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Simulation of the Effect of Air Gaps between the Skin and a Wet Fabric on Resulting Cooling Flow

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Abstract As the moisture content of a fabric increases, the relative water vapor permeability (the relative heat flow responsible for the cooling of the body) also increases and the fabric temperature drops due to the evaporation of the water from the surface of the fabric. In this work on the experimental study of water vapor permeability of wet fabrics, the effect of air layers between the skin of the wearer and the fabric on the total relative cooling heat flow (cooling effect) experienced by the skin of the garment wearer is investigated. It was found out that when layers of 2- and 4-mm thickness were introduced between the skin and the fabric, the relative water vapor permeability or relative cooling heat flow was smaller than when the fabric was in direct contact with the skin, and in this case it did not depend significantly on the fabric moisture content.

Key words thermal comfort, wet fabrics, cooling, heat flow

The actual performance of many protective garments depends on their highly specific protection value and comfort properties. The basic thermal comfort properties are just two: thermal resistance (or insulation), and water vapor resistance (or permeability). This paper deals with water vapor resistance (or permeability) of fabrics in wet state. Fundamental papers on vapor permeability of fabrics in dry state were published by Farnworth et al. [1], Gibson [2], Fan and Chen [3] and others.

When these garments are used under extreme conditions, their thermal insulation and water vapor permeability (WVP)[1] properties change due to increase of their moisture content. One of the first papers on WVP of fabrics in wet state was published by Ren and Ruckman [4]. However, these authors did not use a Skin model in their measurements, therefore they were not able to measure the cooling effects of wet fabrics. As experimentally proved by Hes and Dolezal [5,6], as the moisture content of the fabrics increases, their water vapor permeability decreases, but the total RWVP[2] (cooling effect) due to water evaporation from the fabric surface increases.

This study deals with the effect of air layers between the fabric and the skin on cooling the human body when dressed with a single layer wet garment. Previous studies have been conducted to analyze the effect of moisture content on fabrics' WVP [4,7]; however, no work has been found in the literature that refers to the effect of exactly determined air layers between the fabrics and the skin. The studies where air layers are not taken into account may only be applied to skin tight garments, such as stretch garments. The study of the effect of air layers on RWVP requires the use of measuring methods that are faster and more precise than the ones commonly used, which may not be able to account for the effect of fabric moisture content on the rate of the heat loss (cooling heat flow; W/m^2), as

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the measuring period may take more than 30 min [8]. In this research, this problem is overcome by using the Permetest instrument [9], which enables the determination of the RWVP (%) and the evaporation resistance (Ret) (m^2Pa/W) of dry and wet fabrics within 3–5 min. The measured heat loss resulting from evaporation is registered by the instrument and used for determination of the required parameters RWVP and Ret by means of a computer. Thus, the instrument enables the simulation of the complex thermal perception felt by the wearer of a wet garment.

The objective of this work is to simulate the effect of air gaps between the skin and a wet fabric using the Permetest instrument at the (initially) isothermic regime, to identify the changes of the cooling effect felt by the body as the moisture content of the fabric increases, when air layers are introduced between the fabric and the skin. Thickness of these air layers were 2 mm and 4 mm, maintained by the insertion of small spacer rings between the instrument surface and the fabrics.

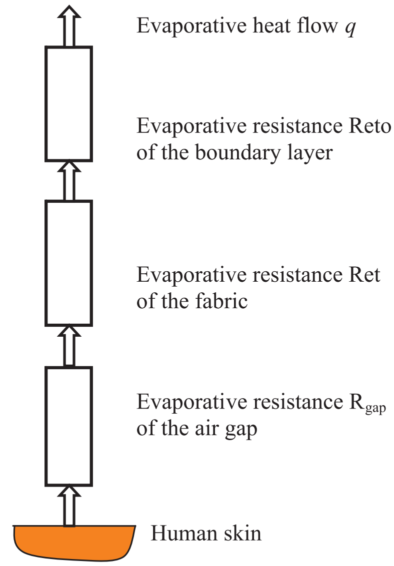

Figure 2 Evaporative resistances (connected in series) during the evaporative heat flow from the skin through the garment

Theoretical

Figure 1 is a schematic diagram of the heat flow generated due to sweat evaporation and its passage through the fabric. This heat flow represents the heat lost by the body, and has a cooling effect on it. There is also heat flow due to moisture (sweat or rain water) evaporated from the fabric surface, which also causes the cooling effect. However, 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 fabric thermal resistance and thermal resistance of the air gap between the fabric and the skin.

