Krzysztof Kowalski,
***Jolanta Janicka,**
***Teresa Massalska-Lipińska,**
Monika Nyka

Technical University of Lodz,
Department of Knitting Technology,
ul. Żeromskiego 116, 90-246 Łódź, Poland

***Textile Research Institute,**
ul. Brzezińska 5/15, 90-103 Łódź, Poland

Impact of Raw Material Combinations on the Biophysical Parameters and Underwear Microclimate of Two-Layer Knitted Materials

Abstract
This paper presents an evaluation of the biophysical properties of 27 variants of two-layer knitted fabrics mainly differing in the kind of raw material used in the conductive and diffusive layers. The method developed for the moisture content monitoring of particular layers of knitted fabric enables to arrange the raw material combinations in the structure of two-layer knitted fabric designed for recreational and sport products. Variants of knitted fabric differing in the moisture content of the inner layer were tested using an artificial skin model to assess moisture transportability in the form of a steam phase, as well as the parameters of the underwear microclimate – the temperature and relative humidity during physical effort by means of a cyclo-ergograph. It is documented that a low content of humidity in the product's inner layer is the reason for a low value of relative humidity in the underwear microclimate during and after physical effort.

Key words: *two-layer knitted fabric, humidity content, biophysical parameters, artificial skin model, underwear microclimate, temperature, relative humidity, test effort.*

Introduction

The problem of the underwear microclimate has recently been the object of interest of many research laboratories and producers of highly specialised outerwear and underwear, who take interest in research results characterising this microclimate. Moreover, the assurance of usage comfort is a priority in light of the growing competitiveness in the textile market. The analysis of factors determining usage comfort states that it is a multidimensional and complex concept. The subjective feeling of comfort results from complex processes where a significant number of stimuli caused by the clothing product and outer environmental factors go to the brain through a network of sense reactions to formulate, as a final effect, the subjective and individual feelings [1].

Usage comfort characteristics could be determined by many biophysical parameters established on the basis of normative regulations and research procedures defined by scientific institutions.

In order to make a complex characterisation of products from the point of view of this phenomenon, basic structural parameters and subsequent biophysical parameters are usually defined: hygroscopicity, air permeability, drying time, steam water resistance (steam water permeability), thermal insulation, and sorption indicators (value of mean sorption, speed of sorption).

The examination of underwear microclimate parameters can be conducted in stationary conditions and during physical activity by means of specialist research stands very often built for this purpose [2]. The crucial problem in laboratory tests is to determine the dynamic of the underwear microclimate, as well as test results after an analysis defining the course in the clothing design with special emphasis on the structure and raw material compositions. Studies of this include homogeneous materials as well as textiles from various elements [2 - 6]. Multi-layer materials are the most preferred to achieve ideal usage comfort. Even though the canon of the multi-layer structure of knitted fabrics with increased biophysical valour is well-know, there is lack of comparative tests in the area of raw materials and structural impact on biophysical properties. Due to the variety of knitted yarns on the textile market, these tests are necessary to choose the most suitable one to form the structure of the knitted fabric required [7 - 9].

From existing knowledge concerning the structure of knitted fabrics with increased biophysical valour, it follows that the obtainment of such knitted fabrics is possible when raw materials of various affinity to moisture are used in a particular layer of the knitted fabric. The task of the knitwear layer which directly sticks to the body is to transport moisture and transfer it to the outer- sorption layer. Moisture transportability and transferability, in the form of a liquid phase, and the ability to cumulate it in the sorption layer could be defined by the measure of the moisture content in particular layers of the knitted fabric. At present, there is a lack of literature data concerning the quantitative share of moisture in particular layers of knitted fabrics and its impact on underwear microclimate parameters, which depends on the type of raw materials used.

The tests conducted proved that the determination of the moisture content in the layers of a two fabric knitted system together with the determination of underwear microclimate parameters give the possibility of specifying clothing design assumptions in a more complete way.

Raw material assortment

In the tests conducted a two-layer knitted fabric was used as research material. The model structure of the two-layer knitwear consisted of:

- A layer made of conductive and diffusive yarns directly sticking to the body. The task of this layer is to discharge and transport moisture from the body in the form of a liquid and steam phase.
- A layer made of sorption yarns which does not directly stick to the skin. The task of this layer is to keep moisture far from the body and evaporate it into the environment.

Evaluation of the biophysical properties and parameters of an underwear microclimate in non-stationary usage conditions was conducted for two-layer knitted fabrics made of two plain stitches bound together by indirect thread by means of tucking loops (***Table 1***) in which the following assortments of yarns were used for the inner layer as raw material with conductive and diffusive properties.

To form the outer layer, cotton yarn of 20 tex linear density, as raw material with sorption properties, was used.

Moreover, the version of knitwear used, recently recommended by producers of sports underwear, was made out of two types of "Trevira" Polyester yarn.

In this knitwear the conductive and diffusive layer was made out of Trevira 167 dtex f 96, while the outer layer was produced from "Trevira" 150 dtex f 256, consisting of microfibres.

