APPROACH TO THE PREDICTION OF THERMOPHYSIOLOGICAL COMFORT

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Abstract: *The comfort is defined as a state of mind where a person expresses the satisfaction with the environment. There are a number of factors influencing the heat exchange processes. Therefore, it is quite difficult to maintain the heat balance. The factors that influence the balance are related to the body, environment and textile. In this chapter, the investigation of textile factors influencing thermophysiological comfort was carried out using the sweating guarded hotplate that measures the heat and water vapour resistance of materials.The investigation has pointed out a number of yarn and knitted fabric parameters that have significant influence to the mentioned transfers. It was also shown that the importance of finishing process is significant. Such cognition makes a challenge for textile experts to project fabrics with satisfactory transfer properties that will enhance the comfort-related characteristics of clothing.*

Key words: *comfort, textile, prediction, sweating guarded hotplate*

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1. Introduction

The comfort is, according to ASHRAE standard, defined as a state of mind where a person expresses the satisfaction with the environment (ASHRAE, 1996). The usual air temperature associated with the feeling of comfort falls into the temperature range from 15 to 28ºC. However, the physiological comfort range for a person wearing clothing ensemble with insulation of 0.6 clo can be achieved without any additional body heat transfer mechanisms (like shivering, vasoconstriction, vasodilatation or sweating), within 22.2 to 25.5ºC. The comfort outside so defined zone is provided by adding or removing additional garments. Each change in the environmental temperature for a 1ºC is compensated by the change of 0.18 clo of clothing insulation (Goldman, 2007).That means that a resting individual in the environment with the air temperature of 20ºC would need about 1 clo to be comfortable. On the other side, needs only about 0.33 clo while resting at 27ºC. The thermal equilibrium between the human body and environment is established if there is a balance between the rate of heat production and the rate of heat loss. The heat production refers to the difference between the total rate of energy production and the rate at which the external work is performed. The rate of heat loss is a sum of different processes that include radiation, convection, evaporation, dry respiration, conduction and storage of heat in the body. It is quite difficult to maintain the heat balance as there is a number of factors influencing the heat exchange processes. A number of expressions were established to describe the processes involved in the comfort equation. As seen on the model of parameters influencing total comfort (Fig.1),the parameters relate to the following:

I. body*:*skin wettedness (w), skin temperature (t_{sk}), DuBois area (A_{Du}), the part of skin included into the transfer by radiation (A_r/A_{Du}) and skin emissivity (ε_{sk})
II. environment:radiant temperature (t_r), air velocity (v), air temperature (t_a), air pressure (p_a) andpressure on skin ($p_{sk,s}$)
III. textile: clothing insulation (I_{cl}), clothing area factor (f_{cl}), clothing temperature (t_{cl}).

It could be seen from the model that among the textile parameters, the insulation, clothing area factor and clothing temperature significantly contribute to the comfort establishment. Besides the mentioned parameters, there are a number of different parameters of textile that in a certain way affect the thermophysiological comfort.

Previous investigations of knitted fabrics recorded certain differences in the transfer of heat through cotton and polypropylene underwear but those, according to the authors (Farnworth & Dolhan, 1985.), should not affect the human thermal comfort. The influence of structural parameters to the heat and vapour transfer was noted for structures with different number of ribs (Ucar & Yilmaz, 2004), where decrease in rib number leads to a decrease in heat loss due to an increase of air amount entrapped between the loops. The aim of our investigation, presented in this chapter, is to define a number of textile fabric parameters that have influence to the transfer properties. The understanding of a single influence is important for the maintenance of thermo physiological comfort.

