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Measurement of thermal parameters of skin-fabric environment

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Abstract

Background and Purpose: *In combination with metabolic heat, the heat generated by human activities and worn garment produce 6 basic factors (sometimes called 6 basic parameters because they are in space and time, but fixed representative values are frequently used in analyses) which define thermal body environments. The aim of this paper is to investigate the impact of one parameter – clothing insulation on the total transfer of heat and water vapor.*

Materials and Methods: *The measurement was carried out on knitted fabrics commercially used for the production of underwear or different types of next-to-skin-wear. The transfer of heat and moisture trough fabrics was observed in two simulated climatic environments (moderate and hot) with the constant parameters metabolic energy and air velocity.*

Results: *The results indicated that the heat resistance increases by laying a knitted fabric layer or under real conditions when the body is dressed in lightweight knitwear by 25%. The test results of the samples under different environment conditions indicated a reduction in heat resistance under moderate conditions. It also applies to the measurement results of the resistance to water vapor transfer, but the differences within the observed relationships are higher than it was in the case of heat transfer resistance.*

Conclusions: *The study showed that both heat and moisture transfers are freely movable controlling elements of comfort perception. Therefore, the optimal design of clothing systems is important factor of comfort.*

INTRODUCTION

Every type of life maintenance is related to substance exchange. The center of body warmth control is located in the brain and regulates warmth transport by blood flow through blood vessels, capillaries to the skin surface and sweat secretion. To control heat exchange, it is possible to protect the body against overheating as well as against undercooling. In this case physical regulation controls heat loss, and chemical regulation controls thermal processes. Body is heated by thermal energy which is produced from the energy generated due to the decomposition of energy-rich carbohydrate molecules and fats. Heat transfer can occur by radiation R, convection C, conduction K, evaporation E, and respiration E_{res} (Figure 1).

Heat transfer by radiation occurs constantly between body and the environment where the body dwells, i.e. in both directions, depending on differences in body skin temperature and the temperature of other surfaces. Average heat loss by radiation varies, and in moderate climatic

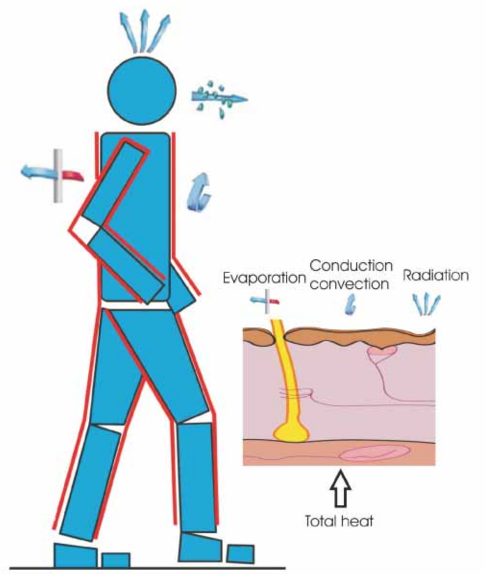

Figure 1. *Heat transfer over the body.*

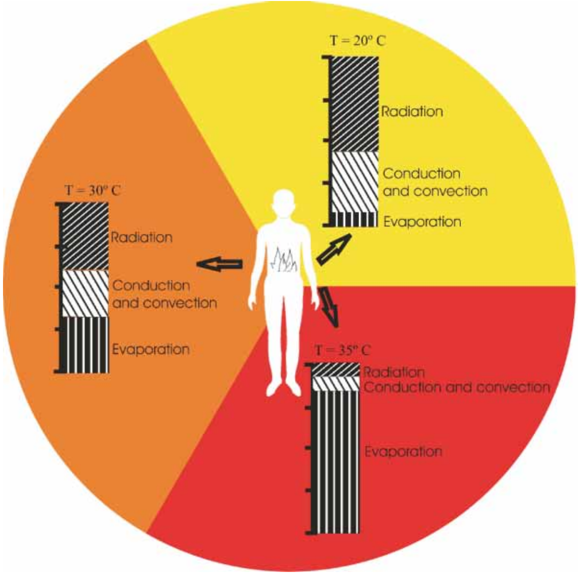

Figure 2. *Total heat loss at environmental temperatures of 20 °C, 30 °C and 35 °C.*