For comparative tests (as a comparative sample) cotton knitwear was made out of bleached yarns, where 15 tex cotton shaped the inner layer and cotton with a linear mass of 20 tex - the outer layer. The layers of knitted fabric were joined by textured Polyamide thread with a low linear mass - PA 22 dtex f 7. The surface mass was contained in the range Mp = 197 ÷ 264 g/m^2, and the thickness - g = 0.79 ÷ 1.19 mm (***Figure 1***).

Methodology

The tests methods presented in this paper are designed to evaluate moisture transferability in the form of a liquid and steam phase from the surface of the skin through the knitted fabric, taking into consideration the moisture collecting function of the outer layer of the knitwear. The research methods used concern:

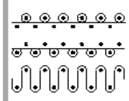
- evaluation of the humidity content in a two-layer knitwear system,
- a simulation test of non-stationary usage conditions by means of an artificial skin model,
- evaluation of underwear microclimate parameters.

Humidity content evaluation method in a two-layer knitwear system

Among the factors that have a vital influence on physiological comfort is the level of humidity in the underwear microclimate. From literature data [10 - 12] it follows that physiological discomfort occurs when the relative humidity in the underwear microclimate is more than 80%. Undoubtedly the humidity content of a knitwear layer in direct contact with the user's body is the factor allowing an increase in relative humidity in an underwear microclimate during physical effort. Taking the above into consideration, tests were conducted to quantitatively determine the humidity content in particular layers of knitwear made of various raw materials.

Two-layer knitwear, presented in ***Table 1***, is composed of two different plain stitches, and moisture transportation from one layer to the other occurs through surface contact, which is due to the indirect thread linking both layers having a low linear mass (22 dtex) and hydrophobicity. In the method suggested moisture transmission also occurs through surface contact. To simulate this, RL knitted fabrics made of a particular type of raw material and next circular test samples of 10 cm diameter were prepared. The circular knitwear samples, double-folded in order to imitate the structure of two-layer knitwear, were jammed in a ring with an outer diameter of 10 cm (***Figure 2***). Then the samples were sprinkled evenly with 2 ml of distilled water at six points of the knitwear surface. In the case of samples made of synthetic yarns of a hydrophobic nature and with natural sorption capacity, the synthetic side of the sample was dripped with water, which is supposed to simulate moisture disposal and transportation onto sorption layer. After

Table 1. *Type of stitch and raw material used in the conductive and diffusive layer.*

Type of stitch	Yarns used in the conductive and diffusive layer
	Staple PES "Coolmax" 20 tex Staple PES "Thermastat" 20 tex Staple PES "Elana" 13 tex Staple PES "Elana" 20 tex Textured PES 167 dtex f 96 Textured PES 110 dtex f 144 Staple PP 20 tex PP 84 dtex f 25 x 2 Textured PA Meryl "Spun" 185 dtex f 136 PA 66 textured 60 dtex f 30 x 2 PA 66 "Tasland" 140 dtex f 102 PA 66 "Skinlife"78 dtex f 68 x 2 Textured PA 156 dtex f 47