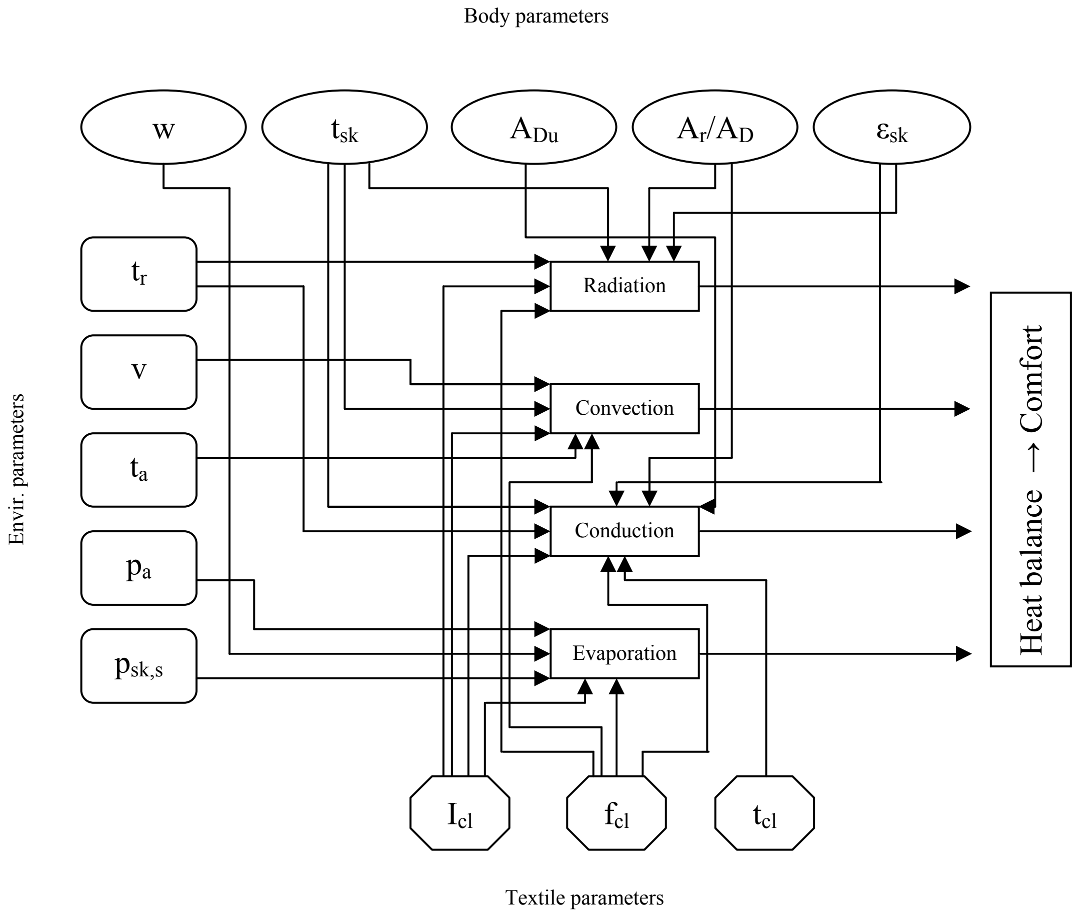

Fig. 1. Model of parameters influencing comfort (Salopek et al., 2008 a)

2. Experiment

2.1 Measuring techniques

The investigation of parameters influencing thermo physiological comfort was carried out using the sweating guarded hotplate. The sweating guarded hotplate (SGHP) is an apparatus that simulates the transfer of metabolic heat and sweat from the skin, trough the textile structure, to the environment (Fig. 2).

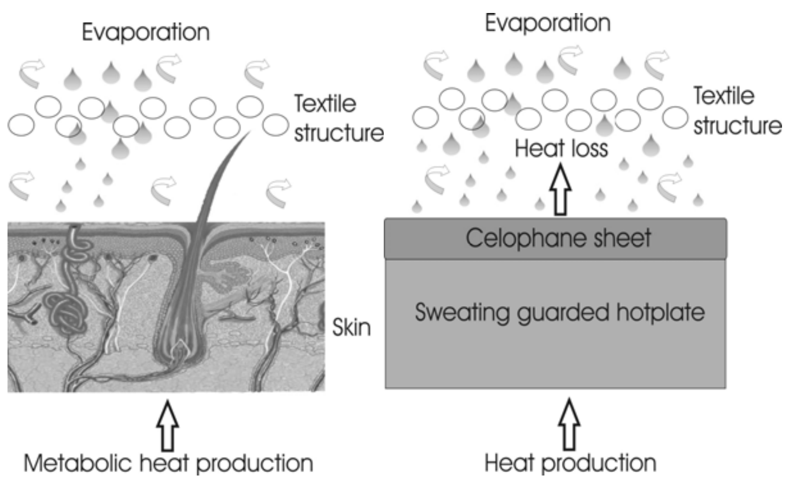

Fig. 2. Heat and vapour transfer through skin and SGHP (Mijovic et al., 2009)

The SGHP system measures the heat and water vapour resistance. It consists of the following parts: metal plate fixed to a conductive metal block containing electrical heating element, temperature controller, heating measuring device, water dosing device, environmental sensors and software (Fig. 3).

