Evaluation of thermal insulation properties and dynamic moisture transfer of knitted fabrics

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Abstract. The purpose of this study is to evaluate the thermo-physiological comfort of weft knitted fabrics and to investigate applied methods of heat and water transfer. The examined weft knitted fabrics had a different structure as well as a material composition. They were made for wearing in moderate alternatively hot climate conditions such as in Europe. Selected properties were measured on the C-Therm Tci and Moisture Management Tester (MMT) devices. We concluded that the weft knitted fabrics made of polyester, of greater thickness and specific density are comfortable in hot and moderate climate conditions. The most suitable alternative is to combine structures and materials in the manufacturing process of knitted products.

1. Introduction

Knitted fabrics are currently the most used textile products for the manufacture of outer clothing such as t-shirts, sports jacket, sweatshirt and so on. They are particularly important in the form of functional clothing. Functional clothing are designed to perform an aesthetic, protective function and surplus-value which can be improved mobility, reduced fatigue, regulation of heat and liquid moisture transport, and the like [1]. They represent the middle or lower layer of clothing which is in a partial or a complete contact with the skin of the wearer. Their function is to isolate heat (or to dissipate of heat) and continues to transport the moisture from the skin to the environment. There are various types of knitted fabrics on the market. They are made of natural and synthetic fibers or their combinations. The structural parameters such as thickness, mass per unit area, specific density, porosity etc. have the greatest impact on their thermo-physiological properties. Therefore, the subject of study was evaluation of insulation and transport properties of knitted fabrics. Thermal insulation properties were documented by a thermal conductivity coefficient and a thermal effusivity. The transfer of liquid moisture was evaluated on the basis of speed of transport ability for the knitted fabrics in relation to the reception and dispersion of the test penetrant (synthetic sweat) in a given volume [2]. The most suitable structures of knitted fabrics and the appropriate material composition were chosen based on the results of the measurements.

2. Experimental part

In this section are described knitted fabrics and their basic parameters. There are also mentioned devices used for measuring the heat transfer and liquid moisture.
2.1. Materials
Table 1 illustrates 10 types samples of weft knitted fabrics for outer clothing. Samples 1 and 2 were different compared to others. They are made as waterprooﬁbre layered knitted fabrics with protective membrane in the middle section. Materials such as cotton, polyester, polypropylene, viscose and wool were used on their production. The measurement of weft knitted fabrics thickness was done on the thickness meter under the following conditions: the load weight of 250 g and the diameter of measured area 50 mm, total compressive force 1.226 N.

Table 1. Material composition and basic parameters of weft knitted fabrics.

| Thickness (mm) | Mass per unit area (g m⁻²) | Composition and structures | Specific density (kg m⁻³) | Porosity (-) |
|---------------|-----------------------------|---------------------------|---------------------------|--------------|
| 1             | 0.92                        | 295                        | Layer knitted fabrics, face side 65 % polyester, middle side of 5% polyuretan membrane, reverse side 30% wool | 322          | 0.77         |
| 2             | 0.90                        | 283                        | Layer knitted fabrics, face side 65 % polyester, middle side of 5% polyuretan membrane, reverse side 30% wool | 314          | 0.78         |
| 3             | 0.66                        | 250                        | Plain weft knitted fabric 95 % viscose 5% elastane | 378          | 0.76         |
| 4             | 0.59                        | 191                        | Plain weft knitted fabric 100% cotton | 322          | 0.79         |
| 5             | 0.37                        | 127                        | Interlock knitted fabric – printed pattern 100% polyester | 340          | 0.75         |
| 6             | 0.55                        | 240                        | Plain weft knitted fabric – printed pattern 95 % polyester 5% elastane | 435          | 0.69         |
| 7             | 0.97                        | 236                        | Interlock knitted fabric 100% cotton | 242          | 0.85         |
| 8             | 1.40                        | 236                        | Plush weft knitted fabric 20% polyester 80% cotton | 169          | 0.88         |
| 9             | 1.57                        | 239                        | Plush weft knitted fabric sheared 80% polyester 20% cotton | 153          | 0.90         |
| 10            | 1.21                        | 215                        | Plush weft knitted fabric 50% polypropylene 50% cotton | 178          | 0.86         |

The calculations specific density \( \rho_s \) (kg m⁻³) and porosity \( p_o \) (%) of knitted fabric in table 1 were made according to following formulas:

\[
\rho_s = \frac{m}{sh} \frac{\rho_s}{h}
\]

where \( m \) (kg) is the weight, \( s \) (m²) is the area, \( h \) (m) the thickness and \( \rho_s \) (g m⁻²) is mass per unit area of weft knitted fabrics.

