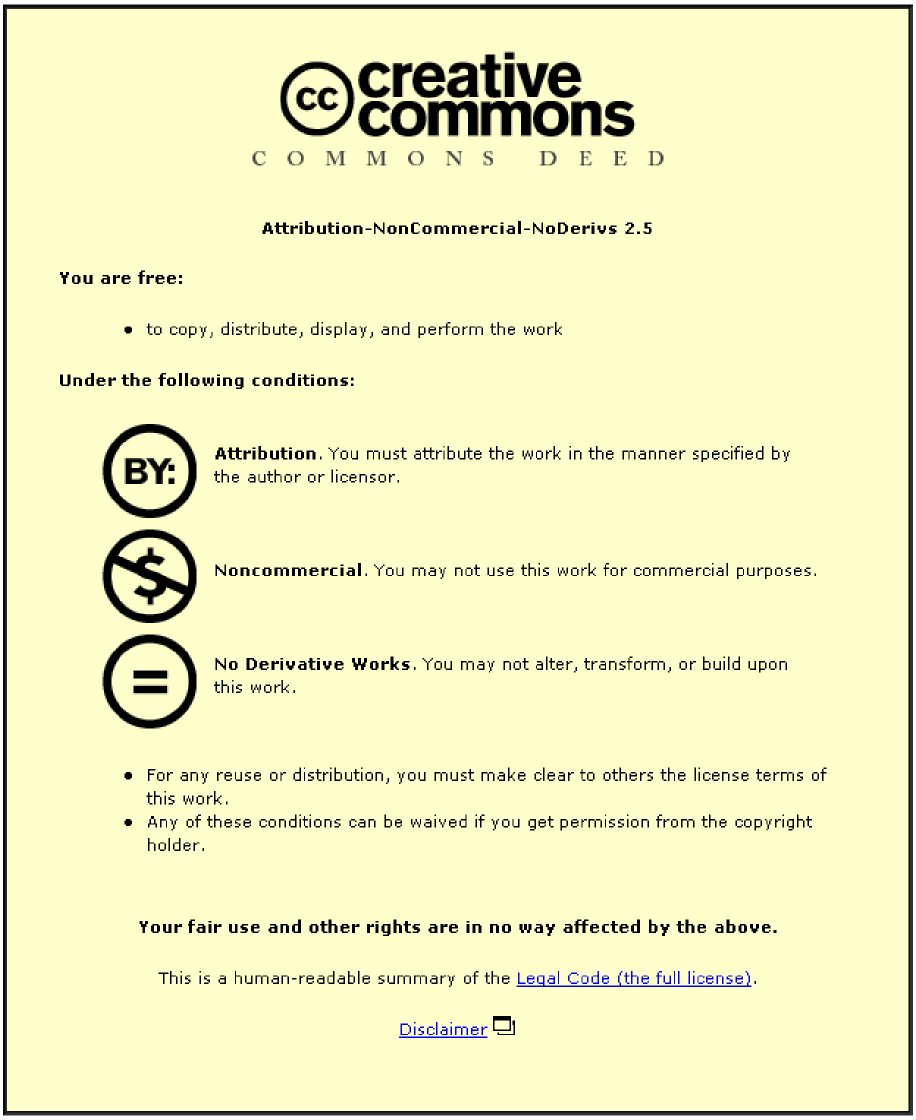

Impact of raw material, yarn and fabric parameters, and finishing on water vapor resistance

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Abstract

The objective of this study is to explore a number of technical-technological parameters affecting the water vapor resistance of knitted fabric and clothing, as well as to develop a predictive model that describes the prominent affecting parameters. Thirty-four knitted fabrics were carefully produced and measured on a sweating guarded hotplate and thermal manikin. The study focused on the influence of the following parameters on the transfer of water vapor: type of textile fibers, yarn and knitted fabric parameters, finishing of fabrics (recipes include bleaching, dyeing and softening) and body activity. The statistical analysis, performed to examine the relationship between observed parameters, indicated medium correlation between water vapor resistance and moisture regain (R=0.7). Furthermore, the relationship between water vapor resistance and the following knitted fabric parameters is especially prominent: mass per unit area, knitted fabric thickness and tightness factor (R=0.9). When the fabrics are made into ensembles, however, effects of material differences become small and the differences between garments more difficult to discriminate; even more so when movement is present.

Keywords: water vapor resistance, sweating guarded hotplate, thermal manikin, knitted fabric

Introduction

Man is, concerning anatomy and organism physiology, predestined for life in moderate and hot climates. Under these conditions the body can maintain thermal equilibrium without additional interventions. But as soon as the ambient temperature drops well under 20ºC, the organism cannot maintain the body temperature for a longer period and in this case clothing takes the role of an additional thermoregulator[1]. The establishment of thermal equilibrium, in which man feels comfortable and needs minimal physiological adjustments, depends on a series of complex interactions among physiological, psychological, neurophysiological and physical factors which should be fulfilled to a certain extent.

The development of science and technology, as well as the improvement of social standards, shifted the requirements of textile customers who prefer garments that provide a satisfactory level of comfort to a higher level[2]. Nowadays many people are, due to the nature of their work, exposed to different atmospheric influences - from heat to cold and frequent weathering factors. Therefore, being able to wear a garment with appropriate protective properties as well as a satisfactory level of comfort is very important.

Clothing plays a very important role in maintaining the equilibrium of heat and moisture transfer and it is one of the essential goals for researchers to define mechanisms of their transfer and the parameters of relevance. According to Niwa's[3] predictions of priorities for textile experts in the future, it is important to take into consideration human sensibility and start a "new textile engineering in which man plays an important role" during textile manufacturing.

Conclusions of previous investigations on textile properties carried out by physiologists[4] are that raw material composition does not significantly affect comfort parameters and that subjects do not recognize the difference between garments made of different raw material compositions or fabrics of different structure. In contrast, investigations done by textile experts indicate that there are relevant differences in resistance to heat and water vapor transfer[5] caused by such material differences.

In an earlier investigation, Oglakcioglu[6] et al. compared knitted fabrics produced from cotton and angora fibres in different ratios. The analysis indicated that 25% of angora fiber caused significant difference in relative water vapor permeability values. Cil et al.[7] investigated comfort-related properties of cotton and acrylic single jersey fabrics taking into account three variables: fiber composition, yarn count and fabric tightness. As far as the yarn count is concerned, the samples from fine yarn gave higher moisture vapor transfer values. Also, the slack fabrics features higher water transfer rates, as did the presence of acrylic fiber in the yarn composition. Sampath and Senthilkumar[8] reported the improvement of water vapour transmission trough single jersey structures after moisture management finish for 15-20%. In another investigation, Sampath et al.[9] reported that untreated fabric made of spun polyester has higher water vapor resistance than the one made of cotton (3.26 m^2 Pa W^{-1} vs. 2.84 m^2 Pa W^{-1}). After moisture management treatment, the decrease in water vapour resistance for polyester fabric is significant (R_{et} is 2.49 m^2 Pa W^{-1}), but not for cotton fabric (R_{et} is 2.73 m^2 Pa W^{-1}). Zhou et al.[10] showed that, among the woollen knitted fabric plated with different yarns, the one plated with cotton yarn is the best at spreading liquid in the bottom surface and shows good moisture management properties. Chen et al.[11] demonstrated that warp knitted fabrics with branching structure absorbed water faster than the corresponding interchanged plain knitted fabrics. The investigation of the relationship between different knitted structure and some thermo-physiological comfort parameters was also conducted by Yanilmaz and Kalaoglu[12]. They concluded that the water evaporation rate decreases with an increase of thickness due to increase of compactness and decrease of air space.