regions it may range from 40 to 60% *(1)*. Heat transfer by convection is caused by the air flow around the body or by movement of liquid drops if the body is in the water. This fact depends to a great extent on the difference in skin and air temperature, and on air (liquid) flow velocity. Under normal conditions, about 30% of heat is exchanged by this type of heat transfer between body and environment *(2)*. The heat quantity transferred by conduction is considerably lower than the quantity transferred by convection, and it becomes essential when people being in contact with cold objects and the like are in the water *(3, 4)*. Heat transfer by conduction applies to 15% of the total heat transfer, and it depends primarily on object vision and the material that is in contact with skin *(5, 6)*. Heat transfer by sweat evaporation is always present, and it increases in hot environment. If environment temperature rises over a comfortable body temperature, hot skin secretes sweat more intensely, causing a rapid increase in body heat loss. Heat transfer by evaporation from skin surface depends on moisture quantity on the skin and the difference between water vapor pressures on the skin and in environment. In a human being, evaporation is always present. Under normal conditions it ranges from 450 to 600 ml a day, meaning that there is a heat loss between 50 and 70 kJ/h *(7)*.

Figure 2 shows the distribution of total heat loss to radiation, evaporation, conduction and convection at environmental temperatures of 20 °C, 30 °C i 35 °C.

Investigations of heat and moisture transfer were conducted both in standard and in extreme conditions, at low and high temperatures *(5, 8)*. Investigations of human response to heat and cold contributed to the creation of thermoregulating models of the man-environment system and the man-garment-environment system *(9)*.

Equation of heat balance includes three terms: those for heat generation in the body, heat transfer and heat accumulation. The degree of metabolic energy of the body M produces energy, enabling the body to do mechanical work W, and the heat remainder is released as heat (i.e. $M - W$). To analyze heat exchange between body and environment, specific production procedures and heat exchange for the human body are used. Fanger *(10)* provides the following relation to meet the conditions for thermal comfort:

$$H - E_{dif} - E_{sw} - E_{res} - C_{res} = R + C \qquad (1)$$

where all terms contain the unit Wm^{-2} and H is metabolic heat production, E_{dif} is external mechanical work or evaporaton by moisture diffusion through the skin, E_{sw} is heat loss by sweat evaporation, E_{res} is heat loss by latent respiration, C_{res} is heat loss by dry respiration over the unit area.

ASHRAE (9) gives the following equation of heat balance:

$$M - W = Q_{sk} + Q_{res} = (C + R + E_{sk}) + (C_{res} + E_{res}) \qquad (2)$$

where all terms contain the unit Wm^{-2}. M is metabolic heat production, W is mechanical work consumption, Q_{sk} is the total rate of heat loss by radiation from the skin, C is the rate of heat loss by convection from the skin, R is the rate of heat loss by radiation from the skin, E_{sk} is the total rate of heat loss by evaporation from the skin, C_{res} is the rate of heat loss by respiration and E_{res} is the total rate of heat loss by evaporation from respiration.

The following is valid:

$$E_{sk} = E_{rsw} + E_{dif} \qquad (3)$$

where E_{rsw} is the rate of heat loss by evaporation from the skin due to sweating and E_{dif} is the rate of heat loss by evaporation from the skin due to moisture diffusion. Equation (2) makes it possible to practically consider heat production within the body ($M - W$), heat loss over the skin ($C+R+E_{sk}$) and heat loss due to respiration ($C_{res} + E_{sres}$).

There is a series of parameters affecting the determination of intensity of each mentioned process of heat transfer. Fanger *(10)* defined six parameters relevant for the preservation of body heat balance using the following expression:

$$\Phi(M,I_{cl},v,t_r,t_a,p_w)=0 \quad (4)$$

where M is metabolism intensity, I_{cl} heat resistance of the clothing, v air flow velocity, t_r average radiation temperature, t_a environment temperature, p_w water vapor pressure of the air.

When the above mentioned procedures of heat transfer are combined together, all the rates of production and heat loss generate the rate of heat accumulation S. When body is in heat balance at constant temperature, the rate of heat accumulation is zero $S = 0$. If there is only an increase in heat, accumulation will be positive and body temperature will rise. If there is only a heat loss, accumulation will be negative and body temperature will decrease *(11, 12)*.

The aim of this paper was to investigate the impact of the I_{cl} parameter on the total transfer of heat and water vapor in two simulated climatic environments with the constant parameters M and v. The aim of the paper was to indicate the difference in magnitudes of equation components of heat balance for the body + fabric and body – fabric system.

