

Thermal Comfort Index as a Method of Assessing the Thermal Comfort of Textile Materials

Abstract

Thermal comfort is an element of clothing utility comfort. It is defined as a state of satisfaction with the thermal conditions of the environment. Thermal comfort refers to the maintenance of a proper relationship between body heat production and loss. Heat exchange between the human organism and its surroundings is a complex phenomenon that depends on many factors connected with the human organism, climatic conditions of the environment, and the properties and structure of clothing. In this paper the most important factors influencing heat exchange between the human body and its surroundings are discussed. A Thermal Comfort Index TCI was elaborated as a complex characteristic of fabric from the point of view of its ability to ensure thermal comfort in given climatic conditions. The index proposed was applied to assess the textile materials chosen.

Key words: thermal comfort, thermal comfort index, thermal insulation.

Introduction

Thermal comfort is defined as a state of satisfaction with the thermal conditions of the environment [1 - 4]. It is also considered as a lack of negative feelings caused by the thermal effects of the environment. Assurance of thermal comfort requires the thermal stability of the human through maintenance of the thermal balance between body heat production and loss [1]:

$$Q - Q_d - Q_w - Q_{ou} - Q_{oj} = Q_p = Q_R + Q_K \quad (1)$$

where:

- Q – metabolic rate of human body in W/m^2 ,
- Q_d – evaporative heat loss from skin surface in W/m^2 ,
- Q_w – heat loss by the evaporation of sweat in W/m^2 ,
- Q_{ou} – latent heat loss by respiration in W/m^2 ,
- Q_{oj} – convective or sensible respiration heat loss in W/m^2 ,
- Q_p – total rate of heat loss from skin in W/m^2 ,
- Q_R – heat loss by radiation from the outer surface of the clothing in W/m^2 ,
- Q_K – heat loss by convection from the outer surface of the clothing in W/m^2 .

The human organism is homoeothermic, which means that it has to maintain its core temperature within close limits around $37\text{ }^\circ\text{C}$. During all kinds of activity, the human body produces a certain amount of heat in the range of 80 W while sleeping to even over 1000 W during intensive effort. The surplus energy can be transferred to the environment in

three ways: respiration, release of dry heat (radiation, convection, conduction) and evaporative heat. The total heat loss at a mean temperature of $20\text{ }^\circ\text{C}$ and relative air humidity of 50% can be divided as follows [5]:

- evaporation – 20%,
- convection – 25%,
- radiation – 45%,
- respiration – 10%.

The above division of heat loss occurs during rest and when there is a lack of ventilation. At a low temperature respiration can exceed 30 % of the total heat loss, whereas at a high ambient air temperature of $34 - 37\text{ }^\circ\text{C}$, the evaporation of sweat is the main cause of heat loss.

Heat exchange between the human body and its surroundings depends on many factors, which can be divided into three groups (**Figure 1**):

- the human organism,
- climatic conditions of the environment,
- clothing.

Thermal insulation of clothing

The protection of the human being against the influence of negative environmental factors is one of the most important functions of clothing. Investigation of the thermal insulation of clothing was first initiated not by textile experts but by specialists in physiology dealing with the design of room air conditioning [5 - 9].

In the years 1937 – 1970, Gagge i co. carried out an investigation of the heat exchange between the human body and its surroundings in which they introduced a unit of clothing thermal insulation Λ_{cl} (*clo*) describing the total thermal resist-