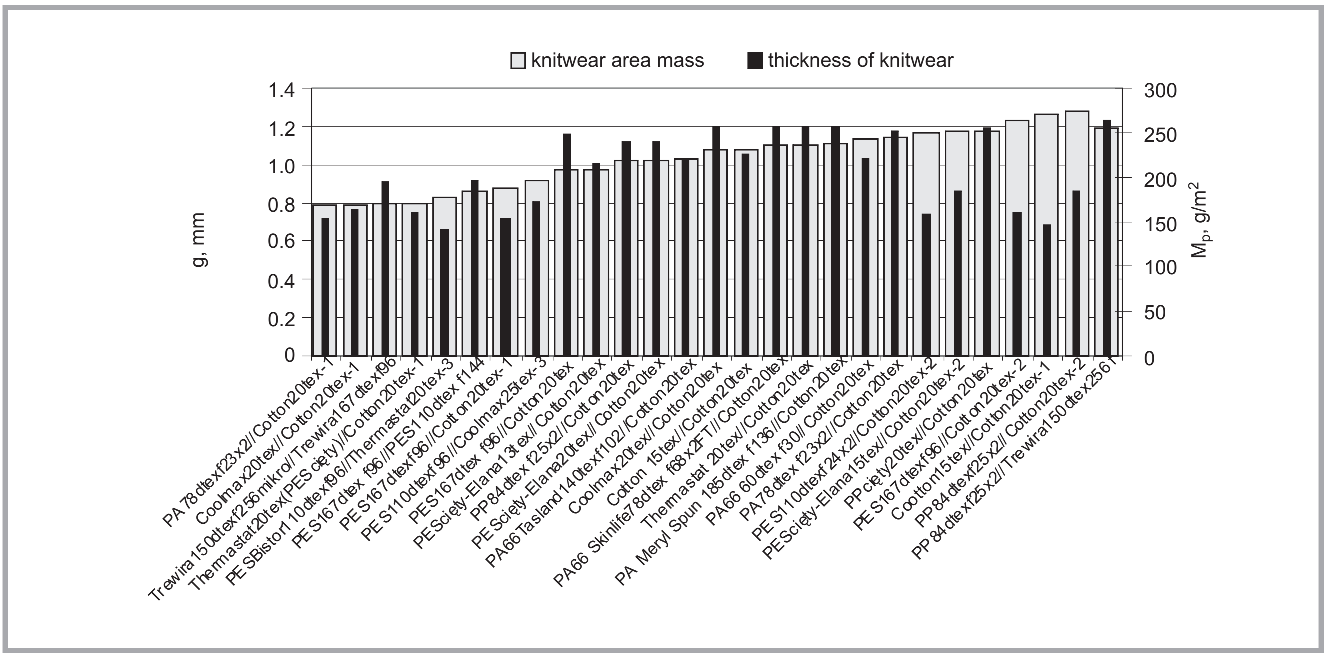


Figure 1. *Thickness and surface mass of the two-layer knitted fabrics.*

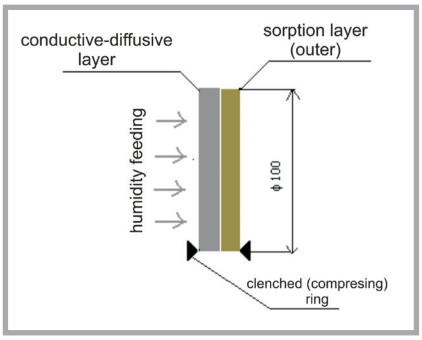


Figure 2. Knitwear arrangement in the evaluation of the humidity content in knitwear layers.

the dripping, the sample was placed in a vertical position, then after 5 minutes it was separated and weighed on laboratory scales with a precision of up to 0.2 mg. Additionally a test of the humidity content in knitwear layers was conducted for four variants of knitted fabrics, where the sorption layer was Viscose yarn of 20 tex, and the hydrophobic [inner] layer was standard silk PES, PA, PP and Viscose of 16.7 tex.

Tests were conducted in isothermal conditions using the following parameters:

- ambient temperature ≈ 23 °C
- air relative humidity ≈ 40%.

The humidity content in the layer which directly sticks to the body was evaluated according to the following index:

$$W_1 = \frac{Z_w}{Z_z + Z_w} \qquad (1)$$

where:

Z_w - humidity content [mg] in the inner layer of the knitwear directly sticking to the body for a mass of knitwear of 1 mg, in mg/mg,

Z_z - humidity content [mg] in the outer layer of the knitwear for a mass of knitwear of 1 mg, in mg/mg.

This index shows that the lowest value of index W_1 has the highest mass of humidity absorbed in the outer layer of the knitwear, which has a positive impact on the creation of a underwear microclimate and reduces physiological discomfort.

Non-stationary simulation test of usage conditions on an artificial skin model

A non-stationary simulation test of usage conditions using an artificial skin model was conducted on a test stand for evaluation of the microclimate under knitwear, presented in ***Figure 3***. The artificial skin model was made by the Institute of Exploitation Technologies in Lodz (Instytut Technologii Eksploatacji z Łodzi). Simulation of non-stationary usage conditions consisted in the intensive calling of the sweating effect by dropping water (4 cm³) onto woven fabric (cotton) with dimensions of 20 × 20 cm. This fabric stuck directly to a measuring panel of 35 °C temperature. The knitwear trial was placed 15 mm from the measuring panel. As distinct from the method proposed in the Umbach study [12], the knitwear trial obtained humidity in the form of a liquid phase from the fabric surface in a cyclic way, which approximately formed real usage conditions. During the tests, the recording of changes in temperature and humidity in the microclimate under knitwear were made. For this purpose a Hygroclip SC04 f measuring sonde was used to measure the temperature and humidity. The accuracy of the temperature measurement was ± 0.3 °C, and the humidity - RH ± 1.5%. On the basis of an analysis of changes in the run of the relative humidity and temperature, a new

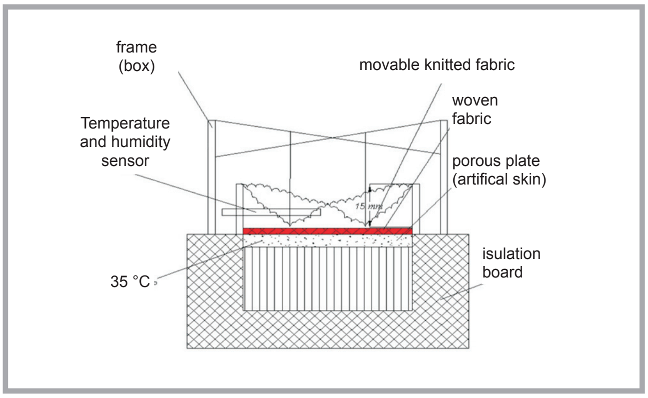


Figure 3. General structure of a stand for the evaluation of the microclimate under knitwear on an artificial skin model.