Figure 2 shows a series of all the evaporation resistances ($Pa.m^2/W$) encountered during the passage of a heat flow (W/m^2), caused by the evaporation of sweat, to the environment.

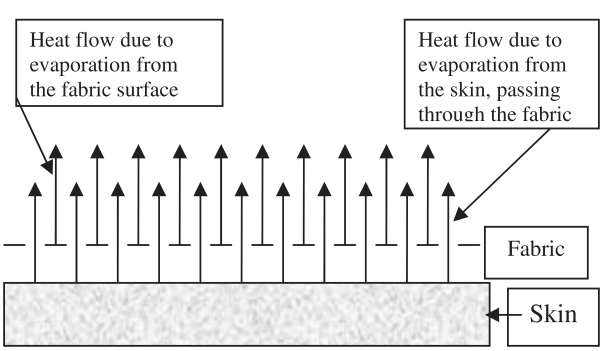

Figure 1 The heat flow generation due to sweat evaporation from the skin surface and moisture evaporation from the fabric surface.

First, we analyze the cooling of the skin caused by moisture evaporation from the fabric surface. Despite the assumption of isothermic conditions, the wet fabric becomes cooler than the surrounding air, as the fabric surface, due to the effect of certain fabric thermal resistance, is not kept at the temperature of the instrument (Skin Model) measuring surface. Cooling flow by convection coming 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:

$$\mathbf{q_{fab}} = \beta(\mathbf{p_{sat,\,fab}} - \mathbf{p_{air}}) \tag{1}$$

Except for dry and very dry fabric states, the continuous water film is present at any level of fabric moisture (we call it the period of constant drying velocity and constant fabric surface temperature). During the mentioned drying period, the partial pressure of water vapor at the skin surface reaches saturation. The cooling flow $\mathbf{q_{fabw}}$ must be in equilibrium with thermal losses by convection into the outside air and heat conduction towards to the skin:

$$\beta(\mathbf{p_{sat,\,fab}} - \mathbf{p_{air}}) = \alpha\Delta\mathbf{t_{air}} + \Delta\mathbf{t_{air}}/(\mathbf{R_{ctw}} + \mathbf{R_{cgap}}) \tag{2}$$

Thermal resistance of a fabric in wet state $\mathbf{R_{ctw}}$ can be in first approximation expressed as linear function of relative moisture of a fabric U:

Figure 3 Permetest – compact Skin Model type fast tester [10].

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

The heat flow causing the skin cooling then follows from the equations:

$$\mathbf{q_{fabw,sk}} = \Delta \mathbf{t_{air}}/(\mathbf{R_{ctw}} + \mathbf{R_{cgap}}) \tag{4}$$

$$\mathbf{q_{fabw,sk}} = \frac{\beta(p_{sat,fab} - p_{air})}{1 + \alpha R_{ct}(1 - kU) + \alpha R_{gap}}[W/m^2] \tag{5}$$

Equation 5 confirms that with increasing fabric moisture, fabric thermal resistance decreases, which causes the increase of cooling flow conducted away from the skin – see the experimental results. Naturally, this explanation is simplified – the fabric moisture increase will probably be followed by an increase of the mass transfer area also, at least to some extent.