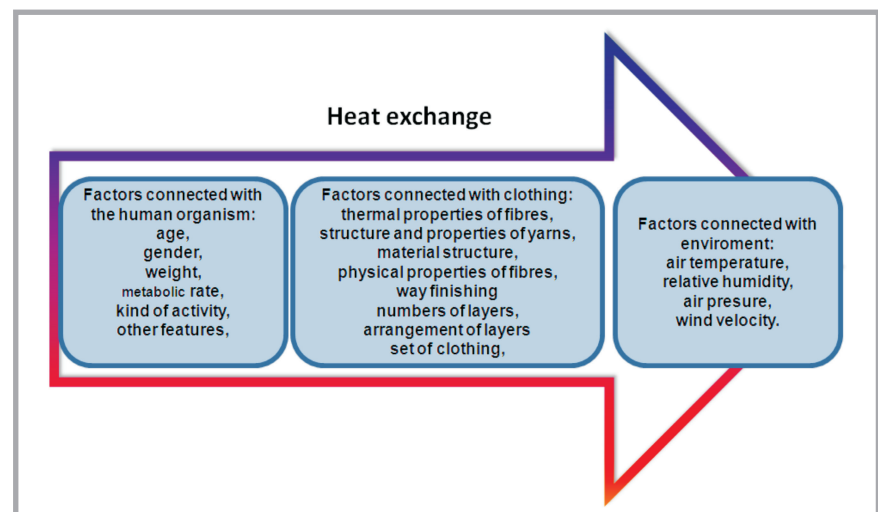


Figure 1. Factors influencing heat exchange between the human body and its surroundings.

ance of the layer between the human skin and the outer surface of clothing.

Clo Λ_{cl} is given by the equation:

$$\Lambda_{cl} = \frac{R_{cl}}{0.18} \quad [\text{clo}] \quad (2)$$

where:

Λ_{cl} – thermal resistance of clothing in clo,
 R_{cl} – total thermal resistance in $\text{m}^2 \text{h}^\circ\text{C}/\text{kcal}$.

One clo corresponds to the intrinsic insulation of a business suit worn by a sedentary resting male in a normally ventilated room at 21 °C, 50% RH and with air ventilation of 0.1 m/s. In these conditions 1 clo of the clothing is equal to 0.155 $\text{m}^2 \text{K}/\text{W}$ [7]. For winter clothes a clo of around 8 is suitable, whereas for summer conditions it is a clo of around 0.5 [8].

The thermal resistance of clothing as a set of textile materials depends mostly on the thickness and porosity of particular layers [10 - 13]. Due to the fact that changes in the porosity of standard textile materials used in clothing are not large, the total thermal resistance of clothing is influenced mainly by the material thickness. Changes in the humidity of textile materials caused by variations in air humidity have an insignificant influence on the value of thermal resistance of textile materials [5].

Irrespective of the thermal resistance of clothing material, a key role in heat exchange is played by the size of air layers closed between the human body and clothing surface, as well as between the

particular layers of clothing. In the case of one-layer clothing, thermal comfort depends on the clothing cut and fitting to the figure of the clothing user. This is exemplified by **Figure 2**, which shows a thermogram from an infrared camera.

In the picture a clear difference in the clothing surface temperature at different parts of the human body can be seen. Due to the large rigidity and low drape of the material, the shirt does not stick to the body on the whole surface equally - it creates folds at different distances from the surface of the body. Thus, beside the places where the shirt material sticks directly to the body's skin, there are places of small distance (several millimetres) between the body's skin and the shirt. In the given conditions – small closed spaces – air is an excellent thermal insulator, limiting heat loss significantly. The temperature along perpendicular line L 1 is in the range of 26.16 °C to 31.77 °C, whereas along horizontal line L 12 it is from 25.47 °C to 31.19 °C, in spite of the fact that, on the whole, the surface of the shirt analysed is made of the same fabric. The difference in temperature between the extreme points on the surface of the shirt is higher than 5 °C.

In the case of very loose-fitting clothing, ventilation of air layers can occur additionally due to the so-called “chimney effect”. At a high air velocity the dynamic pressure can cause the penetration of air stream through the clothing. The amount of air transmitted depends on the kind of material from which the clothing is made. Heat loss due to ventilation can influence the thermal insulation of clothing.

The thermal insulation of multilayer clothing depends not only on the thermal insulation of particular layers but also on their number and arrangement [3, 14], as well as on the number and dimensions of air gaps.

Taking into consideration the complexity of the phenomenon of heat exchange between the human body and the environment, as well as the big number of factors influencing the heat exchange, an unambiguous assessment of the thermal insulation of a given clothing assortment is difficult or simply impossible. Numerous investigations have been undertaken to elaborate comfort models and indexes allowing to predict or assess the thermal comfort assured by clothing. Nevertheless, precise and reliable prediction of the thermal comfort seems to be possible at precisely described conditions of a microclimate for a set of clothing during a given kind of activity. Such a situation can take place in the case of cold protective work wear for workers acting in specific cold microclimates. When designing daily-use fabrics and clothing we do not know their future user. We also do not know the majority of factors influencing thermal comfort connected with both features of the human body and climatic conditions of the environment in which the clothing will be used. However, in equal (standardised) conditions we can measure the thermal properties of particular fabrics – woven or knitted. Next, from the measurement results we can draw conclusions about the fabric's ability to ensure thermal comfort in predicted conditions of clothing application.