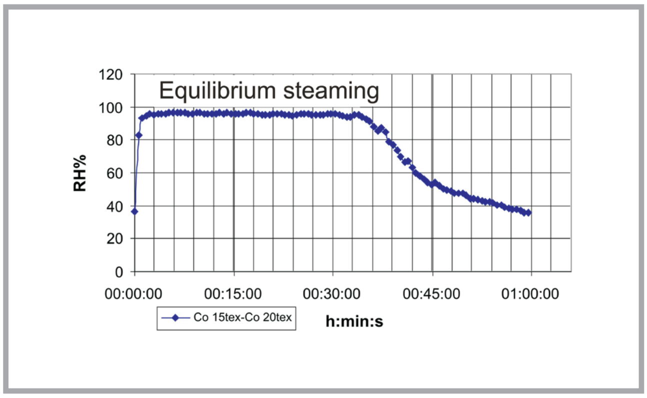


Figure 4. Examples of relative humidity changes under knitwear on an artificial skin model.

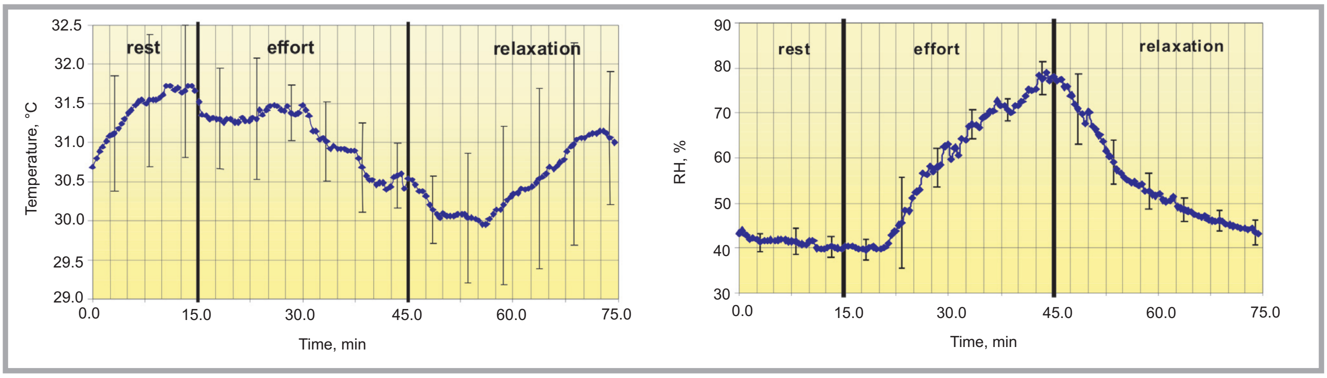


Figure 5. Example of the average temperature and humidity at rest, during effort and the relax phase in a underwear microclimate during a usage test on a cyclo-ergograph, for cotton two-layer knitwear (test conditions: ambient temperature t ≈ 23 °C, ambient humidity RH ≈ 62%, physical loading 50 W, number of measure series n = 6).

