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Relative Thermal Comfort Index as a Measure of the Usefulness of Fabrics for Winter Clothing Manufacturing

Abstract
The paper presents a continuation of work on determining an index of thermal comfort. A Relative Thermal Comfort Index (RTCI) has been elaborated for fabrics designed for winter clothing. Two versions of the index have been suggested: $RTCI_{WI}$ - used to evaluate textiles in windless conditions (Winter Indoor) and $RTCI_{WO}$ - used to evaluate textiles in windy conditions (Winter Outdoor). Various tests were carried out in order to verify the index, including the subjective assessment of thermal comfort by the wearers of vests made of the fabrics under investigation, measurements of air temperature and air temperature changes under clothing as well as measurement of temperature changes in a vest's outer surface caused by heat generated by the human body. Measurements were performed using a wireless temperature sensor and thermovision camera. Statistical analysis showed the conformity of fabric evaluation using $RTCI_{WI}$ with those carried out under utility trials.

Key words: *thermal comfort, Relative Thermal Comfort Index, clothing.*

Introduction

A lot of research has been conducted in order to elaborate a function or general measure that would allow to comprehensively assess a fabric or clothing from the point of view of its capability to ensure thermal comfort [1 – 6]. Among the various options which have been suggested so far, only the comfort indices suggested by the Hohenstein Institute seem to be of practical use [4]. The '*Physiological Comfort Vote*" is used by the Hohenstein Institute to certify certain trade products on the basis of suggested comfort indicators. This index relies on the evaluation of textiles from the point of view of thermal and sensorial comfort, where the scope of certifying tests depends on the product's purpose [7]. Similar rules are used by the Hohenstein Institute to evaluate textile products in the range of other properties, such as antistatic, breathing etc.

Numerous studies of textile thermal protective properties as well as theoretical considerations have allowed to develop a generalised formula for a comprehensive index representing the capability of textiles to ensure thermal comfort (*Thermal Comfort Index*). The formula is as follows [8]:

$$TCI = \sum_{i=1}^{n} a_{xi} \frac{x_i - x_{i\,\min}}{x_i} + \sum_{j=1}^{m} a_{zj} \left(1 - \frac{z_j}{z_{j\,\max}}\right) \quad (1)$$

where:
- TCI – Thermal Comfort Index,
- x_i – the value of i^{th} parameter, which results in an improvement of thermal comfort when increased, where i = 1, 2, …, n,
- x_{imin} – minimum value of i^{th} parameter needed to ensure thermal comfort,
- z_j – the value of j^{th} parameter, which results in a deterioration in thermal comfort when increased, where j = 1, 2, …, m,
- z_{jmax} – maximum value of j^{th} parameter, which is acceptable from the point of view of thermal comfort,
- $a_{x,i}$, $a_{z,j}$ – parameters calculated on the basis of the importance degree of particular properties used for calculations.

The value of *TCI* ranges between 0 and 1. The higher the value of the index, the higher the capability of a fabric to ensure thermal comfort. A certain limitation of *TCI* lies in the fact that the current level of knowledge does not allow to determine minima and maxima, i.e. critical points at which values of particular parameters of fabrics for everyday clothing are acceptable for providing thermal comfort. The basic difficulty in determining these values lies in the impossibility to define conditions in which clothing would be worn, the changeability of these conditions during the wearing of the clothing which result from all the manner of wearing, thermal environmental conditions, individual features and the type of physical activity of the wearer [8]. *TCI* can be used to assess textiles for specialist protective clothing, which have normative requirements for the range of values of an indicator influencing thermal protection. Also the index is useful if a receiver has particular requirements for textiles used in his/ her order. In this case requirements can be taken as critical values, i.e. minimum and maximum values in the formula for *TCI*.

Relative Thermal Comfort Index

In a comparative analysis of fabrics evaluated with *TCI* (1), it is advisable to use a maximum value of the z_j property obtained for the group of fabrics under evaluation instead of the maximum z_{max} value acceptable for providing thermal comfort. Similarly, instead of using the minimum value x_{min} necessary to ensure thermal comfort, the lowest value of the x_i property obtained for the group of fabrics under evaluation and comparison can be used.

However, the value of *TCI* calculated in this manner is not an absolute measure of the quality of fabrics concerning the provision of thermal comfort. Because of unidentified extrema, i.e. the minimum and maximum values of particular parameters which lead to a lack of thermal comfort in specific or predictable climatic conditions if exceeded, it is impossible to definitely confirm the capability of fabric to ensure thermal comfort in specific conditions on the basis of the *TCI* value.