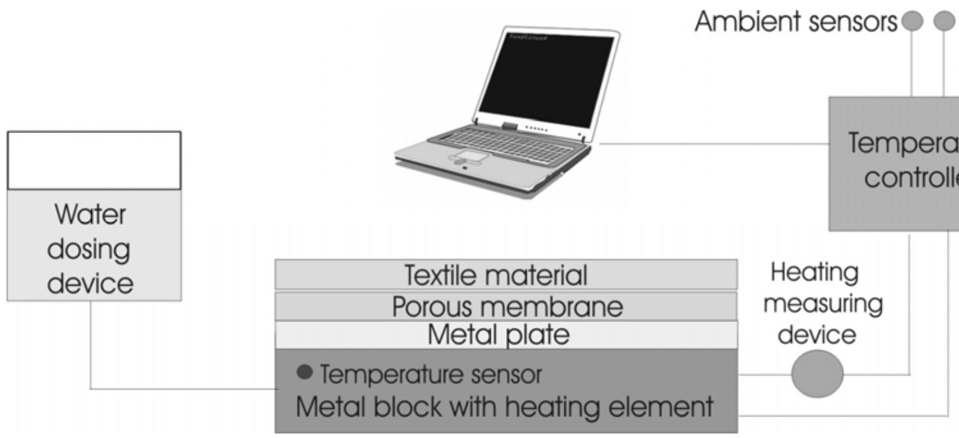

Fig. 3. The system SGHP for measurement of heat and water vapour resistance (Salopek & Skenderi, 2009 a)

The metal plate is heated to 35ºC and the air is ducted to flow across and parallel to the upper surface of heated plate. The heat flux trough test specimen is measured after the steady-state conditions have been reached. During the measurement of watervapour resistance, the metal plate is covered by water vapour permeable and liquid impermeable membrane, so no liquid water contacts the specimen to be investigated. The water that simulates sweat is fed from the water dosing device trough channels mounted into the face of the heating block to the metal plate. The heat resistance (Rct) and water vapour (Ret) resistance is further determined according to the following formulas (ISO 11092, 1993):

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

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

where: R_{ct} - dry resistance of sample only (m^2°C/W), T_s - hotplate surface temperature (°C), T_a - ambient temperature (°C), H/A - zone heat flux (W/m^2), R_{ct0} - bare plate dry resistance (m^2°C/W), R_{et} - evaporative resistance of sample only (m^{2}Pa/W), p_s - saturation vapour pressure at hotplate surface (Pa), p_a - ambient partial vapour pressure (Pa), R_{et0} - bare plate evaporation resistance (m^{2}Pa/W).

In our experiment, the measurements on SGHP were carried out according to the ISO standard (ISO 11092, McCullogh et al., 2004). During the Rct tests, the air temperature and relative humidity were set to 20°C and 65% R.H., while during the Ret tests, the conditions were set to 35°C and 40% R.H. The air velocity was kept constant during both dry and wet measurements at 1 m/s.

2.2 Materials

The measurements of heat and water vapour resistance were carried out on a number of single jersey knitted fabrics (Fig. 4). The fabrics were produced from cotton, cotton/modal, viscose and polyester yarns. The mass of investigated fabrics is 80-140 g/m^2. In order to observe the influence of finishing, a part of the fabrics is finished. The finishing process included the following phases: bleaching, dyeing with LS colors and final finishing.