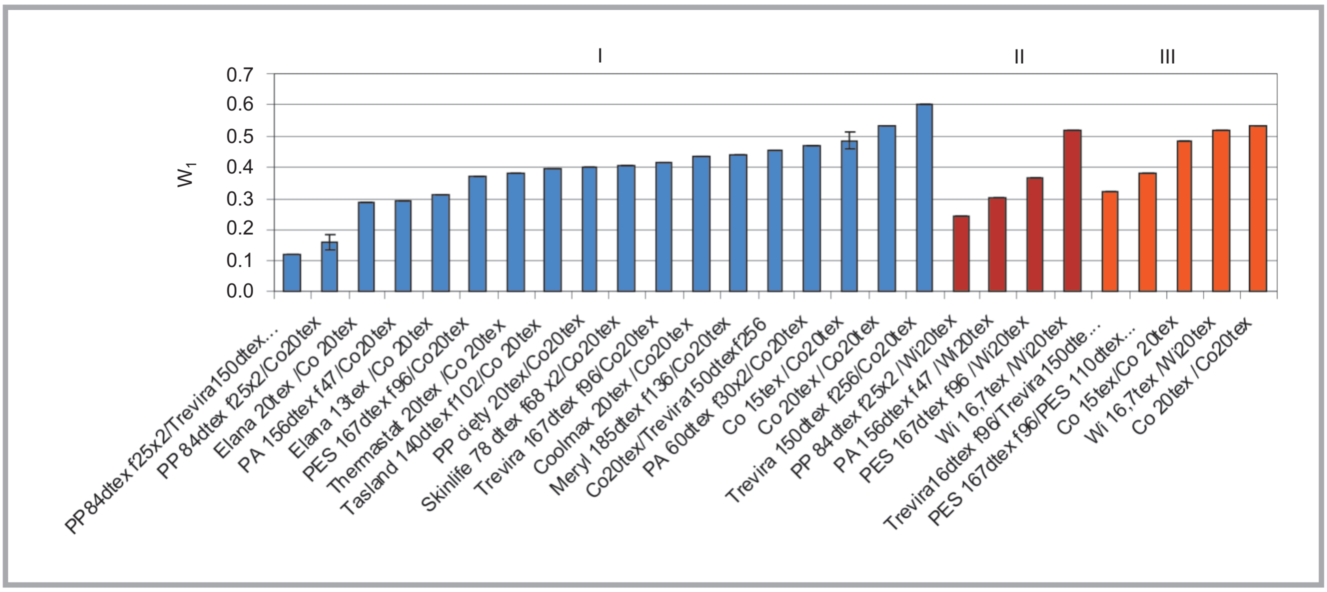


***Figure 6.** Value of index W_1 for the humidity content in the inner layer of knitwear.*

non-dimensional index *Wfp* (2) is proposed for steam phase buffering, which is a quotient of the time of equilibrium steaming (when RH ≈ const, ***Figure 4***) in the case of direct moisture transportation from dripped fabric to the environment without knitwear and the time of equilibrium steaming with the knitwear tested.

$$W_{fp} = t_0/t_1 \qquad (2)$$

where:

t_0 – time of equilibrium steaming in the case of dripped fabric without knitted fabric,

t_1 – time of equilibrium steaming under the knitwear tested.

Theoretically, the value of index *Wfp* could be in the range of 1 ÷ 0 (1 - for the air layer, 0 - for the steam impermeable layer $t_1 \rightarrow \infty$).

Evaluation method of underwear microclimate parameters

Evaluation of changes in an underwear microclimate, which is characterised by its temperature and relative humidity over time, was performed on a test effort stand – a cyclo-ergograph.

To perform the test, T-shirts from two-layer knitwear (***Table 1***) and four raw material variants were made:

1. Co 15 tex/Co 20 tex
2. PP 84 dtex f 25 × 2/Co 20 tex
3. PP 84 dtex f 25 × 2/Trevira 150 f 256
4. Trevira 167 dtex f 96/Trevira 150 f 256

The tests of a microclimate performed with one person gave better test result replicability than in the case of a few people with different metabolisms. The measuring cycle included the following: recording of the parameters mentioned above during the rest phase in cycles of 15 min, during the physical effort phase at a load of 50 W for 30 min., and next during a relaxation phase of 30 min. The initial phase was recorded after the subject put on a T-shirt. Measuring of the temperature and humidity was performed on the user's chest and back. Among the parameters of the underwear microclimate determined on the cyclo-ergograph, the temperature is characterised by a relatively large variation in subsequent (in turn) runs, in spite of testing T-shirts using the same person in the same outer climate.

Tests results analysis

Analysis of the humidity content in knitwear using different-raw materials systems

Figure 6 presents the value of index *W1* for three groups of various raw materials systems in knitwear:

- I group – knitwear made of synthetic or natural yarns and cotton knitwear,
- II group – knitwear made of synthetic yarns and knitwear made of Viscose yarn,
- III group – knitwear in systems made of homogenous raw materials.

The value of index W_1 , informing about humidity participation in the inner layer, are in the range of 0.12 ÷ 0.60. A value below 0.5 shows lower humidity participation in the inner layer than in the outer one. For two variants of knitwear i.e. cotton knitted fabric (Co 20 tex/Co 20 tex) and Polyester/Cotton ("Trevira" 150 dtex f 256/Co 20 tex), the highest participation of humidity was obtained in the inner layer, i.e. the dripped layer. The increased value of humidity participation in the layer made of "Trevira" polyester microfibres compared with with 20 tex cotton shows that it has a better ability to fix the moisture than Cotton yarn. In this case a knitwear layer made of microfibres is characterised by about a 20% higher moisture absorption in the form of a liquid phase, converted to the unit for knitwear mass, than a layer of cotton knitted fabric, which is caused by the higher total surface of fibres and numerous spaces among fibrils, causing higher sorption effectiveness.

The ability of polyester microfibre yarn to absorb a large quantity of humidity was used in the design of two-layer knitwear, where the inner layer was textured polypropylene PP 84 dtex f 25 × 2, and the outer layer - as mentioned above - Trevira 150 dtex f 256. Using such a raw material system in knitwear gives the possibility of obtaining the lowest humidity participation in the inner layer i.e. W_1 = 0.12 in the tests used. The second most favourable case is polypropylene/cotton knitwear (PP 84 dtex f 25 × 2/Co 20 tex), where the value of the index is W_1 = 0.16. It should be stated that for variants made of two types of polyester (Trevira 167 dtex f 96/Trevira 150 dtex f 256), the index is W_1 = 0.33, which is almost three times higher than in the case of the lowest index value – 0.12.