An index calculated on the basis of minimum and maximum values of particular parameters obtained as a result of testing a group of fabrics should be considered as a relative measure of the quality of fabrics from the point of view of their ability to ensure thermal comfort, since it allows a comparative evaluation of fabrics and assessment of the level of fabric quality with regard to the quality of other fabrics evaluated by means of the same procedure.

All things considered, an index calculated on the basis of minimum and maximum values of parameters obtained by measuring a group of fabrics that are under collective evaluation is referred to as Relative Thermal Comfort Index (*RTCI*), the formula of which is as follows:

$$RTCI = \sum_{i=1}^{n} a_{xi}\left(1 - \frac{x_{i\,\min IG}}{x_i}\right) + \sum_{j=1}^{m} a_{zj}\left(1 - \frac{z_j}{z_{j\,\max IG}}\right) \quad (2)$$

where:

- $RTCI$ – Relative Thermal Comfort Index,
- x_i – the value of i^{th} parameter, which results in an improvement of thermal comfort when increased, where $i = 1, 2, \ldots, n$,
- x_{iminIG} – minimum (intragroup - *IG*) value of i^{th} parameter obtained as a result of measuring a group of textiles under collective evaluation,
- z_j – the value of j^{th} parameter, which results in a deterioration of thermal comfort when increased, where $j = 1, 2, \ldots, m$,
- z_{jmaxIG} – maximum (intragroup - *IG*) value of j^{th} parameter obtained as a result of measurements made on a group of textiles under collective evaluation,

$$a_{xi} = \frac{p_i}{\sum_{i=1}^{n} p_i + \sum_{j=1}^{m} p_j} \quad (3)$$

$$a_{zj} = \frac{p_j}{\sum_{i=1}^{n} p_i + \sum_{j=1}^{m} p_j} \quad (4)$$

where:

p_i – significance of i^{th} property (1 ÷ 5),
p_j – significance of j^{th} property (1 ÷ 5).

Two formulas of the Relative Thermal Comfort Index have been suggested for fabrics used for the production of everyday use clothing appropriate for a cold microclimate:

- for fabrics used to produce everyday clothing for outdoor use in a cold microclimate, it is the Relative Thermal Comfort Index Winter Outdoor *($RTCI_{WO}$);* In order to ensure thermal comfort in these conditions, it is necessary to provide protection against excessive loss of heat and against wind penetration while allowing for the evaporation of sweat from the skin surface. Heat is lost as a result of conduction, radiation or convection; in windy conditions the additional air movement (wind) significantly increases heat transfer by convection (forced convection).
- for fabrics used to produce everyday clothing for indoor use in a cold microclimate, it is the Relative Thermal Comfort Index Winter Indoor *(*$RTCI_{WI}$*)*; it is assumed that such conditions are windless, hence only free convection occurs.

The properties of fabrics which influence their capability to ensure thermal comfort as well as significance degrees corresponding to these properties have been selected on the basis of experience, an analysis of the heat exchange processes which take place in various climatic conditions, and the results of numerous prior studies concerning human body protection against cold and thermal discomfort [3, 6, 8].

Thermal resistance is assumed to be a key parameter since body protection against excessive heat loss is an absolute condition for maintaining thermal comfort in a cold microclimate. Consequently, thermal resistance is scored 5, i.e. the highest degree of significance. Air permeability is of importance in windy conditions only, as it determines body protection against wind. The air permeability of fabrics for producing winter clothing for outdoor use has been scored 3; however, this property has not been taken into consideration in the case of fabrics for indoor use in windless conditions in unheated indoor areas. Water-vapour permeability plays the most important role during increased physical activity. Normal conditions of clothing usage in a cold microclimate do not intensify perspiration; therefore sweating is not troublesome in this case – hence the score for this parameter is 2. Thermal absorptivity is the characteristic of how textile feels when touched, i.e. warm or cold. A warm or cold sensation when skin touches clothes is important in winter because it influences the subjective feeling of thermal comfort. Consequently, thermal absorptivity has been regarded as an additional property, hence it is scored 1 (out of 5).