The heat flow coming from the skin (q_{skin}) can be then described by equation (6), provided that the partial pressure of water vapor at the skin surface reaches the saturated level (this assumption is used by many researchers – see Gibson [2]:

$$q_{\mathbf{skin}} = \frac{p_{sat} - p_{air}}{R_{gap} + R_{et} + R_{eto}}[W/m^2] \tag{6}$$

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

$$R_{\mathbf{gap}} = \frac{h}{D_p}[Pa.m^2/W] \tag{7}$$

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

$$R_{\mathbf{eto}} = \frac{1}{\beta}[Pa.m^2/W] \tag{8}$$

The total heat flow (q_{tot}) transferred through the boundary layer on the fabric surface is then given (under certain simplifying assumptions), by the sum of heat flow passing from the skin through the permeable fabric and heat flow caused by temperature gradient between the skin and fabric surface, which is cooled by evaporating of water from the fabric surface, as follows:

$$\mathbf{q_{tot}} = \frac{p_{sat} - p_{air}}{R_{egap} + R_{et} + R_{eto}} + \frac{\beta(p_{sat,fab} - p_{air})}{1 + \alpha R_{ct}(1 - kU) + \alpha R_{cgap}} \tag{9}$$

Where:

p_{sat} – saturated water vapor pressure on the skin surface (Pa) which is tabled and depends on the skin temperature

p_{air} – water vapor pressure of the environmental air (Pa) which is given and is determined by measurement

R_{egap} – evaporative resistance of the air layer ($Pa.m^2/W$) which can be measured or calculated

R_{et} – evaporative resistance of the fabric ($Pa.m^2/W$) which should be determined experimentally

R_{eto} – evaporative resistance of the boundary layer ($Pa.m^2/W$) can be determined experimentally, or its approximate value can be calculated for the known velocity of the parallel air flow

β – convection mass transfer coefficient $\beta \approx \sqrt{v}$ related to water vapor partial pressure and heat flow ($W/Pa.m^2$)

$p_{sat,\,fab}$ – saturated water vapor pressure on the fabric surface (Pa), depending on the fabric surface temperature, which can be determined by the iteration procedure

α – heat transfer coefficient ($W.m^2/K$), which increases with the air velocity

R_{ct} – thermal resistance of a fabric in ultra-dry state ($K.m^2/W$), to be determined experimentally

k – experimentally determined constant characterizing the decrease of thermal resistance caused by the increased moisture U of the fabric – see [12]

Table 1 Specifications of the woven fabrics used in the experiments.

Sample	Fiber content	Mass (g/m^2)	Warp (tex)	Weft (tex)	Density (epc × ppc)
A Simona	100% cotton	215	29.5	33.0	295 × 74
B Solex	100% cotton	218	33.0	50.0	330 × 74
C Darling	100% cotton	222	35.5	35.5	330 × 74
D Vend	100% cotton	250	35.5	50.0	330 × 74
E Frank	100% cotton	295	50.0	60.0	330 × 74

U – relative mass increase of the fabric with moisture content (%), determined by weighing
h – thickness of air gaps between the measuring surface and the fabric (m), determined by measurement
D_p – diffusion coefficient related to water vapor partial pressure and heat flow (W/Pa.m), available in literature on heat transfer
R_{cgap} – thermal resistance of air layer (K.m^2/W), which can be measured or calculated

From equation 9 it may be seen that an increase in an air layer thickness will reduce the total heat flow through the fabric, thus resulting in a lower cooling effect on the body. This observation has important practical consequences when wearing a wet looser garment. The parts of the body in close contact with the fabric may experience an intensive cooling effect, whereas in other parts of the body, where there is a gap between the skin and the wet fabric, the cooling effect can be more limited and so the garment wearer may perceive thermal discomfort.

Experimental

Materials

The materials to be tested consisted of five cotton woven fabrics used for protective clothing. The fabric structure of all fabrics was a 3/1 twill. The reason for choosing these heavy fabrics was that that the RWVP of thin (shirt) fabrics is too high (50–55%) and the time of drying, due to their lower mass, shorter than that of heavier fabrics. Measurements on heavier fabrics with higher evaporation resistance are more precise.

The specifications of these fabrics are shown in Table 1, and fabrics were measured in a laboratory with controlled atmosphere of 21–23°C temperature and a 50–55% relative humidity [12].