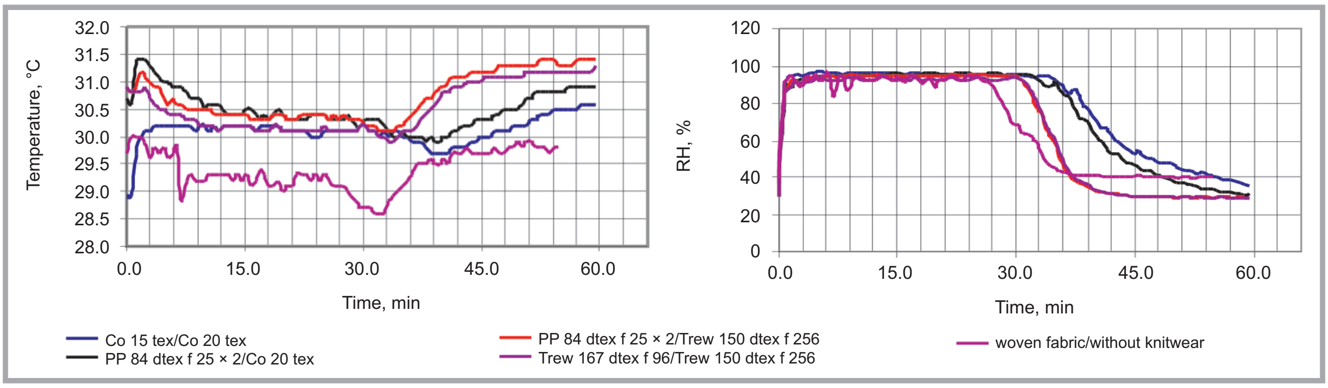


Figure 7. *Temperature and relative humidity run for 4 variants of knitwear on an artificial skin model.*

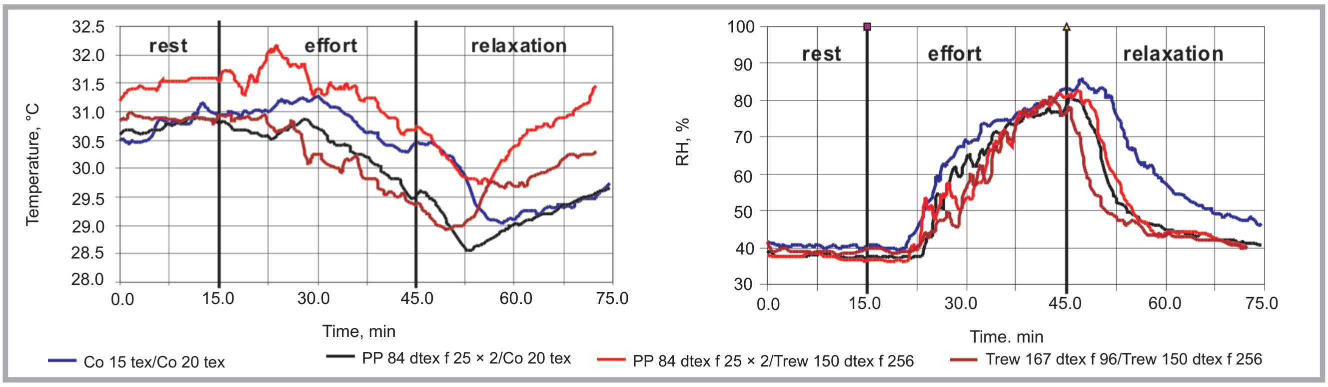


Figure 8. *Temperature and relative humidity run in the rest, effort and relax phase in an underwear microclimate during usage tests on a cyclo-ergograph for four variants of knitwear.*

Among knitted fabrics made of staple synthetic yarns, the lowest humidity value in the inner layer is noted for polyester/cotton knitwear (Elana 20 tex/Co 20 tex and Elana 13 tex/Co 20 tex).

Figure 6, for the second group of knitwear, presents test results of the humidity content in the inner layer for a standard combination of synthetic silk PES, PA and PA with viscose yarn of 20 tex. There appears to be a similar relation in humidity content, but a significantly higher value of the humidity content was obtained in the knitwear layer made of textured polypropylene silk than in the case of a combination of polypropylene/cotton (suitably 0.12 and 0.24). In the third group of knitwear, the value of index W_1 is presented for knitted fabrics made of homogenous raw materials, where the lowest value of the humidity content in the inner layer was obtained in the case of knitwear made of two "Trevira" polyester silk with an inner layer made of microfibres.

Analysing the results obtained, it could be stated that the value of the humidity content in the inner layer in isothermal conditions was in the range of $0.12 \div 0.60$, which makes it possible to arrange the types of yarns actually used in the production of two-layer knitted fabrics in terms of their moisture transferability from the body's surface to the outer layer.

Analysis of microclimate parameters under knitwear – tests on an artificial skin model

The tests performed on the model of artificial skin were used to evaluate moisture transportability in the form of steam. The evaluation included the same knitwear variants as in the case of the cyclo-ergograph test i.e.