The indexes elaborated have the following formulas:

$$RTCI_{OW} = 0.454 \cdot \left(1 - \frac{R_{\min}}{R}\right) + 0.091 \cdot \left(1 - \frac{b}{b_{\max}}\right) + 0.182 \cdot \left(1 - \frac{R_{et}}{R_{et\max}}\right) + 0.273 \cdot \left(1 - \frac{PA}{PA_{\max}}\right) \quad (5)$$

$$RTCI_{OW} = 0.625 \cdot \left(1 - \frac{R_{\min}}{R}\right) + 0.250 \cdot \left(1 - \frac{b}{b_{\max}}\right) + 0.125 \cdot \left(1 - \frac{R_{et}}{R_{et\max}}\right) \quad (6)$$

where:

R – thermal resistance,
b – thermal absorptivity,
R_{et} – water-vapour resistance,
AP – air permeability.

$RTCI_{WI}$ can be useful to evaluate fabrics for clothing used in a cold microclimate in windless conditions, e.g. during winter in an unheated or moderately heated indoor space, refrigerators, etc. where it is not necessary to take into account air permeability.

Experimental verification of Relative Thermal Comfort Index

In order to verify experimentally the formulas for *RTCI* proposed, utility tests of vests made of the fabrics evaluated were carried out. The tests involved the production and use of vests in a cold microclimate. The study included measuring the air temperature under clothes and the temperature of the outer vest surface.

Testing methodology

The utility trials included the evaluation of a group of fabrics commonly used in winter clothing by means of $RTCI_{WI}$ and $RTCI_{WO}$. The group of fabrics evaluated included wool and wool/polyester woven fabrics, polar knitted fabrics and multilayer materials containing nonwoven thermal protective fabric. For comparison, a thick cotton woven fabric was used. All these fabrics were tested for comfort-related properties, taken into account in the indexes elaborated. The study was carried out by means of Alambeta [9 - 11] and a "skin model" [12, 13].

The sweating guarded hot plate test, referred to as the "skin model", is the most popular and world-wide recognised instrument used for measurements of textile thermo-insulating properties. Measurement procedures using the "skin model" have been standardised in Polish Standard PE-EN 31092 [12], which is in agreement with the international standard ISO 11092: 1993. The instrument stimulates the heat and humidity generation processes occurring on human skin. The "skin model" was used to determine water-vapour resistance, which evaluates the "latent" evaporation heat stream passing through a given surface due to a fixed difference maintained in water-vapour pressure [12]. During the measurement of water-vapour resistance, the electrically heated porous plate is covered with a permeable membrane which lets water-vapour pass through but is not permeable to water. The temperature of both the measuring plate and air is maintained at the level of 35 °C (to provide izothermal conditions), whereas the porous layer is kept moist at all times. The heat flow required to maintain a constant temperature of the plate on which the sample is placed corresponds to the amount of evaporated water, which determines the water-vapour resistance of the sample. Heating energy is measured twice: with and without a sample. Water-vapour resistance is calculated as the difference between the water-vapour resistance of the sample, including the boundary air layer (determined after placing the sample on the measuring plate), and the water-vapour resistance of the boundary air layer (determined prior to placing the sample on the measuring plate) [12].

Alambeta is an automatic measuring instrument which is used to assess the basic thermal characteristics of textile products [6, 10, 11, 13]. It belongs to the so-called plate measurement methods, whose principle is based on the convection of heat emitted by the hot upper plate in one direction through a sample of the test fabric towards the cold lower plate adherent to the sample. Alambeta measures not only static thermo-insulaton properties of textiles, such as thermal resistance or conductivity, but also the dynamic thermal characteristics of fabrics, e.g. thermal diffusivity and absorptivity [6]. Moreover, Alambeta directly measures stationary heat flow density on the basis of an electrical energy measurement on a given plate surface, the temperature difference between the upper and lower plate surfaces, and fabric thickness. In the present work Alambeta was used for the assessment of the thermal resistance and thermal absorptivity of the fabrics evaluated.

Air permeability was determined by procedures standardised in Polish Standards [14].

Based on measurement results for each fabric evaluated, $RTCI_{WI}$ and $RTCI_{WO}$ were calculated according to formulas (5) and (6).

The utility investigation consisted in wearing vests made of the fabrics assessed in a cold microclimate in order to evaluate their usefulness for winter clothing manufacturing. The experiment was carried out in a cold room at 16 °C, and it involved wearing vests - each vest was worn for about 40 minutes by one person. During intervals between the trials, the person who tested the vests entered a heated room so as to regain thermal comfort and obtain identical initial conditions for vest wearing. Due to the long duration of the tests, it was impossible to carry out the experiment outdoors because of the inability to maintain identical microclimate conditions for 9 hours, *i.e.* the duration of the experiment. Therefore, it was necessary to limit the study to testing in a cold room.