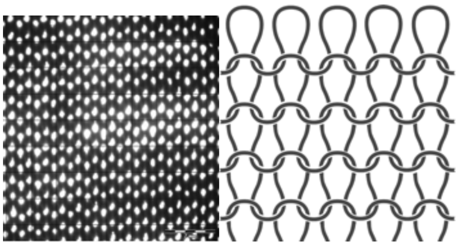

Fig. 4. The knitted fabric:
a. microscopic image, b. structure (Salopek & Skenderi, 2009 a)

3. Results and discussion

The influence of raw material, yarn parameters, fabric structural parameters and finishing process to the heat and water vapour resistance is separately discussed.

3.1 Influence of raw material

A significant contribution to the transfer of heat and moisture should be given by the fiber itself (Salopek et al., 2008 b). As seen from the Fig. 5, the fabrics produced from polyesterhave the highest heatand water vapour resistance among the investigated materials. It could also be seen that the amount of absorbed vapour in fabrics, investigated under the same air humidity, is dependent on the fiber regain. Considering the fiber regain values (cotton 8.5, viscose 12-14, polyester 0.2-0.5), it could be concluded that the relationship between the regain and water vapour resistance is reverse proportional.

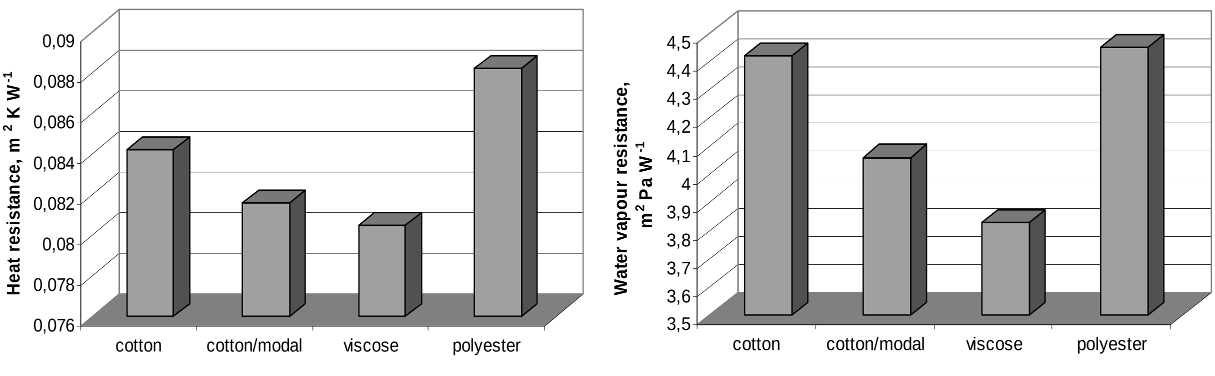

Fig.5. The heat and water vapour resistance of knitted fabrics

3.2 Infulence of yarn parameters

The correlation matrices of Rct/Ret values and yarn parameters indicate the correlations that are significant at p < 05. From the yarn parameters that significantly affect the Rct and Ret, the yarn count, thickness, number of twists and variation of mass should be underlined.

	Heat resistance	Count	Thickness	Twists	Thick places	Nepps	Mass variation	Friction coefficient
Heat resistance	1,00	**0,79**	**0,86**	-0,63	-0,05	0,12	-0,48	-0,13
Count		1,00	**0,99**	**-0,96**	-0,61	-0,47	**-0,89**	0,48
Thickness			1,00	**-0,92**	-0,50	-0,35	**-0,83**	0,35
Twists				1,00	0,74	0,62	**0,93**	-0,64
Thick places					1,00	**0,98**	0,76	**-0,98**
Nepps						1,00	0,68	**-0,99**
Mass variation							1,00	-0,68
Friction coefficient								1,00

Tab. 1. The correlation matrix of heat resistance and yarn parameters

	Vapour resistance	Count	Thickness	Twists	Thick places	Nepps	Mass variation	Friction coefficient
Vapourresistance	1,00	**0,85**	0,80	**-0,92**	-0,61	-0,51	**-0,92**	0,55
Count		1,00	**0,99**	**-0,96**	-0,61	-0,47	**-0,89**	0,48
Thickness			1,00	**-0,92**	-0,50	-0,35	**-0,83**	0,35
Twists				1,00	0,74	0,62	**0,93**	-0,64
Thick places					1,00	**0,98**	0,76	**-0,98**
Nepps						1,00	0,68	**-0,99**
Mass variation							1,00	-0,68
Frictioncoefficient								1,00

