

### Short Communications

#### Effect of composition of knitted fabrics on their cooling efficiency at simulated sweating

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Cooling efficiency of selected underwear knits in the simulated condition of fabric wetting by means of single sweating pulse has been experimentally investigated. The method is based on non-traditional use of the small skin model Permetest with a very short time of measurement. Cooling efficiency has been calculated as the product of cooling heat flow and wet area after application of 0.5 mL of water on the fabric surface to simulate the sweating impulse. It is found that the highest cooling level is exhibited by the knitted fabrics containing polyester filaments with grooved surface, which conducts the liquid moisture along the fabric plane.

**Keywords:** Cooling efficiency, Heat flow, Knitted fabric, Skin model, Single jersey fabric, Wet textiles

Human body represents a thermal machine with low thermal efficiency. Cooling of human body by the sweat evaporation is the only natural mean to take away the excess of heat from the body during heavy physical work in hot environment, and to maintain the thermal comfort of the wearer. The most efficient sweating occurs when all the generated sweat evaporates and the vapor passes through the enough permeable garment system into the relatively dry air outside the body. In such case, the underwear and outerwear systems remain principally dry. However, under less favorable conditions, the sweat accumulates in the clothing and evaporates from the clothing surface. As per the recent study<sup>1</sup>, in such case the cooling efficiency will be substantially lower than that in case of dry sweating. Nevertheless, in many cases, the climatic conditions do not enable full

evaporation of the created sweat from the skin surface, and most of the required cooling effect must be produced on the wet fabric surface. Hence, the problem of water vapour transfer through wet fabric and from its surface attracts the attention of researchers in recent decade.

The cooling heat flow from the fabric surface is mostly caused by convection (if there is some gradient of temperatures), and the cooling heat is given by the latent heat of evaporation resulting from mass transfer by convection. The relationship, as given below, for the mass  $m^*$  (kg/m<sup>2</sup>s) transferred by convection is similar to the next Newton Law for heat flow ( $q$ ) transferred by convection:

$$m^* = \beta_p (p_{wv\ sat} - p_{wv\ out}) \quad \dots(1)$$

$$q = \alpha (t_1 - t_2) \quad \dots(2)$$

where  $\beta_p$  [kg/(m<sup>2</sup> s Pa)] is the mass transfer coefficient; and  $p_{wv\ sat}$  &  $p_{wv\ out}$  (Pa), the water vapor partial pressure levels (saturate and local respectively). The driving force in Eq. (2) is given by the difference of the solid surface temperature  $t_1$  and the surrounding air temperature  $t_2$ . Regarding the second coefficient of transfer proportionality,  $\alpha$  (W/m<sup>2</sup>/K) presents convection heat transfer and its level increases with the air velocity  $v$  (m/s) according to the following empirical relationship:

$$\alpha = 8.3 v^{1/2} \quad \dots(3)$$

Similarly, the convection mass transfer coefficient  $\beta_p$  [kg/(m<sup>2</sup>s/Pa)] is also proportional to the air velocity, due to Levis equation, based on analogy between the heat and the mass transfer and is valid for low air velocities, as shown below:

$$\alpha = \beta_p c K \quad \dots(4)$$

where  $c$  [J/(kg/K)] is the specific heat of humid air at constant pressure; and  $K$ , a constant, which transforms the partial pressure dependent mass transfer coefficient  $\beta_p$  into concentration dependent mass transfer coefficient  $\beta_c$ .

The cooling thermal power  $Q^*$  (W) of free skin surface is given by the following relationship:

$$Q^*_{cool} \text{ (W)} = L S \beta (p_{wv\ sat} - p_{wv\ out}) \quad \dots(5)$$

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$$Q^*_{cool}(W) = q_{cool} S \quad \dots(6)$$

where  $L$  is the latent heat of evaporation (J/kg);  $q_{cool}$ , the cooling heat flow level recorded by the instrument; and  $S$ , the moisture transfer area (m<sup>2</sup>).