The experimental verification of the indexes proposed consisted of the evaluation of the calculated *RTCI*'s compliance with the predicted thermal comfort feeling of a user wearing a vest made of the fabrics evaluated. Thermal comfort is a subjective feeling dependent on various factors, including the personal characteristics of the clothing's user. Hence, the feeling of thermal comfort is difficult to quantify.

For the purpose of the study, it was assumed that the feeling of thermal comfort of a user wearing a vest made of the fabrics under investigation could be estimated and ordered on the basis of two measurable indicators:

- the temperature of air under the clothing - between the clothing and skin of the user,
- the temperature of the outer vest surface.

The temperature measured in both places corresponds to the thermal feeling of a clothing wearer. The temperature of air under the clothing corresponds to the feeling of thermal comfort in a positive manner since the air under the clothing is in direct contact with the skin of the wearer. In a cold microclimate, the higher the temperature of air under the clothing, the better the capability of the clothing (and the capability of the fabric the clothes are made of) to ensure thermal comfort. In turn, the temperature of the outer surface of the clothing correlates negatively with the feeling of thermal comfort in a cold microclimate. A higher temperature of the outer vest surface means that higher amounts of heat have penetrated the heat barrier formed by the clothing. Hence, the higher the temperature of the outer surface of the barrier, the worse the protection against heat loss provided by the barrier.

Therefore, both of the temperatures measured were assumed as a basis for concluding on the thermal comfort of the vest user expected.

Measurement of the air temperature under clothing requires that a wireless temperature sensor be placed under the clothing. The temperature sensor fitted in a case of dimensions 2 cm × 5 cm × 9 cm was placed in a manner preventing it from touching the body and clothes. The air temperature under the clothing was recorded at 5 minute intervals. Also, at the time of taking measurements, the ambient temperature was recorded, which oscillated around 16 °C, ranging between 15.6 °C and 16.4 °C. In order to eliminate the influence of ambient air temperature fluctuations on the results of the analysis, the difference between the temperature of air under the clothing and the ambient air temperature was taken as a measure characterising fabrics from the point of view of the wearer's thermal comfort. The lower the temperature difference is, the lesser the capability of clothing (fabric) to ensure thermal comfort in a cold microclimate. The difference between the temperature of air under the clothing and that of air in a cold room reflects the ability of the heat barrier, *i.e.* the clothing, to protect the air layer adherent to the skin under the clothes against a drop in temperature.

It was observed that for particular fabrics the temperature of the air layer under the clothing made of these fabrics reached the minimum values after different times of vest wearing, depending on the thermal characteristics of the fabric or on

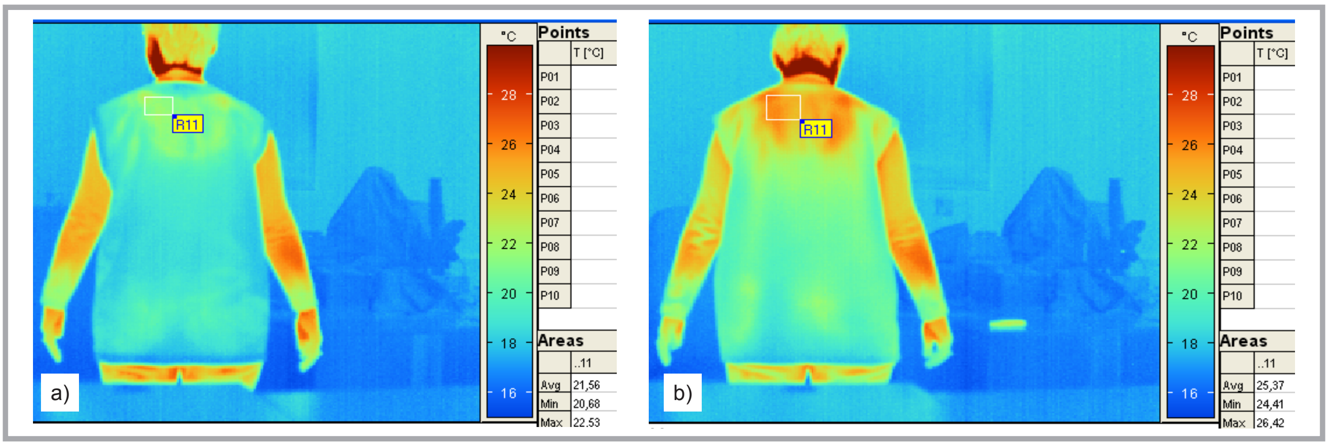


Figure 1. *Exemplary thermogram a) taken in the initial phase of the study and b) after 10 minutes of vest wearing.*

the physiological reactions of the human organism to cooling. Finally, arithmetic means from the differences between the air temperature under the clothing and the ambient air temperature recorded during wearing a particular vest at 5 minute intervals (altogether giving 9 measures) were taken as a measure of the subjective feeling of thermal comfort.