Understanding the way in which the multitude of yarn, fabric and clothing design parameters lead to optimally functioning clothing is important in order to be able to improve the currently available clothing. A vast number of studies looked at specific clothing properties and their relation to its performance. However in most of these studies, where e.g. man made fibers are compared to natural fibres[13], or materials with different properties like the yarn structure[14], or the fabric parameters[15-17], the researchers did not manage to produce yarns/fabrics/clothing that was identical, differing only in one single factor. Hence outcomes could never be fully attributed to a single parameter. In most cases, off the shelve clothing is used, or prototypes are made from different fabrics with different weights, porosities etc. To the authors knowledge no studies have attempted to produce clothing where the whole process from raw material selection, yarn production via fabric production to the clothing production was controlled and thus where clothing was produced where a maximal number of characteristics can be independently analyzed. Therefore the present study aims to analyze the vapor resistance of knitted fabrics and garments made of yarns in which the production was maximally controlled in terms of selection of raw material, yarn properties, parameters of knitted fabric and finishing.

Our preliminary investigations of the parameters of the knitted fabric were performed on a smaller number of carefully designed knitted fabric samples. Concerning the fiber type, it was shown that using polyester with profiled cross-section reduces heat and water vapor transfer, while it is the greatest in the samples of the knitted fabric made of viscose yarns[18]. Knitted fabrics, in which the elastane yarn in parallel with the main yarn was fed into each second course during knitting, have a considerably higher resistance to heat and water vapor transfer than the same structures without the elastane component[19]. Among the yarn parameters affecting mass transfer considerably, fineness and thickness are to be pointed out, while fabric modules (linear, surface and volume), tightness factor, mass per unit area and porosity belong to the most important knitted fabric parameters[20, 21].

For the purposes of the investigation presented in this paper, it was necessary to design garment samples made of the controlled fabrics discussed above and manufacture them under carefully controlled conditions.

Experimental

The present paper explores a number of technical-technological parameters affecting the water vapor resistance of knitted fabric and clothing worn next to the skin, and thereby the thermophysiological comfort of clothing. The parameters studied are: type of textile fibers, various yarn and knitted fabric parameters, influence of fabric finishing (comparison of raw and finished fabrics) and parameters of body activity. Figure 1 shows the production stages, i.e. how the fabrics and garments were produced with the goal of allowing parametric testing of the different properties. Each stage is explained in detail in the following sections.

Yarn raw materials

For the purposes of this study the following raw materials with different absorption properties were selected: 100% cotton, 50/50% cotton/modal, 100% viscose, 100% lyocell (Tencel®) and 100% polyester standard. From the named raw materials combed single yarns were produced. The yarns were made in four counts: 20, 17, 14 and 12 tex for each raw material type. The average twist coefficient of produced yarns (α_{tex}) is 3417.

Knitting

The mentioned yarns were used to make weft-knitted plain single jersey fabrics. The fabrics were knitted on the circular knitting machine Relanit E, gauge E28 with 48 knitting systems made by Mayer & CIE. When designing the knitted fabric, the same course/cm (20 ± 0.5 per 1 cm) was defined for all knitted fabrics. Thus, the machine was adjusted in such a way that the manufacture of the knitted fabric with the mentioned density was possible.

Finishing

After relaxation (for a duration of 120 hours), a piece of each knitted fabric was cut off and prepared for testing as raw (unfinished) knitted fabric. The remaining samples were finished.

The finishing was performed in industrial conditions, according to the standard recipes that are used for the finishing of commercial knitwear in two knitting factories. Due to the fact that different raw materials are used, two recipes were defined. The first recipe was used for finishing of cotton, cotton/modal, viscose and lyocell fabrics. Those fabrics were bleached at 98ºC for 60 minutes, dyed with dyestuff produced by Ciba (rinse for 10 min at 50ºC, neutralised for 10 min at 70ºC, soaped twice for 10 min at 95ºC, rinsed for 10 min at 70ºC and rinsed for 10 min cold) and softened to ensure better sewability of knitted fabric. The second finishing recipe was used for finishing of polyester fabric only. This fabric was bleached at 80ºC for 30 minutes, dyed on 130ºC for 35 minutes and finally softened. Table 1 shows the raw material composition, the yarn count and the label of each fabric.

Garment production

Garment ensembles (T-shirt and shorts) were produced from the finished knitted fabrics made of 100% cotton, 50/50% cotton/modal, 100% viscose, 100% Tencel® and 100% polyester standard, all with the same count of 20 tex (i.e. from knitted fabrics designated as C20f, CM20f, V20f, T20f and PS20f). The construction of garments was made according to the body measures of a Newton manikin[22].

Testing

Within the scope of the experimental part, the following yarn properties were tested: count, twist level, yarn diameter, unevenness parameters, tensile properties, hairiness and coefficient of yarn friction.

The yarn count (Tt) was determined by the use of skein method, as described in ISO 2060[23]. A torsiometer twist tester, produced by Mesdan lab, was used to measure the number of twists (Tm). The measurement was carried out using the untwist/retwist method, according to ISO 17202[24]. The yarn diameter (d) was measured from the yarn images obtained using an Olympus BX51 microscope equipped with camera**.** The parameters that characterize the yarn unevenness i.e. number of thin places (Ntn), number of thick places (Ntk), number of neps (Ntn) and coefficient of mass variation (CVm) were measured using the Keisokki evenness tester, model KET-80. During the measurement, the following sensibility levels were used: -50% for thin places, +50% for thick places and +200% for neps. Tensile properties of produced yarns, i.e. breaking force (F) and breaking elongation (ε_B) were measured on a dynamometer Statimat M produced by Textechno, as described in ISO 2062[25]. The number of fibers in different lengths (2, 4, 6 and 8 mm) was determined using the equipment produced by Zweigle company. The speed of yarn delivery was set to 50 m min^{-1}. Finally, the coefficient of yarn friction (μ) was determined using the F-meter G 534 produced by Zweigle, according to the ASTM D 3108-07[26].