The specific density of a mixed knitted fabric \( \rho_{vlzm} \) (kg m⁻³):

\[
\rho_{vlzm} = \frac{1}{100} \left( \rho_{vl} v_l + \rho_{vl} v_n \right)
\]

where \( \rho_{vl} \) (kg m⁻³) is the density of the first fiber portion, \( \rho_{vl} \) (kg m⁻³) is the density of the other, \( v_l \) (%) is the first fiber portion, \( v_n \) (%) is other fiber portion.

Volume porosity of knitted fabrics \( p_o \) (-):

\[
p_o = 1 - \frac{\rho_s}{\rho_{vl}}
\]

where \( \rho_{vl} \) (kg m⁻³) is the density of fibers, \( \rho_s \) (kg m⁻³) is specific density of knitted fabric or for mixed knitted fabrics used \( \rho_{vlzm} \) instead of \( \rho_s \).
2.2. Measurement of thermal properties on C-Therm TCi device

The standard test method EN 61326-2-4 2013 was used for this testing using TCi [3]. C-Therm TCi is a one-sided interface sensor, electronics and computer software controller (figure 1). The voltage drop on the spiral heater is measured before and during the transient. The conductivity is calculated from the slope of the voltage data. Basically, the sensor is a one-sided interface that reflects the heat [4]. It applies to the heat source with a constant current to a sample. The sample is heated by approximately 1–3 °C during the testing. It absorbs some of the heat depending on its thermal conductivity. The rest causes temperature rise at the sensor interface. The rate of temperature which increases at the sensor surface is inversely proportional to the transfer heat of the sample. The measurement conditions on C-Therm TCi were as follows: the number of measurements 10, temperature 23 °C, and relative humidity of the environment 40 %, the weight of the load 500 g, the diameter of the measured area is 40.7 mm the total force of sample pressure on the sensor 4.91 N.

The thermal conductivity coefficient determines the ability of the textiles to conduct heat under stationary conditions. The thermal flow is stabilized so that the temperature distribution within the textiles does not change. Thermal resistance $R_{ct}$ (K m² W⁻¹) characterizes the ability of the textiles to prevent thermal losses [5]. It is the difference in temperature between the two surfaces of the material which is divided by a resulting thermal flow per unit area in the gradient direction. The thermal resistance is calculated according this formula:

$$R_{ct} = \frac{h}{k}$$

(4)

where $h$ (m) is thickness and $k$ (W m⁻¹ K⁻¹) is thermal conductivity.

Thermal effusivity $e$ (W s¹/² m⁻² K⁻¹) is defined as the square root of the thermal conductivity, the density and specific heat capacity of the textiles [6]. It describes behavior and capability of textiles to retain or dissipate the heat. It is calculated as follows:

$$e = (k \rho_{vl} c_p)^{1/2}$$

(5)

where $c_p$ (J kg⁻¹ K⁻¹) is the specific heat capacity of fibers, $\rho_{vl}$ (kg m⁻³) is the density of fibers and $k$ (W m⁻¹ K⁻¹) is thermal conductivity.