A thermovision camera was used to measure the temperature of the outer surface of the vests. Measurements were taken at the beginning and at 10 minute intervals of wearing a vest. The temperature was measured with a Vario CAM INSPECT 270/25 thermovision camera with a resolution of < 0.1 K, spectral sensitivity of 8 μm – 13 μm, and temperature measurement range of 40 °C – 1200 °C [15].

The fabrics under investigation differed among themselves with regard to basic physico-mechanical properties, including rigidity and formability, which cause that vests made of the fabrics under examination, despite having an identical size and cut, fitted the wearer's silhouette differently. In order to eliminate the influence of the fact that the vests fitted differently to the wearer's figure on the results of the experiment, the temperature was recorded at the back of the vest, slightly below the neck, on the left scapula (***Figure 1***). At this point all the vests fitted identically to the wearer's body.

Figure 1.a presents an exemplary thermogram taken at the initial phase of wearing a vest made of the fabric evaluated. The place at which the temperature of the outer vest surface was recorded is marked on the Figure. The temperature of the outer surface of the vest was calculated as an integral mean of temperatures on the area of the vest surface analysed.

Figure 1.b shows a thermogram for the same vest after 10 minutes of wearing it. Comparison of both thermograms shows that the vest's surface temperature increased significantly (by about 4 °C) after 10 minutes of wearing it, which was caused by the flow of heat from the body to the outer side of the vest. Hence, the temperature of the outer vest surface was taken as a measure of the thermal insulation of the fabric the vest was made of.

Results and discussion

Table 1 presents the set of fabrics of which vests were made and results of their laboratory studies.

For each type of material investigated, Relative Thermal Comfort Index values were calculated based on the laboratory test results according to formulas (5) and (6). The RTCI values calculated are presented in ***Table 2***.

On the basis of the values of $RTCI_{WI}$, the highest scored textile was polar – samples with PR and PS symbols, and on the basis of $RTCI_{WO}$, which also takes into consideration air permeability, the highest scores were obtained for textiles with symbols OG and OP (***Figure 2***). These types of fabrics are multilayered and are used as insulating materials in winter clothing. Moreover they have a significantly lesser air permeability than polar, thus they protect against wind better. For this reason, their high $RTCI_{WO}$ scores seem to be justified.

Figures 3 and ***4*** show the values of $RTCI_{WI}$ and $RTCI_{WO}$ divided into elements relating to particular comfort-related parameters taken into consideration in the calculations. Both diagrams confirm the key importance of thermal resistance (sR element) for the assessment of textile materials with regard to protection against cold, as well as the important role of air permeability (sAP) for the evaluation of textile materials designed for everyday clothing for windy conditions (***Figure 4***).

Table 1. *Set of fabrics used in the utility tests for vest production and test results.*

Symbol	Kind of fabric	Thermal resistance, $W^{-1} Km^2$	Thermal absorptivity, $Wm^{-2} s^{1/2} K^{-1}$	Water-vapour resistance, m^2PaW^{-1}	Air permeability, mms^{-1}
WG	Wool & polyester woven fabric	0.010	256.37	2.56	52.1
BR	Cotton woven fabric	0.012	227.13	3.67	86.0
WF	Wool georgette	0.014	174.87	3.50	797.2
WJZ	Wool flannel	0.014	181.90	3.22	330.7
WZ	Wool coat fabric	0.019	155.40	2.89	234.0
OG	3-layer material: PES woven fabric + nonwoven + woven lining	0.046	73.87	9.05	231.6
OP	2-layer material: woven fabric + nonwoven	0.091	41.86	12.69	84.4
PR	Polar 1	0.108	56.08	9.10	985.0
PS	Polar 2	0.091	64.68	8.33	884.0