The following knitted fabric parameters were determined for all fabrics: stitch density (S), stitch length (l), thickness (t), mass per unit area (m), Munden constants (k_c, k_w, k_s, R), tightness factor (TF) and porosity (ε). The stitch density was determined by multiplying the number of courses and wales per unit area, taking into account EN 14971[27]. The stitch length was determined as proposed in the EN 14970[28]. Knitted fabric thickness was experimentally determined using a thickness meter, with a pressure of 10 cN cm^{-2}. The mass per unit area was determined by weighing a knitted fabric sample with an area of 1 dm^2 on an analytical scale. For the calculation of Munden constants (k_c, k_w, k_s and R), tightness factor (TF) and porosity (ε), the following equations were used[29, 30]:

$$k_c = c \ x \ l \tag{1}$$

$$k_w = w \ x \ l \tag{2}$$

$$k_s = S \times l^2 \qquad (3)$$

$$R = k_c \times k_w^{-1} \qquad (4)$$

$$TF = Tt^{1/2} \times l^{-1} \qquad (5)$$

$$\varepsilon = 1 - \rho_a \times \rho_b^{-1} \qquad (6)$$

where c is the number of courses per unit length, l is the knitted stitch length, w is the number of wales per unit length, S is the stitch density, Tt is yarn count, ρ_a is the fabric density and ρ_b is the fiber density.

The air permeability of the samples was measured using the air permeability tester FX 3300 produced by Textest AG. The measurements were performed according to EN ISO 9237[31], with constant pressure drop of 100 Pa.

To test the water vapor resistance of knitted fabrics, a sweating guarded hotplate (Measurement Technology Northwest, Seattle, USA), model SGHP-8.2 was used. Tests were performed in accordance with ISO 11092[32] - room condition 35°C, 40% relative humidity and air speed 1 m s^{-1}. The temperature of test plate (i.e. “skin”) was 35°C.

Measurements of the water vapor resistance of garment ensembles were performed on thermal manikin Newton produced by Measurement Technology Northwest, Seattle, USA[33]. The manikin was equipped with a walking mechanism. For the purposes of testing the following movement speed was defined: 0 steps/min (static) and 18 double steps/min. Tests on the manikin were done under the same isothermic conditions as testing done using the sweating guarded hotplate; i.e. 35°C and 40% R.H.

The statistical analysis of obtained results was performed using the Statistica Release package, version 8.0. The following statistical methods were used: linear regression, multiple regression and Spearman's rank correlation test.

Results

The basic material test results for yarns and fabrics are presented in Table 2 and 3. The relation of the water vapor resistance of the fabrics to the basic yarn parameters, and the correlations amongst yarn parameters is given in Table 4.

The relation of the water vapor resistance to the knitted fabric parameters, and their correlations amongst each other are given in Table 6. The summary of both regression statistics is given in the Tables 5 and 7.

Figure 2 shows the test results of the water vapor resistance measured on the sweating guarded hotplate, while Figure 3 additionally shows the test results of garment ensembles on the manikin in state of rest and motion.

Experimental uncertainty estimates, used to assess the confidence in the presented results are shown in the Table 8.

The results of knitted fabric air permeability are given on the Figure 4.

Discussion

Impact of raw material composition

The measured water vapor resistances of knitted fabrics are within the range 2.9-4.4 m^2 Pa W^{-1} for raw fabrics, and 2.3-4.0 m^2 Pa W^{-1} for finished fabrics (Figure 2). It is noticeable how the raw samples made of lyocell and viscose fibers (that have the highest moisture regain among the tested samples) on average have a considerably lower resistance to water vapor transfer than the samples made of the other tested raw materials. For example, the difference in the water vapor resistance of the unfinished samples made of cotton and viscose/lyocell fibers with a count of 17 tex (samples C17r and V17r), amounts to 28% (Fig. 2). Furthermore, the test of Spearman's ranks showed that the correlation between moisture regain and water vapor resistance of knitted fabrics is medium (the correlation coefficient obtained is R = 0.74). These results show that both the raw material and the fiber type from which the knitted fabric were made, influence the the water vapor resistance to a certain extent.

Impact of yarn parameters

The differences in water vapor resistances of fabrics of the same raw material, but different counts, ranges from 8% (for knitted fabrics made of the blend of cotton/modal fibers; samples CM20r versus CM12r) to 27% (for the knitted fabrics made of cotton fibers; samples C20r versus C12r). The water vapor resistance decreases for fabrics made of finer yarns (for all observed raw materials), which is in agreement with findings presented by Cil et al.[11]. It is to be assumed that the important cause of the mentioned differences lies in changes in the yarn count and twist level which alters the stitch fullness with the yarn. Among the investigated yarns, the higher the yarn count is, the lower the number of twists is. If from investigated 17 yarns only those with the exact same count (for example, yarns V17r, T17r and CM17r, that have the same count of 16.8 tex and different number of twists: 806, 851 and 870 m^{-1}) are observed, the regularity of the increase of water vapor resistance with the increase of number of twists can be reported. The measured values of water vapor resistance for observed yarns in m^2 Pa W^{-1} are: 3.07 (sample V17r), 3.33 (sample T17r) and 4.19 (sample CM17r). In view of the regression analysis carried out, it is concluded that the relationship between the water vapor resistance of the knitted fabric and the yarn parameters (yarn count, twist level, coefficient of mass variation and coefficient of friction) is medium ($R = 0.7$). Water vapor resistance of the fabric correlates positively with yarn count and friction coefficient. It correlates negatively with number of twists and coefficient of mass variation. In the regression model, among all the variables, the variable of the yarn friction coefficient is statistically significant. The correlation between the mentioned variable and the water vapor resistance is positive and medium ($r = 0.78$; Table 4). The correlation between the water vapor resistance and yarn count and number of twists is also medium ($r = 0.59$ and $r = -0.59$ respectively, Table 4). In the multiple regression analysis, 50% of the variance of the water vapor resistance was explained by the mentioned yarn parameters (Table 5).