![Figure 1. C-Therm TCi thermal conductivity analyser.](image)

2.3. Measurement dynamic transfer of liquid moisture in the MMT device

Liquid moisture flow through textile materials is controlled by two processes: wetting and wicking. Wetting is the initial process, involved in fluid spreading and it is controlled by the surface energies of the involved solid and liquid. As water wets the fibre, the water enters the inter fibre capillary channel and is dragged along by capillary pressure. In this work the dynamic transfer of the liquid moisture were characterized by using the Moisture Management Tester (MMT). The method allows
a quantitative measurement of liquid moisture transmission of the weft knitted fabrics in one step and in several directions. The moisture spreads on both surfaces of the weft knitted fabrics and passes from one surface to another [7]. The advantage of measurement is that the liquid moisture may not simultaneously penetrate into the external environment. Some testing methods perform measurement of penetrant absorption by a texture based on a diffusion, a wicking, a permeability and a drying time. These methods, however, are not able to characterize the kinetics of liquid moisture transfer by knitted fabrics. This method is neither used to test the a transport performance of vapor water and not suitable for coated fabrics, glued fabrics or complex structures fabrics, those with a high water absorbability such as woolen fabrics or thicker fabrics [8]. The device consists of upper and lower centrally located moisture sensors (copper rings) between which the tested textile is inserted (figure 2) [9].

A predetermined amount of testing solvent is applied on upper part of a knitted fabric and it is propagated in three directions. One test provides a comprehensive view of the following physiological properties: a wetting time $W_t$ (s), a water absorption rate $A_r$ (% s$^{-1}$), a maximum wetted radius $M_{WT}$ (mm), a spreading speed $S_s$ (mm s$^{-1}$), one way transport capacity $OWTC$ (%), and an overall capacity for a moisture management $OMMC$ (-). Data were measured on both sides except for $OWTC$ and $OMMC$. The measurement values were classified by software. A water injection time was 20 seconds. An observation time was 120 seconds. At the end of experiment, the water content in a weft knitted fabrics could be confirmed. Measurement conditions were $20 \, ^\circ C$ and $65\%$ RH. All items were measured 5 times. The mean value of measurements was used as the representative value. Based on complex assessment of measurements, MMT can categorize textiles into the 7 types from waterproof to those that have transport moisture controlled [10].

![Figure 2. Device MMT.](image)

3. Results and discussion
This section presents the results of measurements of thermal properties such as: thermal effusivity, thermal conductivity and thermal resistance. The results of measurements dynamic transfer of the liquid moisture were a number of indicators, which were supplemented by graphical output of measurements.

3.1. Thermal properties of weft knitted fabric
Table 2 indicates average values of thermal property measurements on the device C-Therm TCi. The high thermal resistance values were measured for plush weft knitted fabric which had different material compositions (samples 8, 9, 10). The best results were achieved by a plush weft knitted fabric which had a higher content of polyester (sample 9). Besides, the high value of the thermal resistance is also reached in an interlock knitted fabric (sample 7) due to the greater thickness and form of knitted structure. Eventough, layer knitted fabrics (samples 1, 2) contain $30\%$ of wool component.
+ membrane + 65 % polyester they have lower thermal resistance values than plush weft knitted fabric. These are very negative results for relatively expensive materials. It is due to their lower thickness and other use (on the second layer of clothing) compared to others. Samples 3, 4, 5, 6 also have a lower heat insulation capacity due to lower thickness. Their different material properties did not lead to significant changes in a thermal resistance. However, for a given assortment, the thermal resistance value is sufficient. A thermal effusivity is the only parameter that characterizes the thermal effect and determines the ability to preserve or disperse heat through the weft knitted fabric. The highest value of thermal effusivity was measured for samples 3, 4 and the lowest for samples 5, 8, 10. Then samples 3, 4 appear as cold for touch and samples 5, 8, 10 as warmer for touch. Figure 3 and 4 shows a correlation dependency between the observed properties. Again, it has been confirmed, that the increasing the thickness and drop in specific density leads to the increase in the thermal resistance of the weft knitted fabrics [6]. In that case, weft knitted fabrics which have a greater thickness and smaller specific density will be appropriate thermal insulators.