If the body is covered by a fabric, the effective mass transfer is lower, as the total mass (water vapor) transfer resistance includes the boundary layer resistance and the fabric transfer resistance. Nevertheless, if the first clothing layer is in close contact with the skin, then the evaporated sweat penetrates the fabric and finally evaporates from the fabric surface. Systematic experimental study of water vapor permeability (WVP) of wet fabrics has been published recently<sup>1,2</sup>. Despite the fact that thermal comfort properties of fabrics have become important topic of many papers in recent decade<sup>1-8</sup>, there are just few published papers related to the effect of moisture on water vapor permeability of fabrics<sup>6</sup> and their cooling efficiency<sup>7,8</sup>. The reason probably is that the current measuring instruments for the evaluation of thermophysiological comfort of fabrics require more than 30 min for full reading, thus avoiding the precise determination of fabrics humidity effect on their thermal resistance and cooling heat flow, as the humidity decreases during the measurement. Moreover, water vapour permeability testers based on pure detection of air humidity under and above the wet sample cannot record the effect of heat generated or absorbed in the fabric due to its interaction with water vapour. The advanced WVP measurements reflecting the real human body perception of comfort require the use of very fast skin model. That is why the detailed analysis of cooling effect in case of wearing of wet fabrics is almost not available in the literature. Hence, the present study was undertaken to evaluate experimentally the effect of yarn composition on the cooling efficiency of selected knitted fabrics under the simulated sweating impulse, provided that the structure is kept unchanged. The principle of the use of the simulated sweating impulse is not new, it has been used already in the research works carried out in the Hohenstein institute<sup>9</sup>.

In this study, the experiments were carried out by using the fast skin model Permetest<sup>1</sup> (Fig. 1). The air velocity in the first study was kept quite low (0.7 m/s) in order to simulate the mass transfer at low walking velocity. In the second case, the air velocity inside the Permetest instrument was taken as 2.5 m/s.

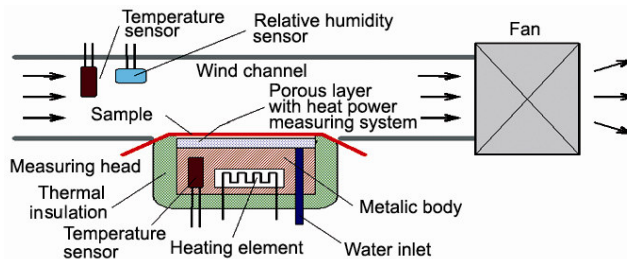


Fig. 1—Principle of the Permetest instrument

### Principle of Permetest Instrument

This small skin model enables fast and easy determination of water vapour and thermal resistance of fabrics up to 10 mm thickness. Results of measurement are expressed in units as defined in the ISO Standard 11092. Water vapour resistance or permeability is measured under isothermal conditions (the measuring head and the air passing along the fabric surface are kept at the laboratory air temperature with the precision 0.05°C), whereas thermal resistance measurements are carried out at the 10°C ± 0.05°C temperature difference. Slightly curved porous surface enables good thermal contact between the measured fabric and the measuring surface, which is covered by a smooth semi-permeable membrane. Results are evaluated statistically and displayed on the screen of a computer<sup>8,10</sup>. Time of measurement is quite less. Full response at fabrics made of man-made fibres is achieved within 3-5 min. The instrument is calibrated using a special 100% polypropylene woven fabric with  $R_{et}$  value determined in the Hohenstein skin model according to the ISO 11092. Thus, very good measurement repeatability is achieved, mostly offering the CV better than 3%. The instrument manufactured by the Czech Sensora Company enables non-destructive testing of fabrics even outside testing laboratories.

Sixteen (16) single jersey fabrics differing in composition and square mass (Table 1) were used. It is necessary to mention that the sensing area of the measuring instrument was, in this case, very small (4 cm<sup>2</sup>), thus enabling to record all the evaporation heat flow related to the smallest wet spots on the samples.