Impact of knitted fabric parameters

The analyzed weft-knitted single jersey fabrics are distinct in comparison to other textile materials because the proportion of holes in the knitted structure is significantly greater than in the case of other textile structure like weaves or non-wovens. As seen from the Table 3, all tighter structures have lower porosity which reduces the air permeability and directly affects the water vapor resistance. This observation is in accordance with data from Yanilmaz and Kalaoglu[12]. Table 7 shows that the relationship between the water vapor resistance and the fabric parameters (thickness, mass per unit area, stitch length, Munden constants, tightness factor and porosity) is very strong ($R = 0.9$) with several high correlation values (Table 6). Water vapor resistance correlates positively with thickness, mass per unit area, stitch length and tightness factor and negatively with Munden constants and porosity. The correlation between the dependent variable (water vapor resistance) and thickness, mass per unit area and tightness factor is very strong. Medium correlation exists between the dependent variable and loop length, Munden constant k_c and porosity. In a multiple regression analysis, the fabric parameters together were able to explain 91% of the variance in the water vapor resistance. The model of multiple linear regression for finished fabrics with the dependent variable of water vapor resistance (R_{et}) and independent variables of thickness (t), mass per unit area (m), stitch length (l), Munden constants (k_c, k_w, k_s and R), tightness factor (TF) and porosity (ε) is:

$$R_{et}/(m^2 Pa W^{-1}) = -7.4 + 7.87\, t/mm + 0.04\, m/(g\, m^{-2}) - 2.86\, l/mm + 2.36\, k_c + 4.48\, k_w - 0.86\, k_s + 0.85\, R - 4.77\, TF/(tex^{1/2}\, mm^{-1}) + 4.10\, \varepsilon \qquad (7)$$

As can be seen from the presented model, there is a significant correlation between the water vapor resistance and the knitted fabric parameters. The validation of the proposed model was additionally carried out on three cotton single jersey fabrics. The results of measured water vapor resistance for additionally measured fabrics differ up to 6% from the values obtained using the proposed model (fabric 1: $R_{et\ measured} = 2.90\ m^2\ Pa\ W^{-1}$, $R_{et\ calculated} = 3.08\ m^2\ Pa\ W^{-1}$; fabric 2: $R_{et\ measured} = 3.20\ m^2\ Pa\ W^{-1}$, $R_{et\ calculated} = 3.12\ m^2\ Pa\ W^{-1}$; fabric 3: $R_{et\ measured} = 4.02\ m^2\ Pa\ W^{-1}$, $R_{et\ calculated} = 4.15\ m^2\ Pa\ W^{-1}$).

The obtained results of experimental uncertainty indicate that the highest contribution to the uncertainty of water vapor measurements came from the resolution of sample cutting equipment (value of standard uncertainty is 0.3; Table 8). The standard uncertainties of the rest of the sources indicated are within the limits proposed on the basis of inter-laboratory research. The positive outcome of the analysis was accomplished due to the fact that the protocol of the measurement included a number of activities intended to reduce the uncertainty in measurement. In order to minimize the uncertainties, the measuring instruments and all sensors used had been calibrated by authorized personnel prior to the measurements and all measurements were carried out by experienced and trained staff[34]. A number of additional good measurement practices proposed by the Guide of uncertainty in measurement[35] were also taken before and during the measurement process. Based on these procedures, it is concluded that the obtained results of water vapor measurement, as well as the proposed model and concluding remarks, are reliable.

Impact of finishing

As can be seen in Figure 4, after the finishing process, the air permeability of all investigated fabrics decreased. The measured decrease of values is up to 20%. The decrease of air permeability in knitted fabrics is due to the relaxation of fabrics that affected the loop shape and, at the same time, the size of holes within the loop. Figure 2 shows that finishing (according to the described recipes that include bleaching, dyeing and softening) reduces the water vapor resistance of all fabric samples. In relation to resistances of unfinished knitted fabrics, the water vapor resistance of the finished versions is lowered between 1% (sample T12) to 40% (sample C14), with a mean of 13%. In comparison, changes in water vapor transmission trough single jersey structures reported by Sampath and Senthilkumar were around 15-20%[8]. The reason for the mentioned reduction of resistance after finishing may be found in changes in the knitted fabric structure caused by the chemical processes performed. Namely, as can be seen from the results presented in Table 3, after finishing there were significant changes in the stitch density and a considerable reduction of the fabric thickness caused the reduction of the water vapor resistance. It becomes evident how changes in the water vapor resistance between unfinished and finished samples are significantly greater in the samples made of natural fibers and blends with natural fibers (a change by as much as -40% for the sample C14) than in the samples made of natural polymers (a change by as much as -10% for the sample T17). The above observation leads to the conclusion that the described finishing process is more suitable for the samples made of natural fibers. Namely, a reduction in the water vapor resistance under warm environmental conditions, in which it is necessary to facilitate the transfer of as much sweat as possible from the skin to the environment, positively affects an individual's perception of comfort. In the investigation reported by Sampath et al.[9], the finishing treatment significantly affected the water vapor resistance of polyester, but not of cotton fabric. The results of this investigation showed the similar decrease of water vapor resistance for both cotton and polyester fabric, amounting to -15%.

Considering the water vapor resistance of unfinished and finished samples, the following model of linear regression can be defined:

$$R_{et\,finished}\,(\mathrm{m^2PaW^{-1}}) = 1.4602 + 0.4555\,R_{et\,unfinished}\,(\mathrm{m^2PaW^{-1}}) \qquad (8)$$

Fabric differences versus ensemble differences

Comparing the vapor resistance of the ensembles (Fig. 3) in static conditions to those of the fabrics, the results seem quite consistent. Apart from PS20f, which seems relatively higher as ensemble then as fabric, the other four fabrics have the same order of vapor resistance for fabric and ensemble. However in relative terms, differences in vapor resistance between different ensembles are much smaller than differences in vapor resistance between fabrics.

Impact of movement

The ranking observed in the static ensemble measurements on the manikin is quite similar to that in the dynamic (walking) tests. Differences in the raw material, which was used to make the knitwear ensemble, are still showing an effect on the vapor resistance. However, just like the differences within the static condition, the differences within the values concerning the knitted fabric raw material during walking are relatively small too, amounting to a maximum of 5% (samples T20f and PS20f). Although the movement speed was relatively slow (18 steps/min), the recorded differences in the resistance of the knitted fabric in the state of rest and motion are significant, amounting to about 18%.

In general, it seems that when measured as ensembles, so with the internal and external air layers included, any effects of raw material become minimal.

Conclusion

Quality characterization of the properties of thermophysiological comfort of textile products requires a systematic approach including measurements and calculations of a series of parameters along fiber – yarn – knitted fabric – finishing – garment. In the present study the whole process of garment production was controlled starting at the fiber level, in order to ensure that like for like comparisons could be made. In order to make particular conclusions with greater certainty, effects of parameters should be considered in groups, using samples of carefully designed properties.

The performed tests indicate that certain yarn and knitted fabric properties affect the knitted fabric water vapor resistance to a greater extent. The following yarn parameters are especially prominent: count, twist level and friction, while the following knitted fabric parameters are the most important: mass per unit area, knitted fabric thickness and tightness factor. It turned out that finishing affects the change of the water vapor resistance of the knitted fabric to a certain extent. The applied finishing treatment of the knitted fabric according to a commercial recipe reduces the water vapor resistance of the knitted fabric, and the structure of the knitted fabric itself becomes more stable. When the fabrics are made into ensembles, however, effects of material differences become small and the differences between garments more difficult to discriminate; even more so when movement is present.

This is due to the strong contribution of the enclosed and surface air layers to the total values, which will be very similar over all garments given the identical design.

Optimal thermophysiological comfort of the knitted structure can be achieved if all parameters of the technological manufacturing and finishing processes have been chosen meticulously in accordance with the requirements determined by the application of the product.