MATERIALS AND METHODS

The investigation was carried out using the knitted fabrics that are commercially used for the production of underwear of different types of next-to-skin-wear. Such products are worn either as one-layered summer wear or as the first layer that is in contact with human skin.

The fabrics were produced in two different structures:

a) single jersey structure made of cotton yarn and

b) single jersey structure made of cotton yarn and elastane yarn that is added in the process of knitting together with the cotton yarn.

The illustration of both structures is given in Figure 3 where the white loops are made of elastane, while the colored loops are made of cotton yarn.

The fabrics were finished according to the recipe that includes optical bleaching, softening and dyeing. Both grey and finished fabrics were included into the investigation. The fabric designation and description are shown in Table 1.

The measurements were carried out in moderate and hot environmental conditions, as shown in Table 2.

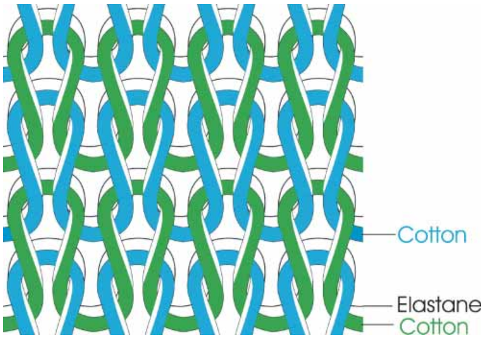

Figure 3. *The fabric structure (cotton + elastane).*

TABLE 1

Fabric designation and description.

Fabric designation	Raw material	Mass per unit area, g m^{-2}	Finishing
S1	cotton	150	Grey fabric
S2	cotton + elastane	184	Grey fabric
S3	cotton + elastane	262	Grey fabric
S1'	cotton	140	Finished
S2'	cotton + elastane	157	Finished
S3'	cotton + elastane	220	Finished

TABLE 2

Environmental conditions.

Condition	Description	Temperature, °C	Relative humidity, %	Air velocity, m s^{-1}
I	Moderate conditions	20	65	1
II	Hot conditions	35	40	1

RESULTS AND DISCUSSION

Sweating guarded hotplate was used for the determination of heat and water vapor resistance. The measuring device is often referred to as«skin model« because of its ability to simulate the heat and moisture (sweat) transfer processes which occur next to human skin *(13)*. It consists of a heated plate that has a constant temperature matching the human skin temperature *(14, 15)*. The fabric sample is placed on the plate and the heat flux from the plate to environment is measured. The results are used to calculate heat and water vapor resistances *(16)*.

Heat resistance was determined according to the following equation:

$$R_{ct} = \frac{(T_s - T_a)}{\frac{H}{A}} - R_{ct0} \quad (1)$$

where R_{ct} is dry resistance of sample only, T_s is hotplate surface temperature, T_a is ambient temperature, H/A is zone heat flux, R_{ct0} is bare plate dry resistance.

Water vapor R_{et} resistance was determined according to the following equation:

$$R_{et} = \frac{(p_s - p_a)}{\frac{H}{A}} - R_{et0} \tag{2}$$

Where R_{et} is evaporative resistance of sample only, p_s is saturation vapor pressure on hotplate surface, p_a is ambient partial vapor pressure, H/A is zone heat flux, and R_{et0} is bare plate evaporation resistance.

Experimentally obtained results of heat resistance – Rct measured in m^2KW^{-1} and water vapor resistance – Ret, measured in m^2 Pa W^{-1} are shown in Figures 4 and 5.

The results are shown for the system that includes fabric (designation S, as shown in Table 1) and the plate (P). Such a system (S + P) represents the simulation of heat and water vapor transfer for a dressed person (i.e. clothing + skin). Both figures show results for the plate only (P), which is the simulation of a nude body. The results are given for measurements in both moderate and hot environment.

The results of heat resistance of the tested materials shown in Figure 4 indicate a difference in the heat resistance between the plate itself (P) and the material + plate system, which was about 0.02 m^2KW^{-1}. In other words, heat resistance increases by laying a knitted fabric layer or under real conditions when the body is dressed in lightweight knitwear by 25%. Table 1 shows that the finishing textile of materials reduces, their mass per unit area (e.g. mass per unit area of sample S1 is 150 gm^{-2}, and after its finishing (sample S1´) the mass drops to 140 gm^{-2}). The finishing process affected the change in heat resistance that was lower for the finished samples (S1´, S2´, S3´) than for the grey ones. Test results for samples under different environment conditions indicated a reduction in heat resistance under moderate conditions.