Elaboration of a function or one general index characterising, in a complex way, clothing from the point of view of its ability to ensure thermal comfort has been the object of investigation for many researchers. Fanger [1] elaborated the *Thermal Comfort Equation* as a function of 6 parameters:

$$f(M, I_{cl}, v, t_r, t_a, P_w) \quad (3)$$

where:

- M – metabolic rate, met ($\text{met} = 58.2 \text{ W}/\text{m}^2$),
- I_{cl} – cloth index in clo,
- v – air velocity in m/s,
- t_r – mean radiant temperature in °C,
- t_a – ambient air temperature in °C,
- P_w – vapour pressure of water in ambient air in Pa.

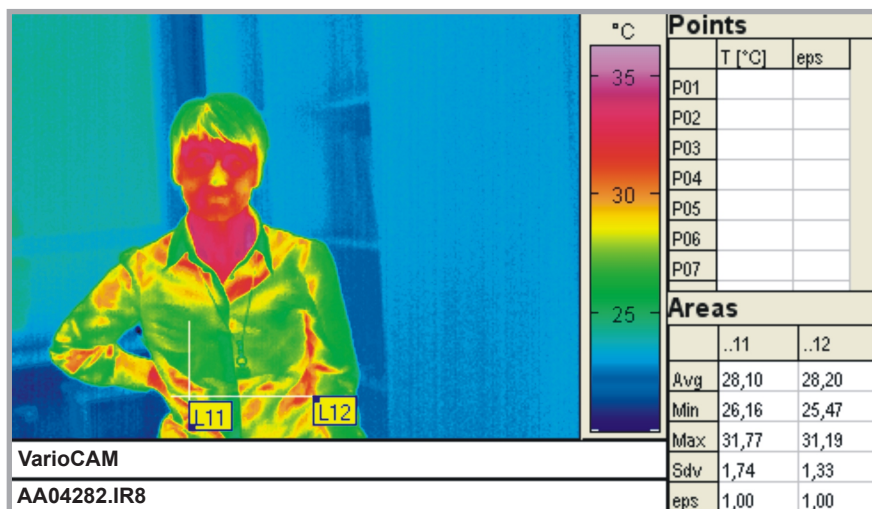


Figure 2. Thermogram illustrating temperature distribution according to the different fittings of particular parts of shirt.

According to Hes [15], the performance of protective garments can be described by two or three principal parameters sufficiently characterising the clothing's protection and wear comfort. Hes proposed an Index of Quality IQ to characterise the complex comfort level of a winter jacket in the following form:

$$IQ = (R - R_{min}) \times (P - P_{min}) \quad (4)$$

where:

- R – thermal resistance in $m^2 KW^{-1}$,
- R_{min} – minimal value of the thermal resistance acceptable from the point of view of thermal comfort in $m^2 KW^{-1}$,
- P – water-vapour permeability in %,
- P_{min} – minimal value of the water-vapour permeability acceptable from the point of view of thermal comfort in $m^2 KW^{-1}$.

Militky and Matusiak [8] elaborated a procedure for the evaluation of a Physiological Index of Comfort IC . The procedure starts with a specification of K properties R_1, \dots, R_K characterising comfort (e.g. thermal resistance, water-vapour resistance, areal weight etc). Based on direct or indirect measurements, it is possible to obtain some comfort characteristics x_1, \dots, x_K (mean value, variance, quantiles etc.) representing comfort properties. Functional transformation of these characteristics (often based on psycho-physical laws) leads to partial comfort functions:

$$u_i = f(x_i, L, H) \quad (5)$$

where L is the unacceptable value of a characteristic (smallest u_i) and H is the value of a characteristic for a fully acceptable product (u_i equal to the highest value - 1). The physiological Index of Comfort, IC , is the weighted average of u_i with weights b_i :

$$IC = ave(u_i, b_i) \quad (6)$$

At the Hohenstein Institutes [16] the Thermophysiological Wear Comfort vote WC_T was elaborated as a combination of the quantities characterising the thermophysiological quality of a textile, according to the following formula:

$$WC_T = \alpha_1 R_{ct} + \alpha_2 F_d + \alpha_3 K_f + \alpha_4 \Delta G + \beta \quad (7)$$

where:

- R_{ct} – thermal resistance
- F_d – moisture regulation index
- K_f – sweat buffering
- F – sweat transport
- ΔG – water retention
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \beta$ – constant values.