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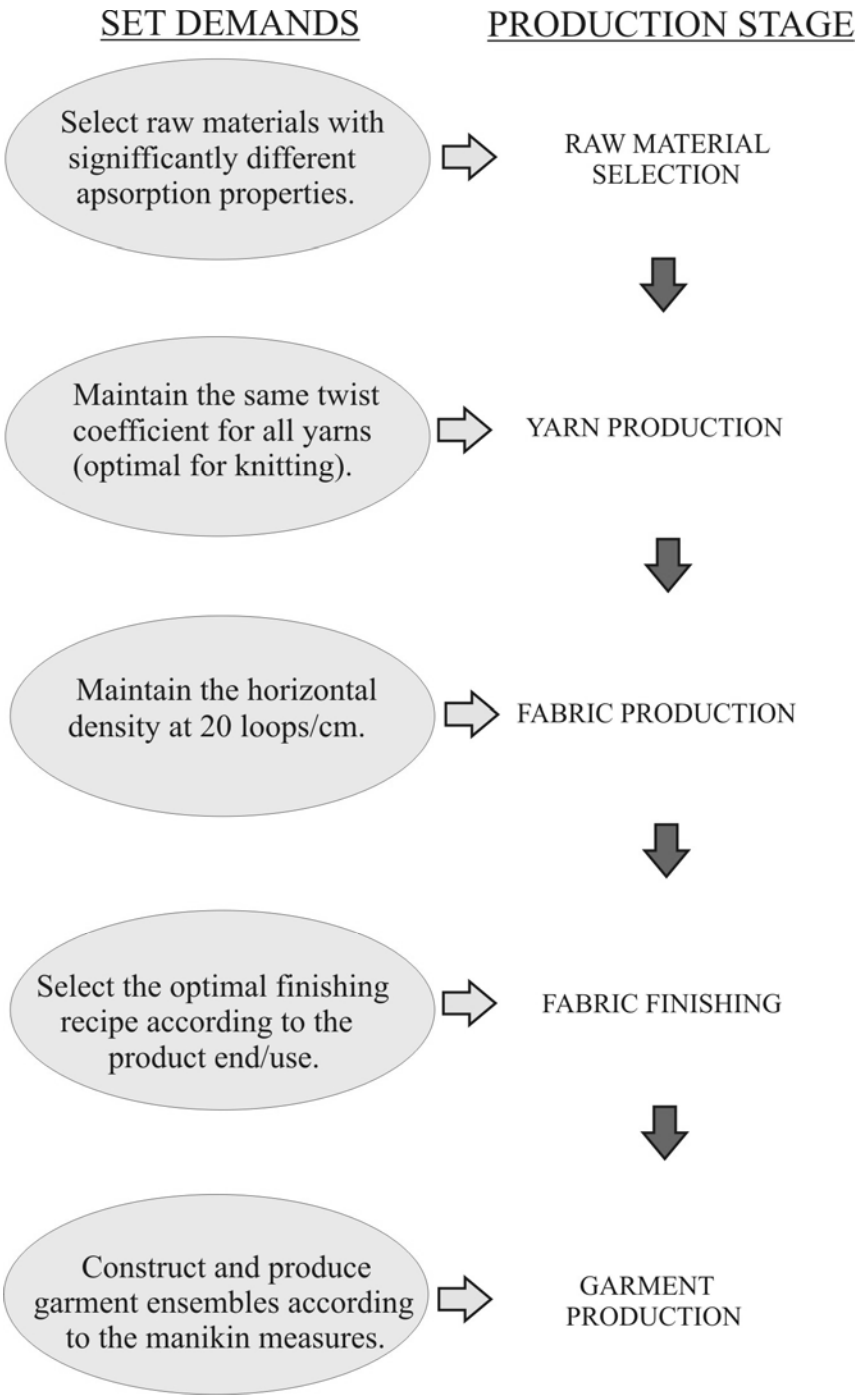

Figure 1. Production stages of textile samples to be examined

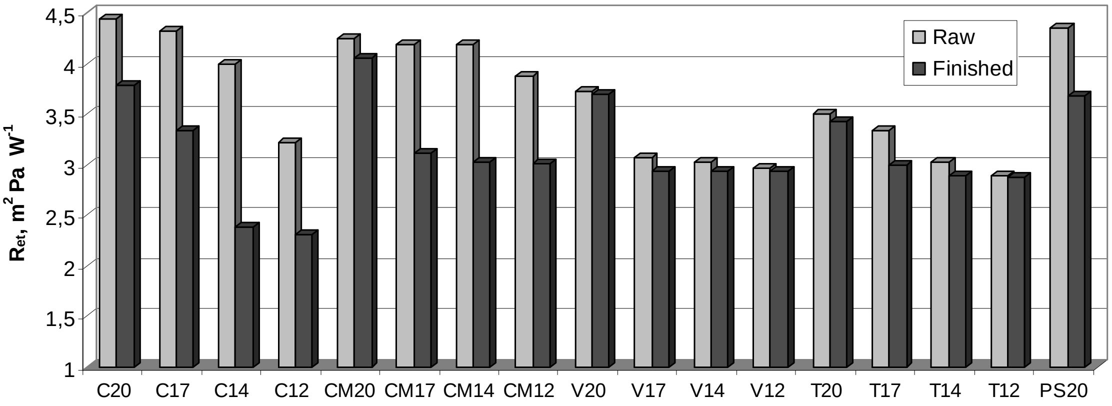

Figure 2. Knitted fabric water vapor resistance as measured on the skin model

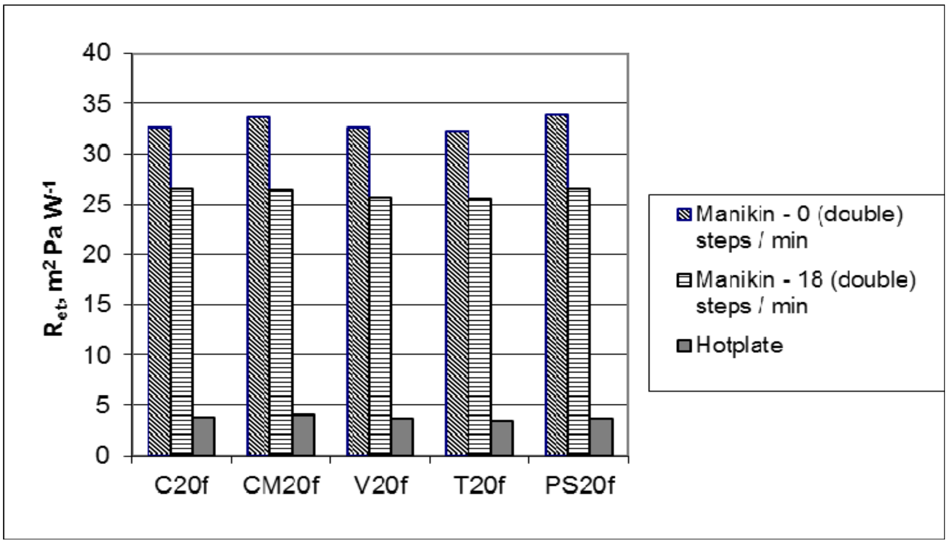

Figure 3. Knitted fabric and garment water vapor resistance as measured on the manikin (static and dynamic) and the sweating hotplate