The temperature of the measuring head of the Permetest instrument was preset to the same level as the temperature of the surrounding air to maintain the isothermal working regime. Then, the first selected air velocity in the instrument

Table 1 — Composition of measured knits and experimental results

Knit fabric	Air velocity $v = 0.7$ m/s				Air velocity $v = 2.5$ m/s		
	$q_{cool}$ W/m <sup>2</sup>	CV %	Wet area diameter, cm	Cooling power ( $P$ ), mW	$q_{cool}$ W/m <sup>2</sup>	CV %	Cooling power ( $P$ ), mW
PAD:elastane (92:8)	88.3	1.63	2.5	43.3	130.0	1.92	63.8
Cotton:elastane (90:10)	79.2	4.82	4	99.5	153.3	4.10	192.6
PES Coolmax:PADf: elastane (69:27:4)	94.2	1.53	3	66.6	125.8	5.0	88.9
Micromod:PA Tactel Diab: elastane (56:36:8)	854.2	5.33	2	17.3	233.3	4.33	73.3
PES Coolmax: PESf: elastane (65:31:4)	55.8	5.17	7	214.7	134.2	3.88	516.5
PESf:elastane (93:7)	66.7	5.73	4.5	106.1	127.5	3.40	202.8
Cotton:modal:elastane (47:47:6)	65.8	4.39	4	82.7	177.5	7.84	223.1
PESf:elastane (89:11)	73.3	5.21	2	23.0	99.2	2.90	31.2
Cotton:modal:elastane (47:47:6)	90.8	4.21	3.5	87.4	129.2	4.27	124.3
PES:cotton:elastane (57:38:5)	62.5	4.0	2.5	30.7	122.5	3.53	60.1
PES Coolmax: elastane (94:6)	49.2	2.93	7	189.3	100.8	1.43	387.3
PES Coolmax:elastane (95:5)	66.7	2.16	5.5	158.5	114.2	3.34	271.3
Cotton:elastane (94:6)	95.0	2.63	2	29.9	135.0	3.70	42.4
PAD Tactel:elastane (94:6)	76.6	3.77	4	96.3	144.2	3.61	181.2
PAD:elastane (94:6)	62.5	4.0	4.5	99.4	124.2	3.07	197.5
PES:micromodal: elastane (35:55:10)	69.2	4.17	4.5	110.6	113.0	2.55	79.7

channel was taken as 0.7 m/s in order to simulate the convection conditions typical for slow walking velocity, characterized by the lowest level of mass transfer. In the second set of measurements, the air velocity was taken as 2.5 m/s. The heat transfer coefficient levels corresponding to these velocities were 6.94 and 13.1 W/(m<sup>2</sup>K) respectively. Following the Lewis analogy, the corresponding mass transfer coefficient for the air velocity 2.5 m/s should be ~1.9 times higher.

Porous layer wetted by 1 mL of water to simulate the sweating human skin was used. Simultaneously, the sweat pulse was simulated by injecting 0.5 mL of water in the middle of the measured sample. After 1 min, knitted underwear fabric was placed on the measuring head. After another minute the diameter of the wetted area was measured and the evaporation heat flow  $q_{cool}$  was recorded.

The wetted area  $S$  (calculated from the wet spot diameter) and the corresponding heat flow level were put in Eq. (6) in order to determine the cooling efficiency (cooling thermal power) of the tested sample. The results are shown in Fig. 2.

For the air velocity 2.5 m/s the results are very similar, just the cooling power levels are ~ 2 times higher<sup>8</sup>. Figure 2 shows that the highest cooling levels of knitted fabrics are mostly achieved due to the presence of Coolmax polyester fibres, which conduct liquid moisture along the fabric plane. However, the absolutely highest cooling effect is shown by the

lower mass fabric (PES Coolmax:PESf:elastane 69:31:4) which is also due to the presence of polyester continuous filament (PESf) and elastane besides the Coolmax filaments contained. When the polyamide (PAD) fibres are present in the structure (PES Coolmax:PADf:elastane 69:27:4), the cooling effects are always lower, probably due to the higher moisture adhesion to these materials. The lowest cooling effect, probably due to the same reason, is also observed for the sample containing 56% micromodal, 36% PAD Tactel Diabolo and 8% elastane.