Test Methods

The tests were conducted with the Permetest apparatus which measures the amount of heat passing through a thermal model of the human skin. The porous sweating surface of the device simulates the skin and records the cooling heat flow caused by perspiration. The fabric sample to be measured is placed on a measuring head over semi-permeable foil and exposed to parallel air flow at a velocity of 1 m/s. As with all the skin model systems, the measurements are carried out under isothermal conditions (here 23°C) [12]. This isothermal principle involves the temperature of the skin model surface, air temperature and fabric temperature, when the fabric is kept in direct thermal contact with the skin model surface. It does not refer to the fabric surface temperature, when there is an air gap between the skin model surface and the tested fabric (see equation 2).

The computer connected to the apparatus determines the evaporative resistance Ret and the thermal resistance Rct of textile fabrics in a similar way to that described in standard ISO 11092, as well as the RWVP (or relative negative heat flow responsible for the cooling of the body). These values serve to reflect the thermo-physiological properties of textile fabrics and garments. The higher the RWVP, the lower the Ret, and the better the thermal comfort of the garment. Due to the very short measuring time, which normally does not exceed 3 min (the steady-state is indicated by the computer), the fabric mass remains mostly unchanged during the measurements.

The experiment consisted of measuring the RWVP and Ret of dry and wet fabrics without an air layer and with air layers of 2 mm and 4 mm thickness, between the measuring head of the apparatus and the surface of the fabric.

All fabrics were tested in various states of moisture content:

1. dry state: the fabrics were in equilibrium with the controlled atmosphere
2. ultra-dry state: the dry fabrics were exposed to dry heat (105°C) for the period of 1 h
3. wet state (various).

The various stages of fabric wetness were achieved by soaking the fabrics in water at 21–23°C with a wetting agent. Subsequently, water was extracted from the fabrics mechanically in a stepwise manner, and then they were exposed to air in a controlled atmosphere. Fabric mass was

Table 2 Simona fabric results.

U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]
h = 0 mm			h = 2 mm			h = 4 mm		
0.0	36.6	6.5	0.0	32.2	7.6	0.0	22.3	10.8
5.5	39.7	6.0	5.5	33.2	7.1	5.5	23.2	10.5
16.1	43.9	5.2	25.0	34.0	6.8	16.1	24.3	10.3
27.8	51.9	4.7	40.0	35.3	6.2	25.0	25.3	10.0
40.7	59.2	3.7	50.0	36.5	6.4	40.0	24.6	10.1
50.0	68.3	2.5	56.4	37.9	6.4	50.0	24.6	10.2
68.5	67.6	2.6	68.5	38.9	6.0	56.4	24.8	9.1
70.9	71.3	2.4	70.9	38.7	5.9	68.5	24.7	9.3
82.1	70.6	1.7	81.8	39.8	5.6	82.1	25.7	8.8
98.2	75.3	1.3	98.2	40.9	5.0	98.2	26.2	8.5

Table 3 Solex fabric results.

U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]
h = 0 mm			h = 2 mm			h = 4 mm		
0.0	36.3	6.7	0.0	31.3	7.9	0.0	24.9	11.2
4.8	39.2	6.2	4.8	31.7	7.7	4.8	24.7	11.1
16.7	44.1	5.9	16.7	32.6	7.3	21.2	24.9	10.8
29.6	48.3	5.5	21.2	33.8	6.8	29.6	25.3	10.4
34.6	55.6	4.7	29.6	34.6	6.4	34.6	25.2	10.9
46.3	53.3	4.5	34.6	35.7	6.6	46.3	25.7	10.2
51.9	65.8	3.8	46.3	36.7	6.1	53.8	25.7	9.9
69.2	68.7	3.6	53.8	37.9	5.9	63.0	25.7	9.6
75.9	67.5	2.7	69.2	37.7	5.8	75.9	26.5	9.2
80.8	67.4	1.7	80.8	37.3	5.9	80.8	26.2	9.5
90.7	70.0	1.9	90.7	38.4	5.9	90.7	26.0	9.0
98.1	70.1	1.5	98.1	39.9	5.5	96.2	28.2	8.9

always determined just before the fabrics were subjected to the permeability measurements [12]. The increase in mass due to the increase in moisture content of the fabrics was calculated from equation (10).

$$U = \frac{(m_v - m_s)}{m_s} * 100[\%] \qquad (10)$$

where:

U – mass increase comparatively to the ultra-dry state, (%)
m_v – specimen sample mass (g)
m_s – ultra-dry sample mass (g)

Results and Discussion

The results are presented in Tables 2 to 6 and Figures 4 to 9.