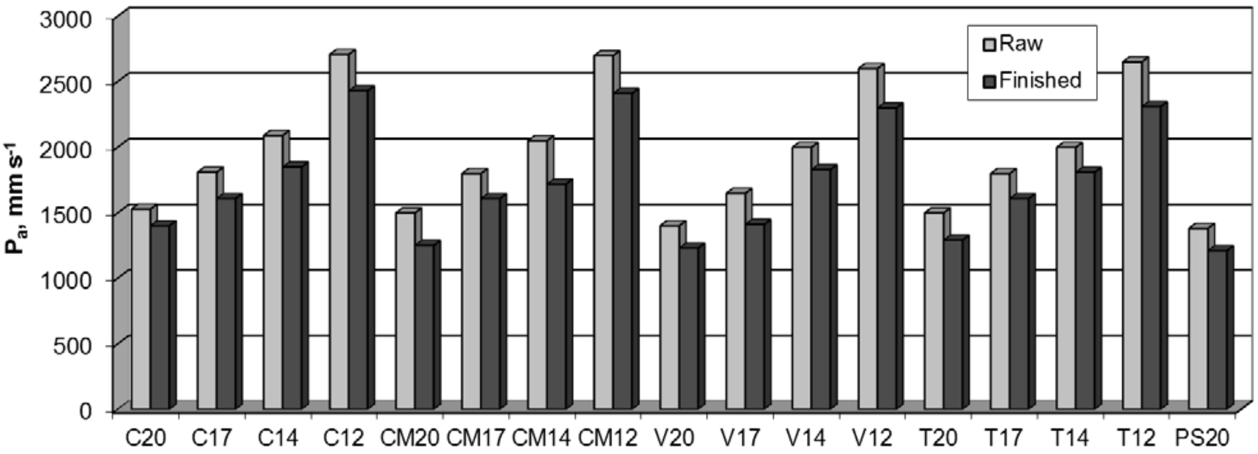

Figure 4. Knitted fabric air permeability

Table 1. Overview of knitted fabric samples and their properties

Nr.	Raw material	Yarn count, tex	Raw or Finished	Designation
1	100% cotton	20	Raw	C20r
2	100% cotton	17	Raw	C17r
3	100% cotton	14	Raw	C14r
4	100% cotton	12	Raw	C12r
5	50/50% cotton/modal	20	Raw	CM20r
6	50/50% cotton/modal	17	Raw	CM17r
7	50/50% cotton/modal	14	Raw	CM14r
8	50/50% cotton/modal	12	Raw	CM12r
9	100% viscose	20	Raw	V20r
10	100% viscose	17	Raw	V17r
11	100% viscose	14	Raw	V14r
12	100% viscose	12	Raw	V12r
13	100% lyocell (Tencel®)	20	Raw	T20r
14	100% lyocell (Tencel®)	17	Raw	T17r
15	100% lyocell (Tencel®)	14	Raw	T14r
16	100% lyocell (Tencel®)	12	Raw	T12r
17	100% polyester	20	Raw	PS20r
18	100% cotton	20	Finished	C20f
19	100% cotton	17	Finished	C17f
20	100% cotton	14	Finished	C14f
21	100% cotton	12	Finished	C12f
22	50/50% cotton/modal	20	Finished	CM20f
23	50/50% cotton/modal	17	Finished	CM17f
24	50/50% cotton/modal	14	Finished	CM14f
25	50/50% cotton/modal	12	Finished	CM12f
26	100% viscose	20	Finished	V20f
27	100% viscose	17	Finished	V17f
28	100% viscose	14	Finished	V14f
29	100% viscose	12	Finished	V12f
30	100% lyocell (Tencel®)	20	Finished	T20f
31	100% lyocell (Tencel®)	17	Finished	T17f
32	100% lyocell (Tencel®)	14	Finished	T14f
33	100% lyocell (Tencel®)	12	Finished	T12f
34	100% polyester	20	Finished	PS20f

Designation legend: C - cotton, CM - cotton/modal, V - viscose, T - Tencel®, PS - polyester, 20 - 20 tex , 17 - 17 tex, 14 - 14 tex, 12 - 12 tex, r - raw, f – finished

Table 2. Test results of the yarn parameters

Designation	Tt, tex	Tm, m^{-1}	d, mm	Ntn	Ntk	Nn	CVm, %	F, cN	ε_B, %	n_1	n_2	n_3	n_4	μ
C20r	19.9	742	0.18	0	13	15	11,5	292.9	5.6	52	20	1	1	0.15
C17r	16.9	842	0.16	0	10	18	11.2	245.5	4.9	50	16	1	1	0.14
C14r	14.3	935	0.15	0	23	10	12.6	205.5	4.5	32	8	0	1	0.14
C12r	12.1	966	0.14	0	27	25	14.1	220.8	4.7	30	8	1	0	0.13
CM20r	19.9	801	0.18	0	8	15	11.1	401.6	5.2	45	6	0	0	0.19
CM17r	16.8	870	0.17	0	10	38	12.3	227.8	4.5	38	4	0	0	0.14
CM14r	14.4	952	0.15	0	35	118	13.3	203.9	4.9	37	4	0	0	0.14
CM12r	12.2	976	0.14	0	60	100	14.2	158.3	4.7	32	6	1	0	0.15
V20r	19.8	802	0.18	0	13	30	12.3	417.2	13.3	35	6	0	0	0.15
V17r	16.8	806	0.17	0	3	38	11.6	360.7	13.7	37	5	0	0	0.14
V14r	14.4	910	0.15	0	3	35	12.1	298.4	12.1	34	6	0	0	0.13
V12r	12.2	950	0.14	0	20	20	13.1	180.2	9.5	26	3	0	0	0.12
T20r	20.1	770	0.18	0	3	18	10.8	713.4	9.8	60	22	1	1	0.13
T17r	16.8	851	0.17	0	0	23	11.2	550.5	9.1	46	9	0	0	0.15
T14r	14.4	915	0.15	0	8	48	12.4	368.8	7.7	49	16	0	1	0.13
T12r	12.1	970	0.14	0	10	42	13.8	295.9	7.6	27	6	0	0	0.10
PS20r	20.0	684	0.20	0	0	0	5.9	363.0	11.9	32	5	0	0	0.18