It has been found that very high cooling levels are always achieved due to the prevailing presence of the Coolmax polyester fibres, which conduct the liquid moisture along the fabric plane. Nevertheless, lower mass along with the use of polyester continuous filament (PESf) and elastane (PES Coolmax:PESf:elastane 69:31:4) shows the highest cooling effect. When the polyamide (PAD) fibres are present in the structure, the cooling effects are always lower, probably due to higher moisture adhesion to these materials, as shown by the sample PES Coolmax:PADf:elastane (69:27:4). The lowest cooling effect, probably due to the same reason, is shown by the sample containing 56% micromodal, 36% PAD Tactel Diabolo and 8% elastane.

The above results do not indicate directly that some materials are less comfortable than the others, they just indicate how much heat is conducted away from

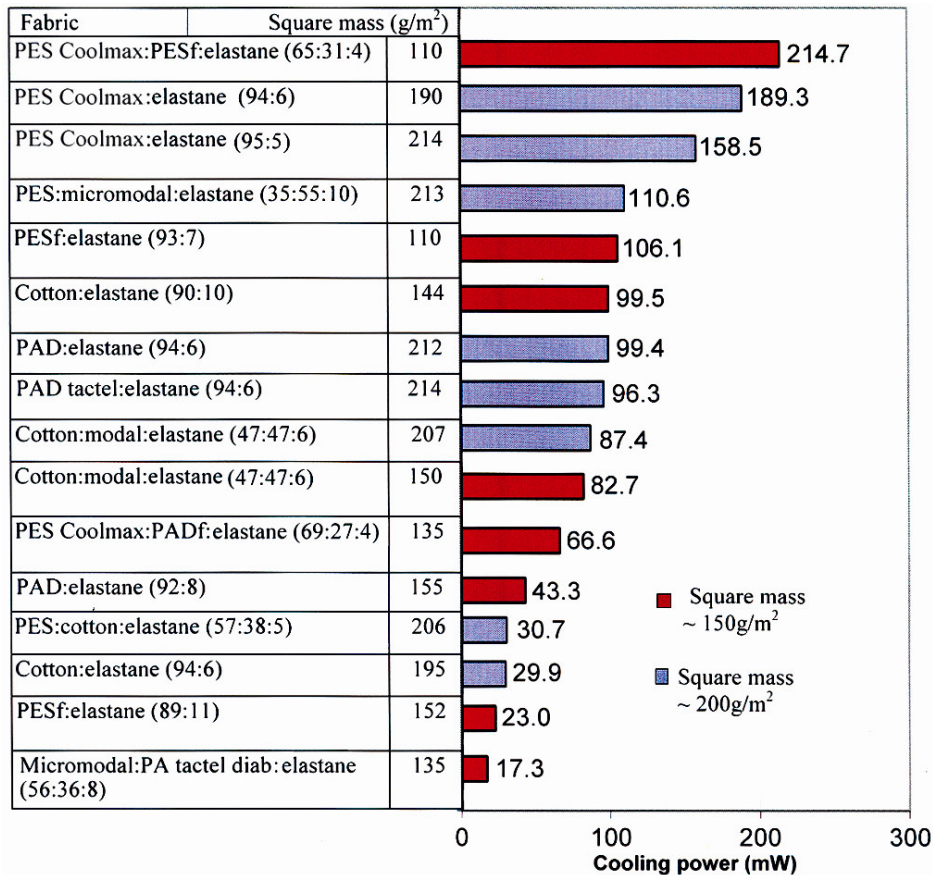


Fig. 2—Cooling efficiency of single jersey knits differing in composition and mass (air velocity 0.7m/s)

the body by evaporation for the case of individual sweat pulse. In practical wearing of garments, the body cooling is given by simultaneous action of many sweating glands. Moreover, this research suffers from certain imperfections given by, to some extent, uncontrolled distribution of moisture in the measuring head before the sample is placed on it. The achieved results will be verified in continuing research.

The study also demonstrates that small fast skin models like Permetest are suitable for the investigation of cooling properties of wet fabrics, as during short duration of measurement the degree of humidity of the sample does not change substantively.

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