Tab. 2. The correlation matrix of water vapour resistance and yarn parameters

3.3 Influence of fabric structure

The transfer of heat through knitted fabric structures is different from the transfer trough other medias. The main reason is the fact that knitted fabrics comprise of repeat units which consist of porous yarns and air spaces. Therefore, the air inside the fabric can be assumed as another insulating material. From the fabric geometry presented in the Figure 4., it can be seen that the conductive heat transfer through knitted fabric takes place through unsupported yarns, interlaced region and air pores (only in case of non-convective mode) (Salopek & Skenderi, 2009 a).

	Heat resistance	Horizontal density	Vertical density	Yarn length in loop	Thickness	Cover factor	Mass	Porosity
Heat resistance	1,00	-0,30	-0,10	0,63	0,57	**0,80**	**0,86**	**-0,84**
Horizontal dens.		1,00	0,10	-0,64	-0,78	-0,60	-0,59	-0,16
Vertical dens.			1,00	-0,65	-0,57	-0,30	-0,43	0,45
Yarn length in l.				1,00	**0,94**	**0,80**	**0,92**	-0,53
Thickness					1,00	**0,90**	**0,91**	-0,41
Cover fact.						1,00	**0,96**	-0,66
Mass							1,00	-0,69
Porosity								1,00

Tab. 3. The correlation matrix of Rct and fabric structural parameters

The matrix of fabric structural parameters and heat resistance (shown in the Table 3) indicate significant correlations between the Rct and the following fabric parameters: cover factor, porosity and mass of fabric per unit area.

The correlation between the Ret and fabric structural parameters, according to the table 4, is significant for the fabric horizontal density, yarn length in a loop, fabric thickness and mass per unit area. There is a positive correlation for all the named set of parameters except for the horizontal density.

	Water vapour resistance	Horizontal density	Vertical density	Yarn length in loop	Thickness	Cover factor	Mass	Porosity
Water vapour r.	1,00	**-0,90**	-0,30	**0,87**	**0,90**	0,80	**0,82**	-0,18
Horizontal dens.		1,00	0,10	-0,64	-0,78	-0,60	-0,59	-0,16
Vertical dens.			1,00	-0,65	-0,57	-0,30	-0,43	0,45
Yarn length in l.				1,00	**0,94**	0,80	**0,92**	-0,53
Thickness					1,00	**0,90**	**0,91**	-0,41
Cover fact.						1,00	**0,96**	-0,66
Mass							1,00	-0,69
Porosity								1,00

Tab. 4. The correlation matrix of Ret and fabric structural parameters

3.4 Influence of finishing

The linear regression model that describes the relationship between the heat resistance of raw and finished fabrics is given by the following expression:

$$R_{ct-finished} = -0.0228 + 1.8603 \cdot R_{ct-raw} \quad (3)$$

The results indicate the higher differences between the heat transfer of raw and finished fabrics. The reason should be the fact that the finishing process caused the changes of knitted fabric structural parameters. The changes have affected the transfer properties of knitted fabrics, in order to enable finished fabrics to allow the higher heat transfer than the raw fabrics. It is to expect that the transfer properties of fabrics finished according to described receipt should enhance the heat-related comfort characteristics of knitted clothing in hot environments (Skenderi & Salopek Cubric, 2009 b)

4. Conclusion remarks

In hot environments, in which investigated fabrics are worn as next-to-skinclothing, it is important that fabric allows higher transfer of heat and water vapour in order to main the balance within the body. In this chapter, the accent was placed to the influence of different parameters to the transfer of heat and water vapour trough textile structure. The investigation has pointed out a number of yarn and knitted fabric parameters that have significant influence to the mentioned transfers. It also indicated importance of finishing process. Such cognition makes a challenge for textile experts to project fabrics with satisfactory transfer properties that will enhance the comfort-related characteristics of knitted clothing.

5. Aknowledgement

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