- Co 15 tex/Co 20 tex
- PP 84 dtex f 25 × 2/Co 20 tex
- PP 84 dtex f 25 × 2/Trevira 150 dtex f 256
- Trevira 167 dtex f 96/Trevira 150 dtex f 256.

For these raw material systems, interesting results were obtained for moisture distribution in the knitwear structure, characterised by index W_1 (***Figure 6***).

The following parameters of the test conditions were used:

- ambient temperature C ≈ 24.5 °C,
- relative humidity HR ≈ 48%

In this work an additional test was conducted to evaluate the microclimate on the dripped fabric without the participation of knitwear. In this case the steam water diffused directly to the environment without knitwear exchange.

The tests conducted resulted in the following statement: for each knitwear evaluated and test variant without the participation of knitwear, where values of relative humidity in the equilibrium steaming phase are rF ≈ const, the particular tests variants have different times of equilibrium steaming and accessing the values determined. Values of the buffering index in the steaming phase, *Wfp*, for the four variants of knitted fabrics evaluated wereadequately determined (see ***Table 2***). ***Figure 7*** presents the temperature and humidity runs.

The temperature and humidity run on the artificial skin model shows, to a certain degree, results of the usage tests presented below for effort and the relaxing phase, which were determined using a cyclo-ergograph. Index *Wfp* could be the defining characteristic of the biophysical properties of knitted fabrics.

Analysis of underwear microclimate parameters from product tests conducted on a cyclo-ergograph

Tests of an underwear microclimate were conducted by means of a cyclo-ergograph for products made of four variants of knitted fabrics:

- from cotton homogenous yarns (Co15 tex/Co 20 tex) – variant I
- from polypropylene and cotton yarns (PP 84 dtex f 25 × 2 dtex/Co 20 tex) – variant II
- from polypropylene and polyester yarns (PP 84 dtex f 25 × 2/Trevira 150 dtex f 256) – variant III
- from homogenous polyester yarns (Trevira 167 dtex f 96/Trevira 150 dtex f 256) – variant IV

The tests were conducted in the following conditions:

- ambient temperature t ≈ 23 °C,
- ambient humidity RH ≈ 62%,
- physical loading 50 W.

Among knitted fabrics of homogenous raw material, cotton knitwear (Co 15 tex/Co 20 tex) has got a high content of moisture in the inner layer (***Figure 6***). In usage tests on the cyclo-ergograph, the relative humidity for this kind of knitwear variant also has the highest values in all phases i.e. rest, effort and relaxation (***Figure 8***). Especially big differences in the value of relative humidity were found between cotton knitwear and the rest of the knitwear variants, even going up to 20 ÷ 30%, are visible in the relaxation phase.

Polypropylene/cotton and polypropylene/polyester Trevira knitwear have similarvalues of relative humidity in particular phases of the usage test. The lowest value of relative humidity was obtained for knitwear made of two Trevira polyester yarns in spite of the higher humidity content in the inner layer than that in polypropylene/cotton and polypropylene/ polyester Trevira knitwear, which is

Table 2. Values of the buffering index for the steaming phase.

No.	Variant of knitted fabrics	W_{fp}
1.	Co 15 tex/Co 20 tex	0.73
2.	PP 84 dtex f 25 × 2/Co 20 tex	0.79
3.	PP 84 dtex f 25 × 2/Trevira 150 dtex f 256	0.84
4.	Trevira 167 dtex f 96/Trevira 150 dtex f 256	0.84

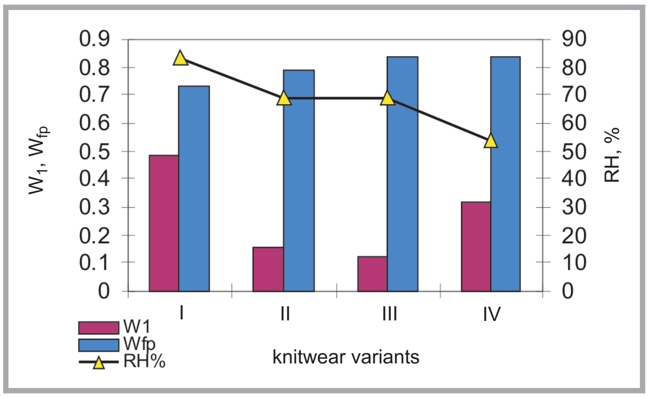


Figure 9. *Comparison of index values of the humidity content in the inner layer, W_1, the buffering of steaming phase, Wfp and values of the relative humidity RH % after 5 minutes in the relaxation phase on a cyclo-ergograph.*

caused by the considerable lower surface mass and thickness of polyester knitwear (Mp = 195 g/m^2 and g = 0.79 mm) compared to the mass of Trevira polypropylene/polyester knitwear (Mp = 264 g/m^2 and g = 1.19 mm). From the analyses of ***Figure 9***, it results that the lower the value of index W_{fp}, the higher the value of relative humidity RH. Also the lower the humidity content in the inner layer of knitwear, the lower the relative humidity of the underwear microclimate, with the exception of the variant with two Trevira yarns, where the higher value of humidity content in the inner layer complies with the lower value of relative humidity. It should be stated that in the cyclo-ergograph tests in the rest phase for all the knitwear variants tested, the value of relative humidity in the underwear microclimate are of a relatively constant level - RH ≈ 40 ± 2.5%, meaning that in stationary usage conditions the type of raw material does not have a significant influence on this parameter of the underwear microclimate.