From Figures 4 to 9, which relate to 100% cotton protective fabrics, it can be seen that without an air layer the relative cooling heat flow or RWVP (%) increases linearly with an increase in the moisture content of the fabric U (%). When an air layer is present, the value of the RWVP

Table 4 Darling fabric results.

U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]
h = 0 mm			h = 2 mm			h = 4 mm		
0.0	36.9	7.2	0.0	30.3	8.2	0.0	24.6	11.2
5.1	38.0	6.8	5.1	31.9	8.0	5.1	25.0	10.9
14.3	43.9	6.1	14.3	32.3	7.7	14.3	25.4	1 0.7
25.0	47.8	4.6	20.7	32.7	7.2	25.0	26.2	10.2
32.2	51.3	4.0	25.0	33.2	6.8	43.1	26.7	9.8
43.1	59.7	3.5	39.3	33.9	6.6	51.8	26.4	9.3
51.8	63.2	2.8	55.2	34.4	6.5	62.7	26.6	9.0
62.7	62.2	2.4	69.6	35.2	6.4	69.6	26.7	8.9
70.7	68.4	2.1	76.3	36.1	6.1	76.3	27.4	8.8
84.5	71.4	1.9	84.5	37.8	6.1	82.1	27.7	8.5
98.3	73.6	1.7	98.3	38.4	5.8	89.8	28.8	8.4
						98.3	29.1	8.1

Table 5 Vend fabric results.

U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]
h = 0 mm			h = 2 mm			h = 4 mm		
0.0	30.0	8.1	0.0	29.6	8.7	0.0	25.1	11.1
6.0	33.7	7.4	6.0	30.8	8.3	6.0	25.6	10.2
25.0	39.4	6.8	28.1	31.4	7.9	23.8	26.7	9.4
34.4	42.2	5.5	34.9	32.8	7.7	28.1	26.5	9.8
48.4	47.3	4.5	40.6	33.5	7.4	34.9	27.4	9.0
59.4	50.3	3.6	48.4	34.3	7.6	48.4	27.8	8.9
67.2	53.9	3.3	59.4	34.7	6.9	54.7	28.1	9.0
73.0	58.7	2.4	67.2	35.3	6.5	67.2	27.4	9.5
84.1	62.0	2.3	73.0	35.5	6.3	71.9	27.7	9.1
95.3	68.3	1.9	84.1	36.9	6.3	84.1	27.9	8.7
			95.3	37.4	6.1	95.3	31.2	7.9
						98.3	29.1	8.1

(%) is lower and its increase with the moisture content of the fabric U (%) is slower. The level of the RWVP (%) decreases with the increasing thickness of the air layer.

From Figures 6 to 8 it can be seen that the lighter in mass the fabrics are, the higher the value of RWVP. These are fabrics made of cotton fibers which are hydrophilic and swell. Therefore, the porosity of such fabrics in the wet state should be lower. Despite this, the RWVP increases with an increase in the moisture content of the fabrics. The increasing thickness of the air layers results in a decrease of the value of RWVP.

Figure 9 shows the effect of moisture content and air layer thickness on the RWVP of the fabric "Frank". The higher the moisture content of the fabrics, the higher is the RWVP and the lower the evaporative resistance. As the air layer thickness increases, the RWVP decreases and the evaporative resistance increases.

From the above, it may be inferred that the cooling of the skin by perspiration from the surface of the textile fabric depends both on the fabric moisture content and on the thickness of the air layer between the skin and the fabric. The highest heat transfer between the skin and clothing

Table 6 Frank fabric results.