Legend: Tt - yarn count, Tm - number of twists per 1 meter, d - yarn diameter, Ntn - number of thin places on 1000 m, Ntk - number of thick places on 1000 m, Nn - number of neps on 1000 m, CVm - coefficient of mass variation, F - breaking force, ε_B - breaking elongation, n_1 - number of fibers of length 2 mm, n_2 - number of fibers of length 4 mm, n_3 - number of fibers of length 6 mm, n_4 - number of fibers of length 8 mm, μ- mean value of friction coefficient

Table 3. Test results of the knitted fabric parameters

Designation	S cm^{-2}	l. mm	t. mm	m. $g\ m^{-2}$	k_c	k_w	k_s	R	TF, $tex^{1/2}$ mm^{-1}	ε
C20r	225	2.91	0.46	142.78	5.2	3.6	19.1	1.4	1.54	0.82
C17r	247	2.85	0.44	123.44	5.4	3.7	20.1	1.5	1.45	0.83
C14r	263	2.75	0.38	100.10	5.4	3.7	19.9	1.4	1.36	0.84
C12r	300	2.70	0.36	91.00	5.4	4.1	21.9	1.3	1.28	0.85
CM20r	237	2.70	0.46	141.01	5.1	3.4	17.3	1.5	1.66	0.80
CM17r	243	2.60	0.44	121.11	5.1	3.3	16.5	1.6	1.59	0.82
CM14r	273	2.60	0.42	107.77	5.1	3.6	18.5	1.4	1.44	0.83
CM12r	300	2.55	0.39	94.30	5.1	3.8	19.5	1.3	1.36	0.84
V20r	247	2.65	0.43	141.67	5.0	3.4	17.3	1.5	1.69	0.76
V17r	253	2.50	0.38	121.50	4.9	3.3	15.8	1.5	1.65	0.79
V14r	263	2.49	0.37	105.80	4.9	3.4	16.5	1.4	1.50	0.80
V12r	310	2.48	0.34	95.82	5.0	3.9	19.4	1.3	1.39	0.81
T20r	253	2.82	0.47	139.18	5.5	3.7	20.2	1.5	1.59	0.81
T17r	260	2.65	0.43	112.81	5.3	3.4	18.3	1.5	1.59	0.83
T14r	260	2.65	0.40	102.54	5.3	3.4	18.3	1.5	1.41	0.83
T12r	300	2.50	0.37	91.58	5.0	3.8	18.8	1.3	1.39	0.84
PS20r	237	2.65	0.42	137.61	5.0	3.3	16.7	1.5	1.69	0.76
C20f	248	2.80	0.43	148.10	4.5	4.3	19.4	1.0	1.60	0.78
C17f	272	2.75	0.38	127.54	4.7	4.4	20.6	1.1	1.50	0.77
C14f	279	2.70	0.32	109.94	4.9	4.2	20.3	1.2	1.39	0.77
C12f	332	2.50	0.30	92.45	4.8	4.4	20.8	1.1	1.39	0.80
CM20f	288	2.60	0.42	150.44	4.7	4.2	19.5	1.1	1.72	0.76
CM17f	288	2.50	0.38	127.71	4.5	4.0	18.0	1.1	1.65	0.78
CM14f	288	2.50	0.34	108.01	4.5	4.0	18.0	1.1	1.50	0.79
CM12f	332	2.30	0.32	95.44	4.4	4.0	17.6	1.1	1.50	0.84
V20f	286	2.55	0.40	150.20	4.7	4.0	18.6	1.2	1.75	0.75
V17f	304	2.45	0.36	131.10	4.7	3.9	18.2	1.2	1.68	0.76
V14f	323	2.40	0.34	111.80	4.6	4.1	18.6	1.1	1.56	0.77
V12f	341	2.40	0.32	104.75	4.7	4.2	19.7	1.1	1.44	0.80
T20f	272	2.70	0.40	150.18	4.6	4.3	19.8	1.1	1.66	0.74
T17f	280	2.60	0.35	128.08	4.4	4.3	19.0	1.0	1.59	0.76
T14f	297	2.55	0.31	112.03	4.6	4.2	19.3	1.1	1.47	0.76
T12f	323	2.40	0.28	94.61	4.6	4.1	18.6	1.1	1.44	0.84
PS20f	263	2.55	0.38	149.38	4.3	4.0	17.1	1.1	1.75	0.78
Min value	225	2.40	0.38	142.78	4.3	3.3	16.5	1.0	1.54	0.78
Max value	263	2.91	0.46	149.38	5.4	4.3	21.9	1.6	1.75	0.82

Legend: S - stitch density, l - stitch length, t - fabric thickness, m - mass per unit area, k_c, k_w, k_s, R - Munden constants, TF - tightness factor, ε - fabric porosity

Table 4. Correlation matrix of the water vapor resistance and yarn parameters

	Tt	Tm	CVm	μ	R_{et}
Tt	1.00	-0.94	-0.67	0.68	0.59
Tm	-0.94	1.00	0.75	-0.71	-0.59
CVm	-0.67	0.75	1.00	-0.49	-0.32
μ	0.68	-0.71	-0.49	1.00	0.78
R_{et}	0.59	-0.59	-0.32	0.78	1.00

Table 5. Summary of the stepwise regression statistics for the prediction of water vapor resistance from yarn parameters

		Beta	Std.Err. of Beta	B	Std.Err. of B	t	p-level
Step 0: R = 0.71; $R^2 = 0.51$; Adj. $R^2 = 0.34$; F = 3.08; Std. Err. = 0.46	Intercept			-3.43	6.34	-0.54	0.60
	Tt	0.68	0.81	0.12	0.14	0.84	0.42
	Tm	0.58	1.04	0.01	0.01	0.56	0.59
	CVm	-0.06	0.51	-0.02	0.15	-0.11	0.92
	μ	0.56	0.29	15.38	8.03	1.92	0.08
Step 1: R = 0.71; $R^2 = 0.51$; Adj. $R^2 = 0.39$; F = 4.45; Std. Err. = 0.44	Intercept			-3.02	4.91	-0.62	0.55
	Tt	0.63	0.61	0.11	0.11	1.03	0.32
	Tm	0.49	0.59	0.03	0.01	0.83	0.42
	μ	0.58	0.26	15.75	7.03	2.24	0.04
Step 2: R = 0.69; $R^2 = 0.48$; Adj. $R^2 = 0.41$; F = 6.48; Std. Err. = 0.44	Intercept			0.98	0.76	1.29	0.22
	Tt	0.17	0.25	0.03	0.05	0.67	0.51
	μ	0.57	0.25	15.60	6.94	2.25	0.04
Step 3: R = 0.68; $R^2 = 0.46$; Adj. $R^2 = 0.43$; F = 12.98; Std. Err. = 0.43	Intercept			1.03	0.74	1.39	0.19
	μ	0.68	0.19	18.63	5.17	3.60	0.01

