Indian Journal of Fibre & Textile Research
Vol. 19, September 1994, pp. 147-150

Diagnostic of the composition of fabrics from their thermal permeability in wet state

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The thermal permeability of wool, polyester and wool-polyester plain and twill weave fabrics in wet state has been investigated. It is observed that the level and the time dependency of their thermal permeability depend substantially on their mechanical structure and chemical composition. On the basis of the deeper knowledge of these dependencies and wet permeability/time behaviour, some fabric parameters can be derived for the diagnostic of the composition of fabrics.

Keywords: Polyester, Thermal permeability, Wool, Woven fabrics

1 Introduction

Because of the relatively high thermal conductivity of water and surface water evaporation, fabrics always exhibit substantially lower thermal resistance in the wet state than in the dry state. This can cause some problems (post-treatment chill) to the garment users in case of liquid sweat occurrence (as a consequence of some sport activity or manual work). To avoid this drawback, special fabrics, fibres or even some sophisticated fabric/garment constructions are used.

In this paper, the time dependency of wet thermal losses (in relation to the dry ones) of wool, polyester and wool-polyester plain and twill weave fabrics has been investigated by using the Permetest instrument[1].

2 Definition and Theoretical Analysis of Thermal Permeability of Fabrics

The thermal permeability of dry fabrics (p_d) can be defined by the following equation:

$$p_d = q_d/(t_1 - t_0) \quad \dots (1)$$

where q_d is heat flux (W/m^2) passing through an unit area of a dry fabric of which one surface is kept at constant temperature t_1 and the other surface is exposed to the flowing air, passing parallel to the fabric surface with a velocity of 1-3 m/s (Fig. 1).

The heat flow conducted from the free fabric surface consists of heat flow by convection:

$$q_{conv} = \alpha(t_1 - t_0) \quad \dots (2)$$

where α is the convection heat transfer coefficient (W/m^2) which increases with the air velocity according to the generally known dependencies[2].

The convection heat flow from free surfaces is always accompanied by the radiation heat flow q_{rad}, which can be expressed by the simplified relationship:

$$q_{rad} = \varepsilon\sigma T^3 (t_1 - t_0) \quad \dots (3)$$

where ε is the surface emissivity of the fabric ($0.7 < \varepsilon < 1$); $\sigma[= 5.67 \times 10^{-8}$ (W^2/k^4)], the radiation constant; and $T_{1,0}$, the mean absolute temperature defined as $273 + (t_1 + t_0)/2$ (K).

For wet surfaces, the effect of heat flow by evaporation should also be included.

$$q_{evap} = r\beta[X''(t_1) - X_0] \quad \dots (4)$$

where r is the heat of evaporation (25,00,000 J/kg for water); β, the mass transfer coefficient (kg/m^{2}s, kg H_2O/kg dry air concentration); X'', the concentration of saturated vapour (kg H_2O/kg

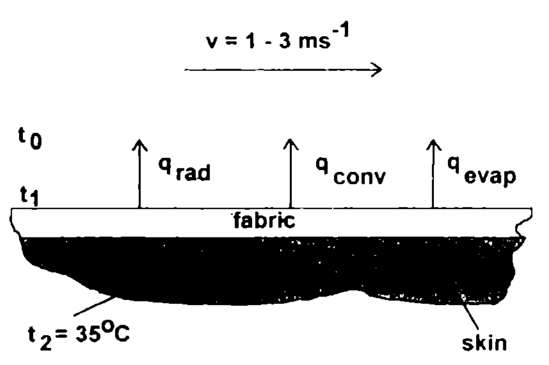

Fig. 1—Heat loss from the fabric in contact with human skin

air) on the fabric surface; and X_0, the concentration of vapour in the environmental air (kg H_2O/kg dry air).

Some newly introduced parameters were measured by using the Permetest instrument (described later). These are relative permeability in dry state (p_d) and relative permeability in wet state (p_w). The relative permeability in dry state is calculated by the following equation:

$$p_d = 100\,(q_d/q_0) \qquad \ldots (5)$$

where q_0 is the heat flow from the bare (uncovered) human skin with the temperature of 35°C, simulated by the Permetest instrument; and q_d, the heat flow passing through the dry fabric into free space (according to Eq. 1) where the covered surface is kept at 35°C (t_2) either by putting it on human skin or by being attached to the heated plate in the Permetest instrument.

In both the cases, heat is transferred by convection and radiation. Applying Eqs 2 and 3 and the basic laws of heat transfer, we obtain:

$$p_d = 100/\{[\alpha + \varepsilon\sigma T^3_{2,0}][h/\lambda_d + 1/(\alpha + \varepsilon\sigma T^3_{1,0})]\} \qquad \ldots (6)$$

where λ_d is the thermal conductivity of a tested fabric in dry state (W/m K); and h, the fabric thickness (m).