U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]	U [%]	RWVP [%]	Ret [Pa.m^2/W]
h = 0 mm			h = 2 mm			h = 4 mm		
0.0	29.2	9.6	0.0	27.4	9.1	0.0	20.7	13.8
5.3	31.9	9.2	5.3	28.6	8.5	5.3	21.9	13.2
17.3	38.3	8.8	21.1	29.5	8.1	17.3	21.3	12.5
35.5	43.1	7.1	33.3	30.6	7.7	27.4	22.6	12.2
48.7	45.7	6.7	49.3	31.9	7.2	33.3	22.8	11.1
59.2	47.0	5.7	59.2	32.9	7.8	46.7	23.4	11.0
65.8	49.7	4.5	65.8	33.5	7.4	59.2	24.9	10.4
71.1	51.0	3.4	71.1	34.3	7.2	71.1	25.5	10.7
79.5	57.5	2.4	78.7	34.6	6.9	80.3	26.7	10.3
90.8	62.7	1.7	90.8	35.9	6.6	90.8	26.5	9.8
100.0	65.7	2.1	100.0	36.5	6.3	100.0	27.5	9.4

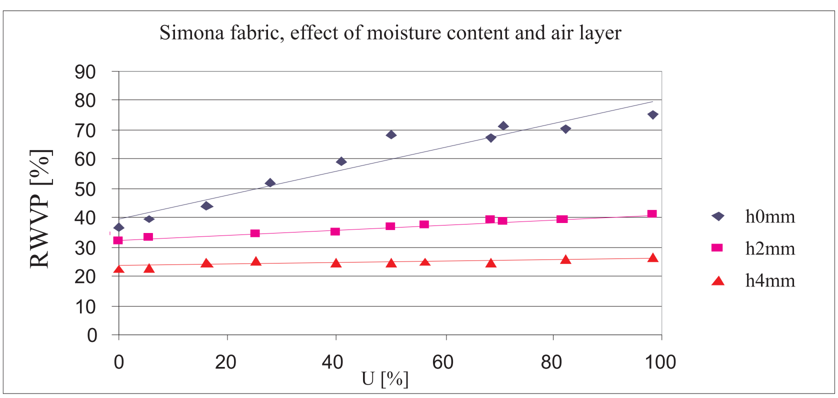

Figure 4 Effect of fabric moisture content and air layer thickness on the RWVP of the "Simona" fabric (%). The dependence of moisture content and air layer on the RWVP for the "Solex" fabric was very similar.

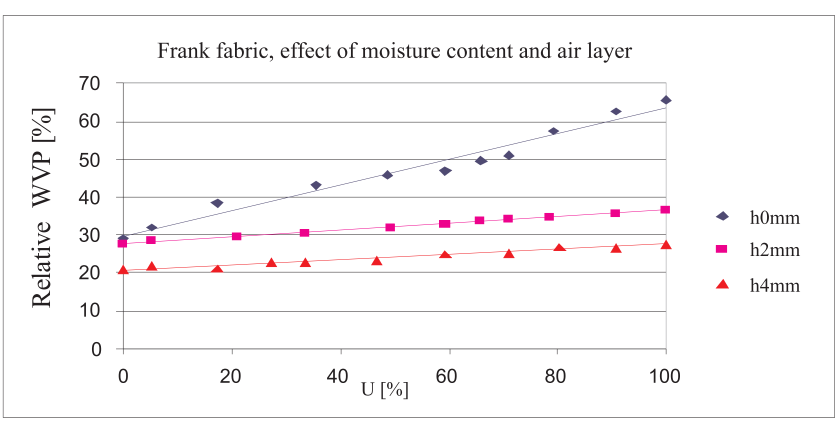

Figure 5 Effect of moisture content and air layer thickness on the RWVP of the "Frank" woven fabric. The dependence of moisture content and air layer on the RWVP of the "Darling" woven fabric is similar.