Table 6. Correlation matrix of water vapor resistance and knitted fabric parameters

	t	m	l	k_c	k_w	k_s	R	TF	ε	R_{et}
t	1.00	0.92	0.58	-0.20	-0.01	-0.09	-0.14	0.80	-0.58	0.86
m	0.92	1.00	0.60	-0.19	-0.02	-0.11	-0.04	0.88	-0.72	0.84
l	0.58	0.60	1.00	0.18	0.59	0.53	-0.20	0.16	-0.60	0.36
k_c	-0.20	-0.19	0.18	1.00	0.31	0.74	0.58	-0.38	0.20	-0.37
k_w	-0.01	-0.02	0.59	0.31	1.00	0.87	-0.48	-0.40	-0.17	-0.09
k_s	-0.09	-0.11	0.53	0.74	0.87	1.00	-0.03	-0.48	-0.24	-0.26
R	-0.14	-0.04	-0.20	0.58	-0.48	-0.03	1.00	0.06	-0.16	-0.21
TF	0.80	0.88	0.16	-0.38	-0.40	-0.48	0.06	1.00	-0.53	0.80
ε	-0.58	-0.72	-0.60	-0.20	-0.17	-0.24	-0.16	-0.53	1.00	-0.34
R_{et}	0.86	0.84	0.36	-0.37	-0.09	-0.26	-0.21	0.80	-0.34	1.00

Table 7. Summary of the stepwise regression statistics for the water vapor resistance and knitted fabric parameters

		Beta	Std.Err. of Beta	B	Std.Err. of B	t	p-level
Step 0: R = 0.95; R^2 = 0.91; Adj. R^2= 0.78; F =7.45; Std. Err. = 0.22	Intercept			-7.40	12.78	-0.58	0.58
	t	0.72	0.48	7.87	5.21	1.50	0.17
	m	1.90	0.90	0.04	0.02	2.12	0.07
	l	0.83	0.48	-2.86	1.66	-1.71	0.12
	kc	0.77	0.95	2.36	2.91	0.80	0.44
	kw	1.47	1.49	4.48	4.55	0.98	0.35
	ks	-1.92	2.06	-0.86	0.92	-0.93	0.38
	R	0.10	0.36	0.85	3.07	0.27	0.78
	TF	-1.23	0.93	-4.77	3.63	-1.31	0.23
	ε	0.24	0.25	4.10	4.22	0.97	0.36
Step 1: R = 0.95; R^2= 0.91; Adj. R^2 = 0.81; F = 9.46; Std. Err. = 0.21	Intercept			-6.23	11.35	-0.55	0.60
	t	0.63	0.35	7.00	3.92	1.78	0.11
	m	1.89	0.84	0.04	0.01	2.24	0.05
	l	-0.77	0.42	-2.68	1.44	-1.85	0.10
	kc	0.76	0.89	2.33	2.74	0.85	0.41
	kw	1.26	1.22	3.86	3.72	1.03	0.32
	ks	-1.73	1.83	-0.77	0.81	-0.94	0.37
	TF	-1.14	0.83	-4.42	3.21	-1.37	0.20
	ε	0.25	0.22	4.38	3.85	1.13	0.28
Step 2: R = 0.95; R^2 = 0.90; Adj. R^2 = 0.82; F = 11.05; Std. Err. = 0.20	Intercept			1.12	7.23	0.15	0.87
	t	0.48	0.30	5.36	3.37	1.59	0.14
	m	1.70	0.80	0.03	0.01	2.13	0.06
	l	-0.66	0.39	-2.28	1.34	-1.69	0.12
	kw	0.24	0.24	0.76	0.75	1.00	0.34
	ks	-0.19	0.28	-0.08	0.12	-0.67	0.51
	TF	-0.79	0.70	-3.06	2.74	-1.11	0.29
	ε	0.34	0.20	5.79	3.42	1.69	0.12
Step 3: R = 0.94; R^2 = 0.89; Adj. R^2 = 0.83; F = 13.54; Std. Err. = 0.20	Intercept			-1.29	6.11	-0.21	0.83
	t	0.44	0.29	4.90	3.20	1.52	0.15
	m	1.60	0.76	0.03	0.01	2.09	0.06
	l	-0.59	0.36	-2.05	1.26	-1.61	0.13
	kw	0.13	0.16	0.39	0.51	0.76	0.46
	TF	-0.59	0.62	-2.29	2.42	-0.94	0.36
	ε	0.41	0.16	7.02	2.83	2.47	0.03
Step 4: R = 0.94; R^2 = 0.88; Adj. R^2 = 0.83; F = 16.76; Std. Err. = 0.19	Intercept			0.79	5.37	0.14	0.88
	t	0.44	0.28	4.84	3.14	1.53	0.15
	m	1.72	0.73	0.03	0.01	2.34	0.03
	l	-0.56	0.35	-1.94	1.23	-1.57	0.14
	TF	-0.75	0.58	-2.91	2.24	-1.29	0.22
	ε	0.41	0.16	6.93	2.78	2.49	0.02
Step 5: R = 0.93; R^2 = 0.87; Adj. R^2 = 0.82; F = 19.44; Std. Err. = 0.20	Intercept			-5.08	2.95	-1.71	0.11
	t	0.38	0.29	4.21	3.19	1.31	0.21
	m	0.86	0.33	0.01	0.01	2.60	0.02
	l	-0.13	0.14	-0.46	0.48	-0.95	0.35
	ε	0.42	0.16	7.10	2.85	2.48	0.02
Step 6: R = 0.93; R^2 = 0.86; Adj. R^2 = 0.82; F = 25.79; Std. Err. = 0.20	Intercept			-6.81	2.32	-2.93	0.01
	t	0.32	0.28	3.58	3.11	1.15	0.27
	m	0.87	0.33	0.01	0.01	2.65	0.01
	ε	0.47	0.15	8.05	2.66	3.02	0.01
Step 7: R = 0.9; R^2 = 0.84; Adj. R^2 = 0.82; F = 37.17; Std. Err. = 0.20	Intercept			-7.18	2.32	-3.08	0.01
	m	1.21	0.15	0.02	0.01	7.99	0.01
	ε	0.53	0.15	8.95	2.570	3.47	0.01

Table 8. Results of uncertainty analysis of water vapour measurements on sweating guarded hotplate

Standard uncertainty component	Source of uncertainty	Value of standard uncertainty	Combined standard uncertainty	Expanded uncertainty
u(R_{et})	Water vapor resistance measurement, m^2 Pa W^{-1}	0.02057	0.02057	0.04114
u(R_{etr})	Repeatability from the previous measurements	0.00008		
u(T_c)	Chamber temperature, ºC	0.012	0.032	0.064
u(T_{tp})	Test plate temperature, ºC	0.003		
u(Ts)	Temperature sensor calibration, ºC	0.03		
u(v_a)	Air velocity, ms^{-1}	0.002	0.003	0.006
u(vs)	Air velocity sensor calibration, ms^{-1}	0.002		
u(rc)	Resolution of sample cutting equipment, mm	0.3		