The WC_T value can lie between 1 – very good and 6 – unsatisfactory. According to Umbach [16], in order to describe the total wear comfort, the thermophysiological wear comfort vote WC_T should be given together with the sensorial comfort vote WC_S , which corresponds to the sensitivity of skin to mechanical irritations.

An interesting and complex solution was elaborated by Hes [15], who developed the Comfort Evaluation System (CES), consisting of a square matrix of relative comfort parameters, as follows:

$$\begin{bmatrix} \mathbf{R} & \mathbf{Re} & \mathbf{bw} \\ \mathbf{B} & \mathbf{G} & \mathbf{Fw} \\ \mathbf{F} & \mathbf{Cw} & \mathbf{b} \end{bmatrix}$$

where:

- \mathbf{R} – thermal resistance
- \mathbf{Re} – water-vapour resistance
- \mathbf{bw} – moisture absorptivity
- \mathbf{B} – bending rigidity
- \mathbf{G} – shearing rigidity
- \mathbf{Fw} – wet friction coefficient
- \mathbf{F} – dry friction coefficient
- \mathbf{Cw} – compression work
- \mathbf{b} – dry thermal absorptivity

The parameters in the upper row represent the thermal comfort, values in middle row - sensorial comfort, and parameters in the bottom row - fabric handle.

Matusiak applied the rank method for the evaluation of woven fabrics with respect to thermal comfort [17]. The rank procedure is simple, but it does not take into consideration the importance of the particular parameters used for assessment. Moreover, the rank method does not take into consideration the boundary values of all comfort-related parameters, which are the basis of fabric evaluation. Using the rank method, it is possible to compare fabrics and to rank them from the best to the worst in terms of thermal comfort in the climatic conditions of clothing utility predicted.

■ Thermal Comfort Index

In this study, the theoretical consideration and investigation of textile materials in the aspect of their thermal properties allowed to elaborate a complex index characterising the ability of textile materials to ensure thermal comfort. The Thermal Comfort Index (TCI) has the following form:

$$TCI = \sum_{i=1}^n a_x \frac{x_i - x_{i \min}}{x_i} + \sum_{j=1}^m a_z \left(1 - \frac{z_j}{z_{j \max}} \right) \quad (8)$$

where:

- TCI – Thermal Comfort Index,
- x_i – value of the i^{th} property, whose increment causes an improvement in thermal comfort; $i = 1, 2, \dots, n$,
- $x_{i \min}$ – minimum value of property x_i acceptable from the point of view of thermal comfort,
- z_j – value of the j^{th} property, whose reduction causes an improvement in thermal comfort; $j = 1, 2, \dots, m$,
- $z_{j \max}$ – maximum value of the property z_j acceptable from the point of view of thermal comfort,

$$a_x = \frac{p_i}{\sum_{i=1}^n p_i + \sum_{j=1}^m p_j} \quad a_z = \frac{p_j}{\sum_{i=1}^n p_i + \sum_{j=1}^m p_j}$$

where:

- p_i – degree of importance of the i^{th} property ($1 \div 5$),
- p_j – degree of importance of the j^{th} property ($1 \div 5$).

The equation is valid when each value of $x_i \geq x_{i \min}$ and each value of $z_j \leq z_{j \max}$. Otherwise when at least one property does not take the value necessary for thermal comfort assurance, a lack of comfort occurs. In this case there is little point in calculating the comfort index.

Elements: $(x_i - x_{i \min})/x_i$ and $(1 - z_j/z_{j \max})$ take values of 0 to 1, which allows to prevent the neglecting of important comfort properties despite their small absolute value. TCI values are also in the range of 0 to 1.

The original name of the index elaborated was the Physiological Comfort Index PCI [8]. Physiological comfort is a very complex phenomenon that covers not only the thermal but also the sensorial feeling resulting from fabric handle or its ability to accumulate electric charge. Due to this fact, the name 'Thermal Comfort Index' seems to be more adequate than 'Physiological Comfort Index'. The index elaborated, TCI , characterises fabrics mainly with respect to the thermal feeling of the clothing user.

