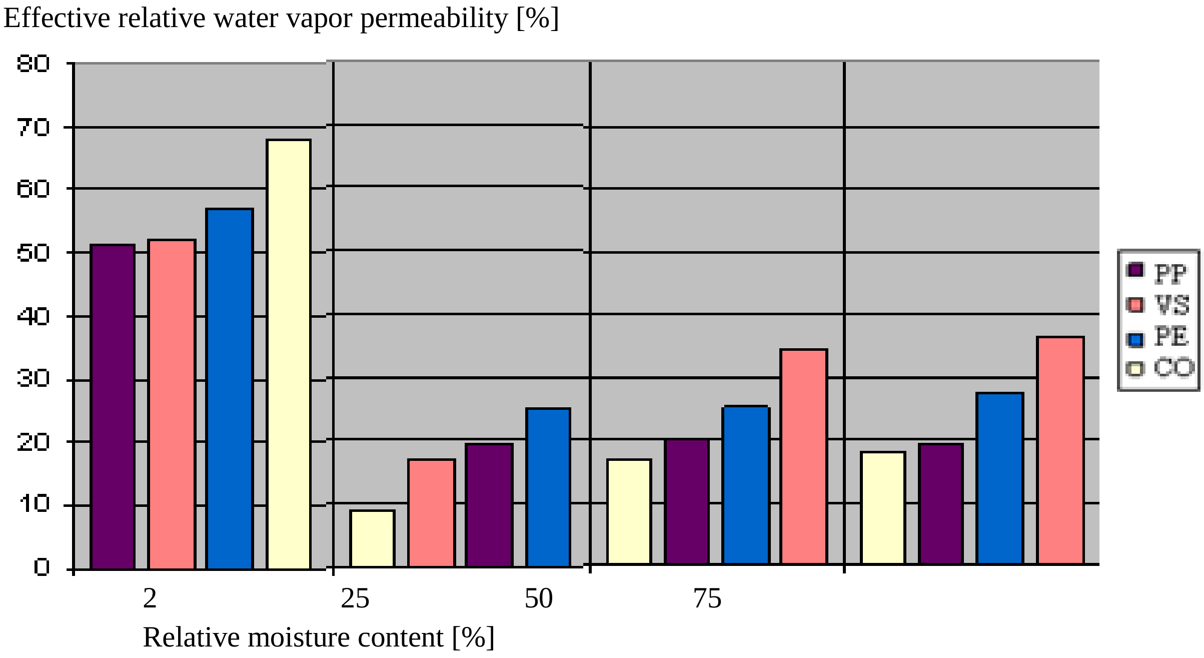


Figure 4. Effective RWVP of various fabrics at the 50% relative moisture content

3. Results and discussion

The obtained results of measurement of WVP confirm that with increasing fabric moisture *U*, the WVP, due to the creation of continuous water film and swelling effects decreases (for some fabrics very significantly), but from the level of the relative moisture content *U* over 50% the WVP due to some unknown reason starts (for all the studied samples) to increase. Thus, the 50% relative moisture content seems to be an important point, where the effective WVP of the wet fabrics changes. That is why the proposed new standard method for determination of WVP of fabrics in wet state may consist of the above described two steps based on measurement of WVP at the relative fabric humidity 50%, both without and with the impermeable foil inserted between the wet sample and the measuring surface of the tester. The difference between the direct measurements and the measurement with a foil then presents the required level of the relative cooling flow or WVP of fabrics in wet state.

The determined substantial decreases of the WVP of the studied 30 fabrics in wet state indicate, that in cases, where the clothing or garments is used in wet state, the garment wearer can suffer from big thermal discomfort. Thus, the importance of the hydrophobic treatment or use of hydrophobic fibers is evident.

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