Table 2. The results of thermal insulation properties on device C-Therm TCi.

| Sample | Thermal effusivity $e$ (W s$^{1/2}$ m$^{-2}$ K$^{-1}$) | Thermal conductivity $k$ (W m$^{-1}$ K$^{-1}$) | Thickness $h$ (mm) | Thermal resistance $R_{ct}$ (K m$^2$ W$^{-1}$) |
|--------|------------------------------------------------------|-----------------------------------------------|-------------------|-----------------------------------------------|
| 1      | 167                                                  | 0.08                                          | 0.92              | 0.0115                                        |
| 2      | 163                                                  | 0.08                                          | 0.90              | 0.0113                                        |
| 3      | 209                                                  | 0.10                                          | 0.66              | 0.0066                                        |
| 4      | 204                                                  | 0.10                                          | 0.59              | 0.0059                                        |
| 5      | 140                                                  | 0.07                                          | 0.37              | 0.0053                                        |
| 6      | 180                                                  | 0.09                                          | 0.55              | 0.0061                                        |
| 7      | 168                                                  | 0.08                                          | 0.97              | 0.0121                                        |
| 8      | 149                                                  | 0.08                                          | 1.40              | 0.0175                                        |
| 9      | 169                                                  | 0.08                                          | 1.57              | 0.0196                                        |
| 10     | 154                                                  | 0.08                                          | 1.21              | 0.0151                                        |

![Figure 3](image3.png) **Figure 3.** Dependence of thermal resistance on thickness.

![Figure 4](image4.png) **Figure 4.** Dependence of the thermal resistance on specific density.

3.2. Dynamic transfer of the liquid moisture of weft knitted fabric

Table 3 shows the results of measured indicators in tested of weft knitted fabrics on face and reverse side. The liquid moisture transmission rate through any clothing item depends on moisture content of the fabric, type of material used, perspiration rate, atmospheric stimuli like temperature, wind speed and relative humidity. Figures 6–8 shows the summary results of some measurement results such as: a water absorption rate, a maximum wetted radius, a spreading speed on the knitted fabrics.
Table 3. Average values dynamic transfer of liquid moisture (T is face sides, B is reverse sides).

| Sample | $W_t$ (s) | $A_r$ (% s$^{-1}$) | $M_{WT}$ (mm) | $S_r$ (mms$^{-1}$) | OWTC index (%) | OMMC (-) |
|--------|----------|------------------|--------------|-----------------|---------------|---------|
|        | T        | B                | T            | B               | T             | B       |
| 1      | 9.36     | 120              | 74.49        | 0               | 19            | 0       | 1.91  | 0   | 820.73 | 0  |
| 2      | 12.28    | 56.97            | 60.16        | 2.96            | 12            | 5       | 0.75  | 0.17| 363.15 | 0.35|
| 3      | 7.82     | 6.60             | 49.42        | 55.26           | 11            | 12      | 1.52  | 1.77| 58.04  | 0.33|
| 4      | 3.07     | 25.14            | 44.82        | 3.21            | 20            | 5       | 4.20  | 0.24| 659.99 | 0.50|
| 5      | 2.47     | 2.45             | 43.92        | 57.45           | 29            | 29      | 6.66  | 6.89| 282.86 | 0.75|
| 6      | 26.09    | 26.16            | 38.49        | 44.92           | 20            | 20      | 4.03  | 3.99| 132.53 | 0.51|
| 7      | 4.77     | 4.83             | 34.87        | 45.36           | 15            | 15      | 2.33  | 2.34| 127.05 | 0.41|
| 8      | 3.37     | 3.82             | 26.11        | 42.63           | 17            | 16      | 2.96  | 2.63| 237.78 | 0.55|
| 9      | 26.18    | 22.52            | 64.89        | 11.45           | 5             | 5       | 0.46  | 0.65| 746.33 | 0.52|
| 10     | 11.87    | 9.02             | 121.13       | 5.10            | 5             | 10      | 0.44  | 1.13| 1390.15 | 0.52|

Figure 5 shows content liquid moisture on face (T) and reverse (B) sides of the knitted fabric (one of five measurement). The exposure time was 120 seconds. Samples 5, 6 have got the smallest thickness, the highest wettability and a high diffusion capability. These samples are made of polyester and will rapidly disperse moisture. The difference was also in the wettability between the face (T) and the reverse (B) side of the weft knitted fabrics.