The index elaborated, TCI , can be applied to assess different textile materials in terms of the thermal comfort predicted. In order to calculate the value of TCI according to the formula presented (8), it is first necessary to establish the kind and number of parameters as criteria for the

Table 1. The set of materials investigated.

Symbol	Description	Material	Mass per square meter, gm ⁻²	Thickness, mm
C 1	plain woven fabric; warp 15 tex, 30 cm ⁻¹ ; weft 20 tex, 25 cm ⁻¹	cotton	98.4	0.17
C 2	plain woven fabric; warp 15 tex, 30 cm ⁻¹ ; weft 40 tex, 24 cm ⁻¹	cotton	148.7	0.20
C 3	plain woven fabric; warp 15 tex, 30 cm ⁻¹ ; weft 60 tex, 16 cm ⁻¹	cotton	150.8	0.31
P 1	nonwoven stitched (Figure 3.a)	cotton	190.0	2.96
P 2	fluffy nonwoven	PES	62.3	1.18
P 3	3-layer material: lining+ nonwoven + net (Figure 3.b)	PES	191.4	2.03
P 4	fluffy nonwoven (Figure 3.d)	PES	78.4	3.77
P 5	2-layer material: lining + nonwoven (Figure 3.c)	PES	120.5	3.93
P 6	fluffy nonwoven	PES	157.1	8.45

Table 2. Results of measurement.

Symbol	λ , Wm ⁻¹ K ⁻¹ × 10 ⁻³	b , Wm ² s ^{1/2} K ⁻¹	R , W ⁻¹ K m ² × 10 ⁻³	h , mm	R_{et} , m ² PaW ⁻¹	AP , dm ³ m ⁻² s ⁻¹
C 1	41.5	278.0	4.0	0.17	8.113	816.9
C 2	51.5	284.0	4.7	0.20	8.785	135.0
C 3	52.5	250.0	6.0	0.31	8.374	57.2
P 1	38.4	57.3	77.6	2.96	11.704	1111.9
P 2	30.8	38.8	38.2	1.18	9.014	1111.9
P 3	37.8	61.1	53.8	2.03	6.364	227.1
P 4	41.2	26.1	91.4	3.77	5.324	1111.9
P 5	43.9	34.2	89.6	3.93	8.928	380.2
P 6	54.5	29.6	155.0	8.45	21.486	685.1

assessment. This should be done on the basis of the knowledge and experience of the investigator or designer. Next the parameters chosen have to be divided into two groups: positive properties - x and negative properties - z . Moreover, the appropriate degree of importance can be established for each property used for calculation.

At this stage of the investigation we do not have the necessary data to assume the acceptable minimum or maximum values of the particular parameters applied for the calculation of the *TCI*. This problem should be the subject of further research. The main barrier is a lack of information about the conditions of clothing usage predicted as well as the dynamic changeability of these conditions resulting from the way of clothing usage, the climatic conditions of the environment as well as the individual features and kind of clothing user activity.

In the comparable analysis of textile materials by means of *TCI*, the minimum or maximum values of particular parameters from all their values obtained as a result of fabric measurement can be taken as $x_{i \min}$ and $z_{j \max}$.

Experimental

The Thermal Comfort Index elaborated was applied to assess the selected textile materials on the basis of the results of instrumental measurement. The textile materials chosen differed significantly with respect to their thermal properties, being the objects of evaluation. There were fabrics characterised by significantly different structures: cotton woven fabrics made using the same warp: 15 tex, nominal density 30 cm⁻¹; PES nonwoven of various thickness, and multilayer thermoinsulating fabrics. The materials investigated are presented in **Table 1**.

Measurement was done by means of an Alambeta and sweating guarded hot-plate test. The following properties were measured:

- λ – thermal conductivity,
- b – thermal absorptivity,
- R – thermal resistance,
- h – fabric thickness,
- R_{et} – water-vapour resistance.

Moreover, the air permeability (*AP*) was assessed according to the standardised method PN-EN ISO 9237:1998. The results obtained are presented in **Table 2**.