The relative wet fabric permeability is related to the dry thermal permeability according to the following relationship:

$$p_w = 100\,(q_w/q_d) \qquad \ldots (7)$$

where q_w is the heat loss of woven fabric in wet state.

Applying all the mentioned ways of heat flow transmission, including q_{evap}, the following relationship can be obtained:

$$p_w = 100\,\frac{h/\lambda_d + 1/(\alpha + \varepsilon\sigma T^3_{2,0})}{\dfrac{h}{\lambda_w} + \dfrac{1}{\alpha + \varepsilon\sigma T^3_{1,0} + \beta r[X^4(t_1) - X_0]/(t_1 - t_0)}} \qquad \ldots (8)$$

where λ_w is the fabric thermal conductivity in the wet state.

The parameter p_w, if being solved theoretically, cannot be found by any analytical method. An iterative solution is necessary where the pre-chosen temperature of outer layer (t_1), which affects the value of X'' (see the i-X diagram of humid air), should be checked up from the equation:

$$t_1 = t_2 - \frac{p_w h}{\lambda_w}(t_2 - t_1) \qquad \ldots (9)$$

Whereas the level of p_d is lower than 100%, the value of p_w always surpasses 100%.

2 Materials and Methods

All the fabric samples of similar mass per unit area (201.6-280.6 g/m^2) were woven with a plain or twill weave. The composition of the samples (Table 1) differed from pure wool to polyester-wool to pure polyester[3].

2.1 Measuring Apparatus

The Permetest instrument represents a new generation of measuring instruments, characterized by a very fast response, thus enabling to perform dynamic unstationary measurements also. The instrument protected by patents[4] and described[5,6] depends on the transformation of the amount of evaporated water (kg/s) passing through the fabric into the directly measured heat flow, caused by the effect of the heat evaporation. Fig. 2 shows a simplified cross-sectional view of Permetest instrument.

The metal block (1) is covered by a porous sheet (2), which distributes the water to be evaporated along the whole surface of the sheet. The water is injected into the porous surface through channel (3) joined with the preheating chamber (4) and dosing device (5). The block can be kept at the demanded temperature by a heating coil

Table 1—Structure and composition of fabric samples

Sample code	Fabric	Weave	Mass g/m^2	Ends/10 cm	Picks/10 cm	Linear density, d tex		Thickness mm
						Wool	Polyester	
1A	Wool	Twill	266.8	264.0	251.0	25 × 2	—	0.85
2A	Wool/Polyester (45:55)	Twill	277.8	267.6	251.6	25 × 2	3.6	0.59
3A	Polyester	Twill	266.6	239.6	244.5	—	3.6	0.51
1B	Wool	Plain	201.6	202.0	180.5	25 × 2	—	0.56
2B	Wool/Polyester (45:55)	Plain	211.0	201.2	179.5	25 × 2	3.6	0.54
3B	Polyester	Plain	203.0	196.0	178.0	—	3.6	0.51

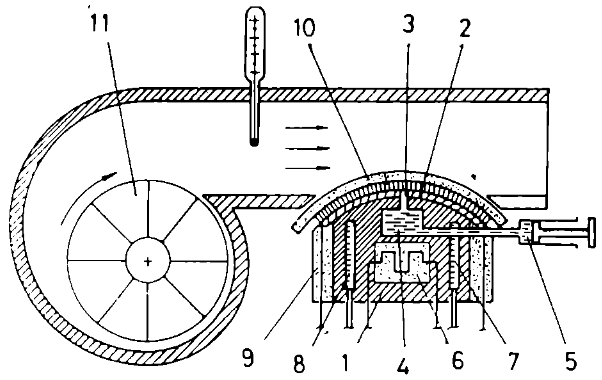

Fig. 2—A simplified cross-sectional view of the Permetest instrument

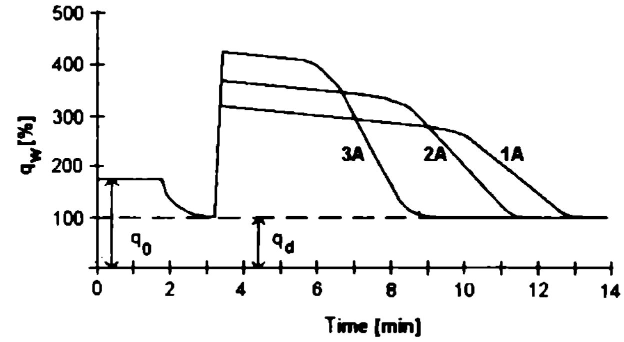

Fig. 3—Heat loss of woven fabrics of various composition in wet state [1A—wool; 2A—wool-polyester; and 3A—polyester]

(6), which is connected with a regulator. The block temperature is measured by thermometers (7) and (8). To maintain the pre-set temperature, the outer surface of the block (1) is covered by a insulating wall (9).