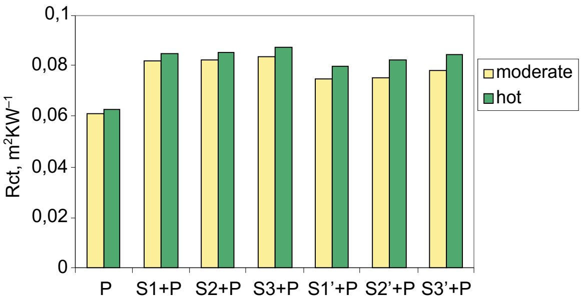

Figure 4. *The heat resistance of the fabric + plate system in moderate and hot environment.*

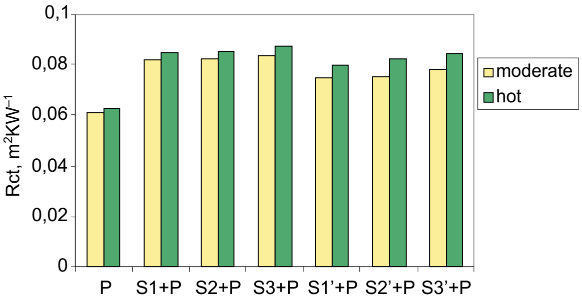

Figure 5. *The water vapor resistance of the fabric + plate system in moderate and hot environment.*

The above described phenomenon applies to the measurement results of resistance to water vapor transfer (Figure 5), so that the differences in observed relationships were higher than in case of heat transfer resistance.

Figure 6 shows the range of air temperature, pressure and relative humidity in which an individual dressed in a garment made of the tested materials should feel comfortable. PMV (Predicted Mean Vote) index was used to predict the mean value of the comfort assessment of persons under equal climatic conditions. The values were obtained on the basis of the physical measurement of heat transfer which was correlated with the empirical values of comfort assessment performed by a number of subjects who assessed comfort under definite conditions on the basis of ASHRAE seven-point scale with grades from –3 (cold) to +3 (hot) *(17, 18)*.

The presented figure shows the comfort range of the tested materials whose thermal insulation was up to 0.3 clo (where clo is the unit of thermal insulation to which it applies that 1 clo = 0.155 m^2 K W^{-1}) and for the materials whose thermal insulation was 0.5 clo. The range in which the person dressed in a garment with an insulation of 0.3 clo, (as for the tested materials), was 27.5–29° C, with relative humidity of 17–73% and pressure from 0.25 to 0.75 mbar. The comfort range for the materials worn in summer, which provide higher thermal insulation (0.5 clo), was 27–28.5° C, with relative humidity from 20 to 73.5% and air pressure from 0.25 to 0.75 mbar.

It has been established that the interaction of 6 factors causes human response. Under specific situations other

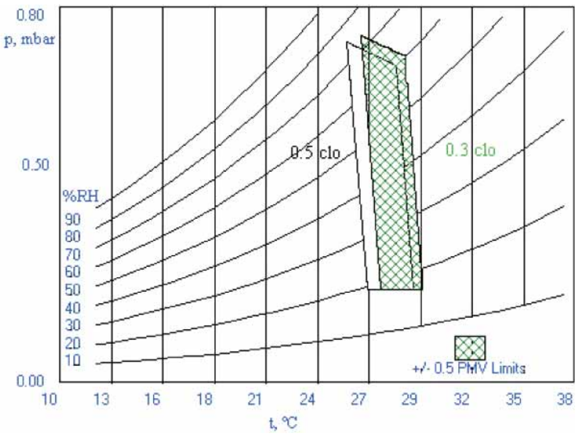

Figure 6. *Comfort range.*

factors are influential, e.g. bodily posture will influence heat exchange between the body and environment to a great extent. Therefore, 6 basic factors create a minimum requirement for a potential conceptual basis for considering the thermal environment of a human being *(19)*. By controlling heat loss it is possible to protect the body against overheating as well as against undercooling; thermal process is available for regulation purposes below neutral temperature range. The procedures controlling heat losses are specified as physical regulation, and the procedures controlling thermal processes as chemical regulation. Thermal process is adjustable primarily by a change in blood circulation through the skin, by different temperature drops between the body and environment, as well as by thermal processes of the body of different intensity. Heat transfer is thus a freely movable controlling element of the temperature control circuit.

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