On the basis of the results, the *TCI* values were calculated according to the formula elaborated (8) assuming the application of the fabrics investigated to winter clothing. For the calculation of *TCI*, the following properties were taken:

- thermal resistance
- water-vapour resistance
- thermal absorptivity
- air permeability

with the degree of importance given in **Table 3**.

The thermal resistance R was taken as a positive parameter - x , because its increase causes an improvement in thermal comfort. Thermal absorptivity b , water-vapour resistance R_{et} and air permeability AP were taken as the negative parameters - z , because their increase causes a worsening of thermal comfort. The lower the water-vapour resistance, the better the sweat release and, in the same way, the more comfortable the feeling is. The lower the air permeability, the better the protection against wind, which improves the thermal comfort, especially in winter conditions. Furthermore, the lower thermal absorptivity of fabrics means that they are warmer to the touch.

The properties mentioned above are considered as the most important for thermal comfort in a cold climate. It was also possible to apply other thermal properties of fabrics, for instance their mass per square meter or thickness. Both are important from the point of view of thermal comfort. The bigger the mass and thickness, the better the thermal insulation of fabrics. Nevertheless, a bigger mass and thickness can lead to a worsening of utility comfort, especially the freedom of movement.

The degrees of importance of particular thermal properties applied to *TCI* calculation were established on the basis of the author's knowledge and experience as an investigator and clothing user.

Table 3. Degree of importance of the properties used for *TCI* calculation.

No.	Property	P	a
1.	Thermal resistance	5	0.3125
2.	Thermal absorptivity	2	0.1250
3.	Water-vapour resistance	4	0.2500
4.	Air permeability	5	0.3125
	$\sum P_i$	16	

On the basis of the formula elaborated (8), values of *TCI* were calculated for all materials assessed. The results obtained are presented in **Figure 4**. For comparison, values of *TCI* were also calculated on the basis of 5 parameters: the 4 mentioned above (**Table 3**) and the mass per square meter of the fabric – *TCI 2*. The mass per square meter was considered as a negative parameter, with a degree of importance equal to 1.

The results presented confirmed the substantial differences in the textile materials assessed with respect to their ability to ensure thermal comfort in winter conditions. The highest value of *TCI* occurred for materials P 5 and P 6. The results of the assessment are consistent with expectations. Materials P 5 and P 6 are textile materials designed especially for the insulating layer of winter clothing. Material P 6 is a thick PES nonwoven, whereas material P 5 is a 2-layer material consisting of PES nonwoven and lining (**Figure 3**). According to the *TCI* values, both materials are comparable with respect to thermal comfort, although their particular thermal properties are completely different. The nonwoven P 6 is characterised by the highest thermal resistance of all the materials investigated but also by the highest water-vapour resistance. In comparison to nonwoven P 6, the 2-layer material P 5 is characterised by a lower thermal resistance but also by a much lower water-vapour resistance and air permeability.

Due to the comparable values of *TCI* of materials P 5 and P 6, the clothing designer has to weigh up which basic property is the most important with respect to the clothing designed and make appropriate corrections of the importance degrees. Next the values of *TCI* should be calculated once again.

The lowest value of *TCI* was noted for material C 1, which is thin cotton woven fabric and not really appropriate for winter clothing. Therefore the evaluation of fabric C 1 using the *TCI* index *TCI* index seems to be correct.

Values of *TCI* calculated on the basis of 4 fabric properties: thermal resistance, water-vapour resistance, thermal absorptivity and air permeability (series *TCI 1* in **Figure 4**) are at the same level as values of *TCI* calculated on the basis of 5 parameters (series *TCI 2* in **Figure 4**). Application of the mass per square meter