Figure 6 shows the rate of liquid moisture absorption measured from the face and reverse of side. Samples 1, 2, 4, 9 and 10 had and low or zero liquid moisture absorption rates from back side. This suggests that the water spreads faster through the front side of the knitted fabric (minimum through the
back side of the knitted fabric). Samples 1, 2 are weatherproof breathable layer knitted fabrics. They contain a special waterproof membrane that will not transport of liquid moisture but vapour yes. The rate absorption surface should be low, but the measurements did not confirm it (as seen in figure 5). More liquid moisture passes through back sides of samples 3, 5, 6, 7, 8, 4, 10. This is advantageous for a direction of sweat dissipation from the skin through a knitted fabric to the environment or another clothing layer. These values are defined as a maximum wetting radius. This is the maximum radius of wetting area at the end of given time when the knitted fabric begins to penetrate. Samples 3 and 5 (with reverse side) received the most liquid moisture in the short time.

Figure 7 shows the maximum wetting radius measured on both sides of knitted fabrics. Samples 3, 5, 6, 7, 8, 9 had approximately the same wetting radius on both sides, except for samples 1, 2, 4, 10. Samples 5, 6 had a higher wetting radius compared to other samples, as can be seen on the figure 5. Fig. 8 shows the radial dissipated of liquid moisture $S_s$ on the face and reverse of the knitted fabrics surface to reach the maximum radius. Moisture in samples 5, 6 passed fastest and equally on both sides. The sample 9 had the smallest values among all the knitted fabrics. Sample 1 dissipated liquid moisture only through the face side. The same happened in the sample 2, but to a smaller extent. In both cases, it would be preferable if these samples received liquid moisture from the reverse sides.

Based on MMT measurements, weft knitted fabrics was classified into 7 types (table 4) [2]. Sample 1 has a waterproof effect and therefore has been correctly classified in step in degrees 1 based on measurements. Classification of sample 2 to a degree 6 shows, that the layered knitted fabrics with protective membrane in the middle section does not meet the basic requirements. Other weft knitted
Fabrics (except sample 3) were classified in degrees 6 and 7. This weft knitted fabrics will be suitable for a penetration or a controlled liquid water penetration.

Table 4. Classification in degrees of waterproof.

| Degrees | Sample | Name of degree                        |
|---------|--------|---------------------------------------|
| 1       | 1      | Waterproof textile                    |
| 2       | -      | Water repellent textile               |
| 3       | 3      | Slow absorbing and slowly drying textile |
| 4       | -      | Fast absorbing and slowly drying textile |
| 5       | -      | Fast absorbing and fast-drying textile |
| 6       | 2, 4, 9, 10 | Fabrics with a water penetration textile |
| 7       | 5, 6, 7, 8 | Moisture control textile              |

4. Conclusion
In the work, the thermo-physiological properties of the weft knitted fabrics assortment, such as a different thicknesses, a material composition and a different structure and a usage, were measured. The thermal conductivity and thermal effusivity were measured on the C-Therm TCi device. From the results of thermal conductivity test and from the thickness measurements, the values of thermal resistance of weft knitted fabrics were recalculated. Plush weft knitted fabric (samples 8, 9, 10) had the best thermal insulation properties due to higher thickness and its knitted structure. The material composition of weft knitted fabrics did not have an impact on improving the thermal insulation properties. The influence of thickness and specific density on the changes of thermal insulating properties is significant. The transfer of the liquid moisture properties of weft knitted fabrics were measured by using the Moisture Management Tester (MMT). Measurement values were classified by software. It can be evaluated together, that weft knitted fabrics which are made of polyester and with interlock structure will have the best of the liquid moisture properties. Variable results of measurements samples 1 and 2 on the MMT showed the inappropriateness of using this measurement method. Interlock knitted fabric with 100% polyester (sample 5) will be the best fastest and most intensive to dynamic transfer of the liquid moisture. Has been confirmed that individual weft knitted structures and materials have to be combined in different parts of the clothing to achieve necessary thermo-physiological comfort.

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