Table 2. Calculated values of RTCI

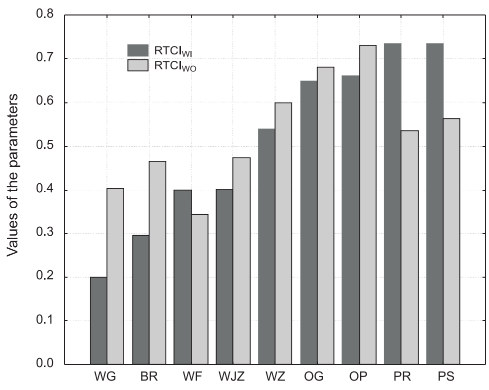
Symbol	$RTCI_{WI}$	$RTCI_{WO}$
WG	0.200	0.404
BR	0.296	0.465
WF	0.399	0.342
WJZ	0.401	0.473
WZ	0.538	0.600
OG	0.650	0.681
OP	0.661	0.730
PR	0.736	0.535
PS	0.736	0.563

Changes in the air temperature under clothing and differences between the air temperature under clothing and the ambient air temperature varied with the fabrics the vests were made of. The quickest drop in air temperature between the clothes and the body was recorded in the case of the vest made of WF fabric – thin wool georgette. For the WF fabric the quickest drop in air temperature recorded nearby the skin and the quickest drop in the difference between the air temperature under the clothing and that of the surroundings were observed as early as 10 minutes after the beginning of the experiment. In turn, in the case of WG fabric the minimum value was reached 25 minutes from the beginning of the test. PR polar had the smallest recorded difference between the ambient air temperature and the air temperature under the clothing after 40 minutes from the onset of the measurement. Differences in the course of changes in the ambient air temperature and the air temperature under the clothing are caused by the different thermal insulation properties of the textiles the vests were made of [16].

Taking into consideration the different courses of changes in the air temperature between the clothes and the body and the different course of changes in air temperature differences in both areas - internal (under the clothing) and external (room), the mean of differences between the ambient air temperature and the air temperature under the clothing calculated as an arithmetic mean of differences in the air temperature recorded every 5 minutes during wearing the vest was taken as a measure of the predicted sensation of thermal comfort in a cold microclimate (***Table 3***). The relation between the mean temperature differences and values of $RTCI_{WI}$ is presented in ***Figure 5***. The results show that the higher the value of $RTCI_{WI}$, the higher the mean difference between the ambient air temperature and the temperature of air between the clothing and the body of the user.

The thermovision camera test results showed that for all types of vests the highest increase in vest surface temperature appeared 10 minutes after the beginning of wearing the vest. After this period, the vest surface temperature stabilised at a level similar or slightly below that recorded after the first 10 minutes.

The temperature of the outer vest surface recorded 10 minutes after the beginning of the experiment varied with the fabric the vests were made of. Vest surface temperatures recorded with a thermovision camera after 10 minutes from the beginning of wearing the vests are presented in ***Table 4***. The results are taken as a measure of the thermal insulation of the fabrics the vests were made of on the grounds previously stated.



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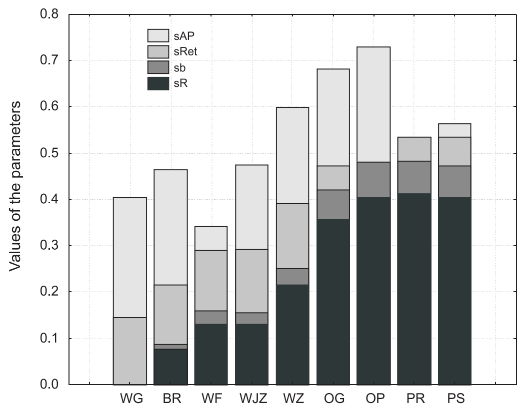

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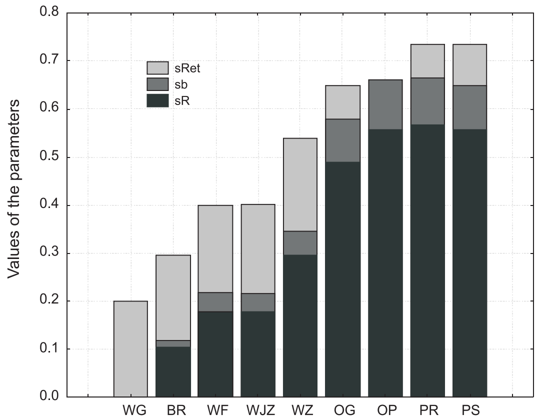
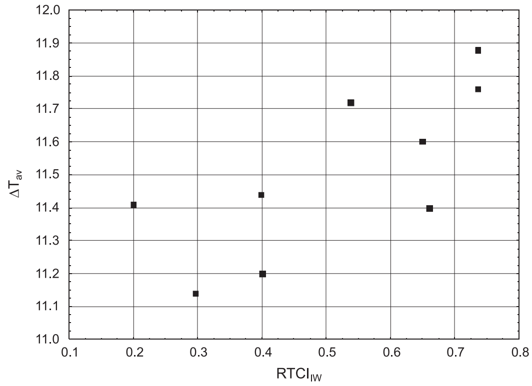


Figure 4.