Summary

Determination of the humidity content in the layers of a two-knitwear system in relation to the parameters of an underwear microclimate and also tests conducted on a test effort stand – a cyclo-ergograph and artificial skin model are the basis of the following conclusions:

1. The values of humidity mass participation in the inner layer of two-layer knitwear determined, conducted under isothermal conditions, were in the range of 0.12 ÷ 0.60, which created the possibility of arranging the types of yarns actually used in the production of two-layer knitted fabrics in terms of their ability to transfer moisture from the body's surface and transport it to the outer layer. Measuring the humidity content in particular layers of knitted fabric gives the possibility of matching, in a rational way, raw materials to form the structure of two-layer knitted fabric, because the connection of a conductive and diffusive layer with sorption does not always lead to a low content of moisture in the inner layer.

2. The lowest value of moisture participation - W_1 = 0.12 – in the inner layer was found for the knitwear system made of Polypropylene and Polyester yarns (PP 84 dtex f 25 × 2/Trevira 150 dtex f 256), next was W_1 = 0.16 for Polypropylene and Cotton fabric (PP 84 dtex f 25 × 2/Co 20 tex), and in the case of Polypropylene and Cotton fabric from staple synthetic yarns (Elana 20 tex/Co 20 tex and Elana 13 tex/Co 20 tex) W_1 ≈ 0.3.

3. The outer layer of two-layer knitwear made of Polyester microfibres has about a 20% higher humidity content in the form of a liquid phase, converted to the unit for knitwear mass, than a cotton knitted layer.

4. The highest variability of relative humidity in a underwear microclimate. up to 30%, according to the type of raw materials used in the production of the knitwear, was founded for the relaxation time after physical effort. The lowest values of relative humidity and the shortest time to obtain the initial parameters of the microclimate for this phase was found for variants of two-layer knitted fabric with a combination of textured polypropylene and knitted fabric made of homogenous raw material i.e. Trevira Polyester yarn with the outer layer from microfibres.

5. In tests during the relaxation phase, conducted by means of a cyclo-ergograph, the values of relative humidity in the underwear microclimate are of a relatively constant level - rF ≈ 40 ± 2.5% for all the knitwear variants tested, which means that the influence of the type of raw material on this underwear microclimate parameter is not essential in stationary usage conditions.

References

1. *Collective study 'The active, biophysical clothes made of multilayered materials, utilize in changeable climate conditions' Project No. ROW-II-257/2007, The Textile Institute 2009.*
2. *Collective study 'Modelling and designing of knitted structures with intended biophysisal valour together with empiric verification' Research Project No. 4 T08E 014 22 , ITTD TRICOTEXTIL 2004.*
3. *Oğlakcıoğlu N., Marmaral A.; Thermal comfort in the selected knitted structure, Fibres & Textiles in EE No. 64 (5/2007)*
4. *Bartkowiak G.; Dynamic of microclimate humidity under protective barrier, Fibres & Textiles in EE No. 35 (4/2001)*
5. *Massalska-Lipińska T. et. al.; The selection of raw materials and knitted structure, and physiological comfort, Przegląd Włókienniczy, No. 1, 2003.*
6. *Massalska-Lipińska T. et. al.; The influence of raw materials and structure on biophysical propertes of fleecy fabric, Przegląd Włókienniczy, No. 2, 2003.*
7. *Kowalski K., et. al.; The influence of raw materials type on parameters of underwear microclimate in nonstationary usage conditions, 42. Congress IFKT, ISBN 83-917 476- Lodz 2004.*
8. *Szucht E.: The words directions in developing the knitted fabrics with high physiological comfort, Technik Włókienniczy, 1990 No. 3, pp. 85-88.*
9. *Ceglarska L., Grabowska B.; The knitted materials designed for underwear and sport clothing having high usage properties, Technik Włókienniczy, 1990 No. 3 p. 91.*
10. *Umbach K. H. „Hautnahe Synthetics mit gutem Tragekomfort" Chemiefasern-Textilindustrie 8/1980. pp. 721-728*
11. *Umbach K. H.: „Bekleidungsphysiologische Gesichtspunkte zur Entwicklung von Sportkleidung", Wirkerei und Strickerei Technik, 1993 no. 2 pp. 108-114.*
12. *Umbach K. H.; „Messmethoden zur Prüfung physiologischer Anforderungsprofile an Zivil-Arbeits- und Schutzbekleidung sowie Uniformen" Melliand Textilberichte 11/1987 pp. 857-865.*

Received 16.12.2009 Reviewed 01.03.2010