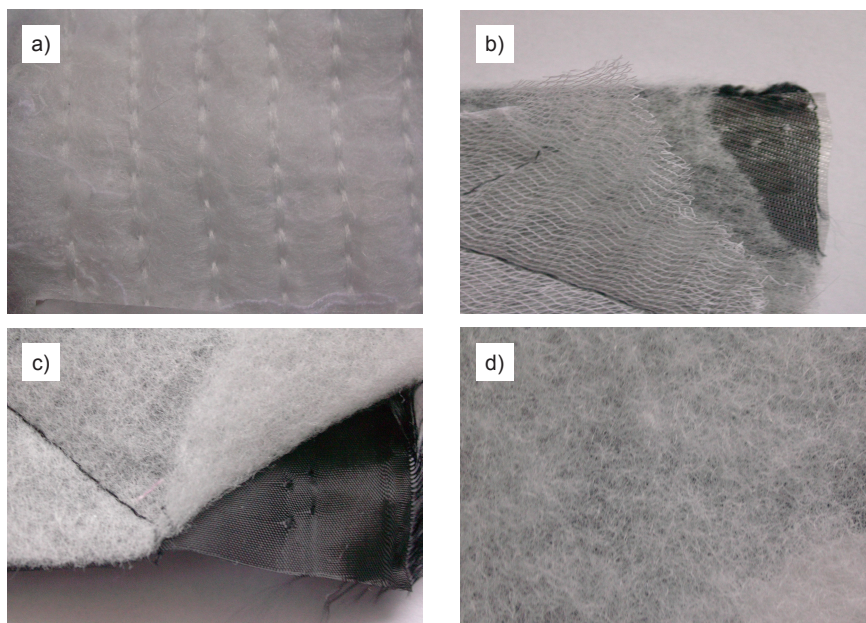


Figure 3. Pictures of chosen investigated textile materials; a) nonwoven stitched, b) 3-layer material, c) 2-layer material, d) fluffy nonwoven.

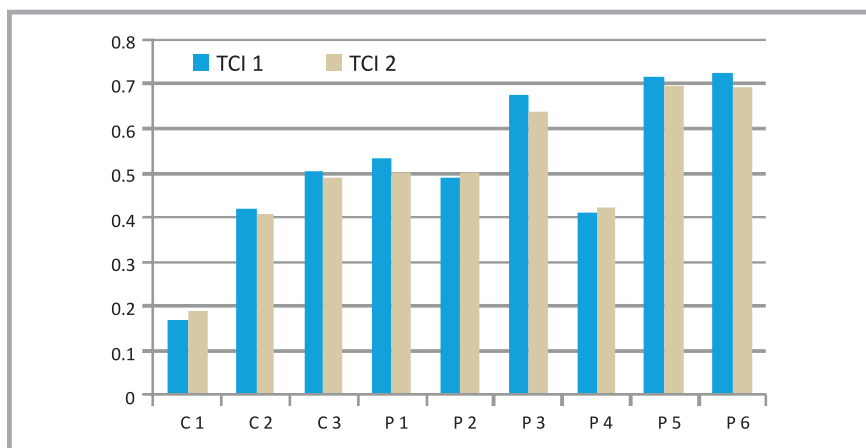


Figure 4. Calculated values of *TCI*: *TCI 1* – values calculated without the mass per square meter of fabric, *TCI 2* – values calculated with mass per square meter of fabric.

to the calculation of *TCI* did not influence the results of fabric assessment in the range of their ability to ensure thermal comfort.

Conclusions

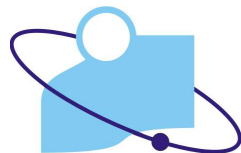
On the basis of the investigation presented, it can be stated that the Thermal Comfort Index – *TCI* elaborated enables the assessment of fabrics with respect to their ability to ensure total thermal comfort on the basis of particular measurable thermal properties of fabrics. Due to the lack of scientific basis to establish minimum and maximum values of particular thermal properties necessary for thermal comfort, in order to calculate the values of *TCI*, the minimum or maximum values of particular parameters from all

the values of these parameters obtained for the group of fabrics investigated can be taken as $x_{i \min}$ and $z_{j \max}$.

The choice of properties for calculation of the *TCI* should take into consideration the predicted application of clothing made of the fabrics evaluated. The degree of importance of particular comfort properties of fabrics should be established on the basis of the experience and knowledge of the textile designer. Nevertheless, it is necessary to carry out investigations in order to determine extreme values of the thermal properties of fabrics acceptable to assure thermal comfort.

The investigation aimed at the elaboration of a Thermal Comfort Index as a complex characteristic of textile materi-

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fax: +4842 6792638

Contact persons:

Katarzyna Grzywacz tel. (+4842) 6163 195, e-mail: grzywacz@iw.lodz.pl
Joanna Koprowska tel (+4842) 6163 116, e-mail: koprowska@iw.lodz.pl

als in the aspect of the thermal comfort of clothing made of these materials will be continued.



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