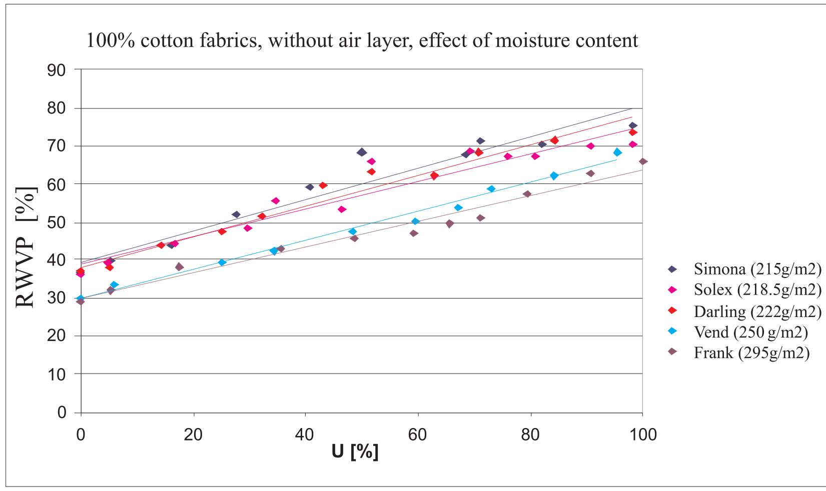

Figure 6 Effect of moisture content on RWVP of 100% cotton fabrics without air layers.

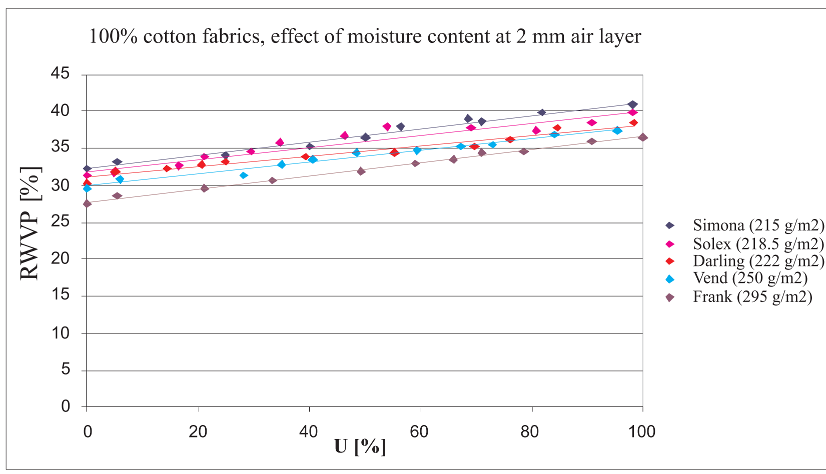

Figure 7 Effect of moisture content on the RWVP of 100% cotton fabrics with an air layer of 2 mm thickness.

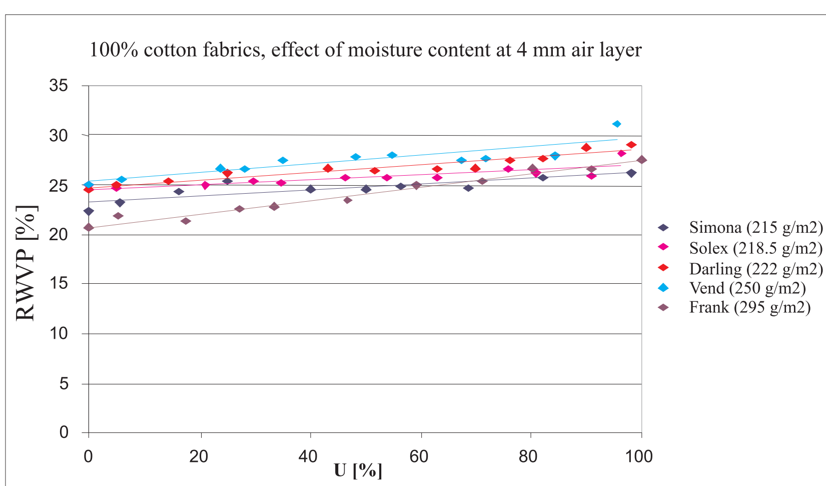

Figure 8 Effect of moisture content on the RWVP of 100% cotton fabrics with an air layer of 4 mm thickness.