Figure 2. *Values of $RTCI_{WI}$ and $RTCI_{WO}$ for the textile materials under examination.*

Figure 3. *Values of $RTCI_{WI}$ for the group of fabrics used for vest production: sR – an element associated with thermal resistance, sb – an element associated with thermal absorptivity, sRet – an element associated with water-vapour resistance.*

Figure 4. *Values of $RTCI_{WO}$ for the group of fabrics used for vest production: sR – an element associated with thermal resistance, sb – an element associated with thermal absorptivity, sRet – an element associated with water-vapour resistance, sAP –an element associated with air permeability.*



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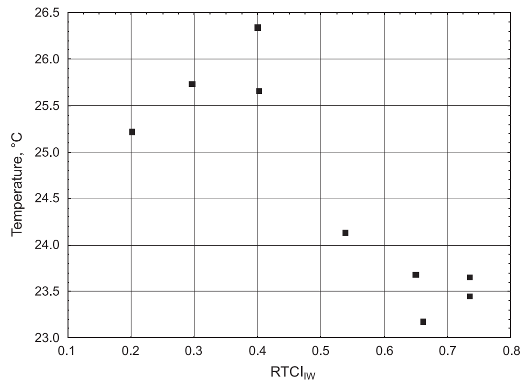

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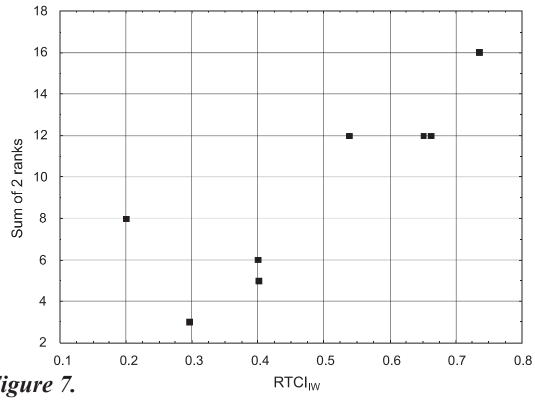

Figure 7.

Figure 5. *Correlation between $RTCI_{WI}$ values and mean differences in the ambient air temperature and the temperature of air under the clothing.*

Figure 6. *Relationship between the values of $RTCI_{WI}$ and temperature of the outer vest surface after a 10 minute use.*

Figure 7. *Comparison of fabric evaluation with $RTCI_{WI}$ and a sum of ranks admitted during the utility investigation.*

Figure 6 presents a correlation between temperatures of the outer vest surface (given in ***Table 4***) and values of $RTCI_{WI}$. The higher the values of RTCI, the lower the temperature of the outer vest surface, meaning that the fabric of which the vest is made restrains heat loss by the body to the surroundings in a better way than fabric which recorded a higher surface temperature after a 10 minute use.

Analysis of the conformity of $RTCI_{WI}$ and methods of thermal comfort evaluation applied in the utility investigation

On the basis of the results of evaluation by means of the particular methods applied in the utility investigation, each vest was ranked. The highest rank was assigned to the vest which was scored as having the highest quality in a given method.

A list of the ranks assigned on the basis of the results of the three methods of evaluation applied is shown in ***Table 5***. Also the table presents a sum of the rank assigned on the basis of two methods: measurement of air temperature in a skin - clothes area and thermograms from a thermovision camera (excluding $RTCI_{WI}$).

The results of the evaluation suggest that there is an agreement between the values of $RTCI_{WI}$ and the sum of ranks assigned during the utility tests (***Figure 7***).

A conformity analysis of the methods applied to evaluate a group of 9 fabrics with regard to their capability of ensuring thermal comfort was conducted with a Kendall's conformity coefficient [17].

Because of the fact that connections were made, i.e. identical ranks, the coefficient was calculated according to the following formula:

$$W' = \frac{12\sum_{i=1}^{n}\xi_i^2 - 3k^2n(n+1)^2}{k^2n(n^2-1) - kT} \qquad (7)$$

where:

ξ_i – sum of ranks assigned to the fabric investigated,

n – number of investigated fabrics,

k – number of evaluation methods,

$$T = \sum_{j=1}^{k} T_j \qquad (8)$$

$$T_j = \sum_{1}^{u} t(t^2-1) \qquad (9)$$

u – number of connections for evaluation method j,

t – number of identical evaluations in the following connection.