During the measurements, the textile sample (10) covers the slightly curved distributing layer. The free surface of the sample is then exposed to a parallel air flow whose velocity can be adjusted from 1 to 3 m/s. Air flow is generated by a fan (11).

2.2 Measuring Procedure

The measuring head of the instrument was heated to 35 + 0.5°C, thus simulating the temperature of an human skin.

The distributing layer of the instrument was filled with water (simulating sweat) and then dried by an absorbing fabric in order to fill all internal channels of the instrument up to the level of the distributing layer. After this, 0.2 ml of water was injected again into the layer.

After the distribution of the water in the whole layer, the fabric samples were located on this wet layer, which simulates any underwear filled with liquid sweat. Then the measuring head covered by the sample was exposed to the parallel air flow with the velocity of 3 m/s.

Table 2—Experimental results

Sample	p_d, %	T_d, min	p_w, %	T_w, min
1A	66.3	3.7	338.0	13.3
2A	68.0	2.3	356.3	10.6
3A	74.3	1.0	421.4	7.2
1B	71.9	3.6	375.8	11.6
2B	73.7	1.9	355.5	11.1
3B	75.9	1.2	357.3	10.2

The electric signal of the heat flow sensor was then recorded by a line recorder. The recordings are shown in Fig. 3. The recordings for dry state (i.e. the measurement performed without any water in the distributing layer) and wet state of fabric demonstrate the heat losses of a body heated to 35°C and covered by the fabric under test.

3 Results and Discussion

It is seen in Fig. 3 that the level q_0 represents the heat losses of a free uncovered measuring head, thus simulating the heat losses of a nude person. Applying one garment layer reduces the steady-state heat losses to the level q_d. Dry heat permeability of a fabric p_d was then calculated by Eq. 5.

In the demonstrated case, the p_d achieves 70%. It was found that for all the tested fabrics, this parameter lies in the interval 65-75%. It is clear that the lower the p_d, the better is the fabric insulation.

The increase in heat losses of wet fabric (q_w) in relation to that of dry fabric expresses the wet heat permeability (p_w) given by Eq. 7.

It is clear from Fig. 3 that p_w changes (generally decreases) with the time. The time T_w, for which p_w reaches again the level, as at the beginning of the experiment, is generally shorter for polyester than for wool, because of the lower level of internal adhesion forces of polyester liquid water. The values of T_w for different samples are given in Table 2.

As regards the level of p_w, it is always greater than 1. Supposing that the wet garments user starts to perceive the cool feeling after sometime but not too late (he is getting to be accustomed), we have introduced the "1 MINUTE COOL FEELING", i.e. the feeling after one minute of the occurrence of liquid sweat. Table 2 gives this value for various materials.

Fig. 3 shows clearly that in case of drying of wet polyester fabric, the water is not absorbed too much inside the yarns, because of the hydrophobic nature of polyester. Therefore, water creates a continuous film, enabling fast evaporation. Polyester fabric gets dry sooner than similar wool fabric, but the level of heat losses during the evaporation is higher, just because of continuing of water film on the fabric, e.g. because of the presence of continuous water bridges with higher thermal conductivity.

On the other hand, wool samples absorb water inside the yarns, in their cortex, but individual yarns are not connected by water bridges.

The wool yarn surface scales, which always keep dry (if the amount of water is low or if they are not mechanically damaged), separate the yarn water reservoirs so that no continuous water layer occurs.

Naturally, also some absorption heat effects can be significant.

Such a wet permeability/time behaviour, specific for textile of different compositions, permits to use these diagrams for some diagnostic purposes.

Therefore, the wool-polyester (55/45) drying curve should lie somewhere between wool and pure polyester curves. In practice, this assumption really came true and can be seen in Fig. 3.

Of course, in the practical experiment, the shape of any drying curve depends also on finishing treatment of the tested fabric, thermal contact between the instrument and fabric, and specially on the mechanical structure (weave) of fabric. It has been observed that by changing the wool-polyester fabric structure we can simulate the typical pure wool fabric curves; for example, when using the plain weave, the differences between drying curves for fabrics in plain weave did not exhibit significant dependencies on the chemical composition of the samples (Table 2).

Therefore, the diagnostic method outlined in the paper represents only a new idea, which should be further developed.

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