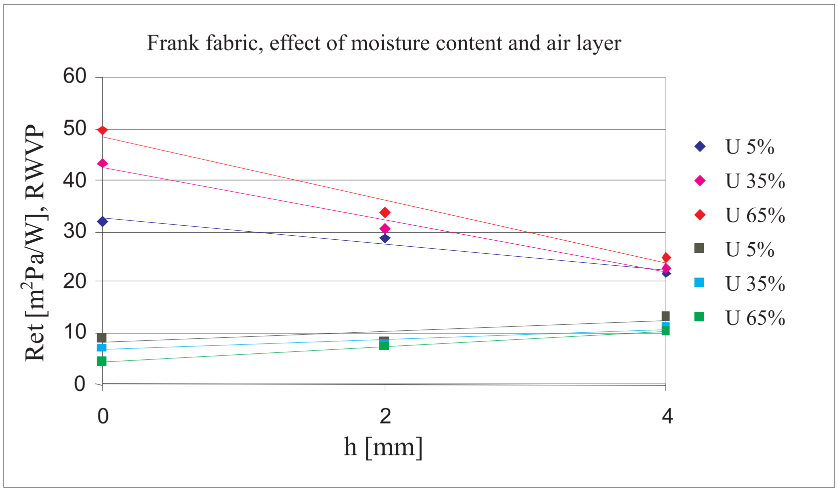

Figure 9 Effect of air gap thickness on the RWVP for "Frank" woven fabric (diamonds) and evaporative resistance Ret (squares). The exact data of moisture content were extrapolated.

appears when the fabric is close to the skin. The RWVP also depends on the mass of the fabric: the higher the mass, the lower the RWVP.

Other preliminary results achieved [13] and presented [14] elsewhere, show similar trends for five different cotton/polyester protective fabrics and for five different 100% cotton denim fabrics. However, for the cotton/polyester protective fabrics the increase of RWVP with the moisture content and its decrease with the air layer thickness is not so accentuated. The explanation is that wetting does not result in swelling of the polyester fibers. This, in turn, does not result in a decrease of the fabric pore size and does not reduce the amount of mass transfer through the fabric.

Conclusions

In this work, a Permetest skin model was used to simulate the cooling effect felt by a wearer of wet cotton garments when the fabric is worn directly on the skin or with an air gap between the skin and the fabric. When the fabrics are wet, then the total relative cooling heat flow consists not only of the flow transferred through the fabrics, but also of flow caused by moisture evaporation from the fabric surface.

It was found that the cooling effect of wet fabrics due to temperature drop cannot be felt by the skin with the same intensity along the whole body. The highest cooling effect should be perceived at the arms and wherever the wet fabric contacts directly with the skin [11]. In other body parts without direct contact between the skin and fabric, the cooling effect should be much lower.

All these findings are known from practical life experience, but in this paper the cooling levels were determined in quantitative terms. In measurements without air layers, the cooling effect increased with an increase in the fabric moisture content. In measurements involving 2 mm and 4 mm-thick air layers, the total cooling effect has been kept almost constant with an increase in the fabric moisture content. In agreement with the included theoretical analysis, the cooling effect with air layers was several times lower than the cooling effect with direct fabric–skin contact. These findings can be used to design better protective clothing for extreme climatic conditions.

Notes

1. Water vapor permeability (WVP) (or breathability) is the ability of fabric to allow water vapor to penetrate, measured in grams per square meter per day (g $m^{-2}day^{-1}$). Besides this often-used meaning, WVP can be also understood as an inversion parameter to evaporation resistance Ret to be expressed in W/(m^2Pa).
2. Relative water vapor permeability (RWVP) (or relative cooling effect) is the relative heat flow responsible for the cooling of the body.

$$\text{RWVP}(\%) = (q_v/q_o) \times 100$$

Where q_v is the heat flow (W.m^{-2}) passing through the measuring head covered by the sample, and q_o is the heat flow passing through the uncovered measuring head (W.m^{-2}).

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