Kendall's conformity coefficient is in the range from 0 to 1. Low conformity is represented by low values of coefficient W', and high conformity - by high values of coefficient W' almost reaching 1 [17].

The value of Kendall's conformity coefficient W' calculated on the basis of the investigation results was 0.7753, mean-

Table 3. *Arithmetic means of differences in the ambient air temperature and the temperature of air under the clothing, recorded at 5 minute intervals of wearing the vests*

Material	WG	DB	WF	WJZ	WZ	PG	PP	PR	PS
ΔT	11.41	11.14	11.44	11.20	11.72	11.60	11.40	11.76	11.88

Table 4. *Temperature of the outer vest surface after 10 minutes of vest use*

Integral means of vest surface temperatures at the measuring area in °C								
PS	PP	PR	DB	PG	WZ	WG	WJZ	WF
23.66	23.18	23.45	25.74	23.68	24.14	25.22	25.66	26.34

Table 5. Set of ranks assigned on the basis of the three methods used to evaluate the thermal protection of vests.

Textile	Ranks according to			Sum of 2 ranks (excluding $RCTI_{WI}$)
	$RCTI_{WI}$	Temperature near the skin	Temperature of outer vest surface	
PR	8.5	8	8	16
PS	8.5	9	7	16
OG	7	3	9	12
OP	6	6	6	12
WZ	5	7	5	12
WJZ	4	2	3	5
WF	3	5	1	6
WG	2	1	2	3
DB	1	4	4	8

ing that the conformity of evaluation by means of all the methods used for the assessment of a fabric's capability to ensure thermal comfort was good.

In order to verify the significance of Kendall's conformity coefficient for the whole population, a null hypothesis was made that there is a lack of agreement between the evaluations. The hypothesis is proved if:

$$k \cdot (n-1) \cdot W' \leq \chi^2_{\alpha;n-1} \quad (10)$$

or is rejected when:

$$k \cdot (n-1) \cdot W' > \chi^2_{\alpha;n-1} \quad (11)$$

In this case, the extreme value χ^2 for a test probability $P = 0.95$ and $n - 1 = 8$ degrees of freedom is 15.507 [17]. Therefore, the value of the expression: $k (n-1) \cdot W' = 18.607$ calculated on the basis of experimental data is higher than the extreme value χ^2, hence the null hypothesis that there is no conformity between the methods applied for the evaluation of fabrics has to be rejected.

Summary

To sum up, we can state that the results of the utility investigation confirmed that the method of the adopted Relative Thermal Comfort Index $RTCI_{WI}$ is correct.

The statistical analysis of results obtained during the experiment showed that the evaluation of a fabric's capability of ensuring thermal comfort in a cold microclimate by means of the $RTCI_{WI}$ index elaborated is compatible with assessment based on the estimation and arrangement of the thermal sensation on the basis of measurement results of the following:

- the temperature of air within the under-clothing sphere,
- the temperature of the outer surface of vests made of the fabrics investigated.

Experimental verification was carried out for an $RTCI_{WI}$ elaborated for fabrics designed for winter clothing used in a cold microclimate in windless conditions, i.e. indoors. Comparison of the values of $RTCI_{WI}$ and $RTCI_{WO}$, which also includes air permeability, allows to presume that $RTCI_{WO}$ permits the evaluation of a fabric's capability of ensuring thermal comfort outdoors in a cold microclimate. This is confirmed by the fact that, on the basis of $RTCI_{WO}$, both types of polar fabrics, i.e. PR and PS, which are characterized by a high level of air permeability, meaning that they do not protect against wind, received lower ranks than multilayer material PP, which has a similar level of thermal resistance but allows much less air permeability than PR or PS fabrics.

The elaborated indexes proposed for fabric evaluation do not provide unambiguous information as to whether a particular type of fabric would definitely ensure thermal comfort in a cold microclimate. In order to receive an answer to this question, it is necessary to precisely specify the conditions of using the fabric, not only concerning microclimate parameters but also personal features of the user and the type and intensity of physical activity. However, it is not possible to define the above-mentioned conditions accurately for the mass production of everyday clothing.

The indices proposed allow to perform a comparative analysis of textiles and order them with respect to their usefulness and application in thermal insulation clothing:

- used indoors in a cold microclimate – $RTCI_{WI}$ based,
- used outdoors in a cold and sometimes windy microclimate – $RTCI_{WO}$ based.

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