# THERMAL PROPERTIES OF DIRECTIONALLY ORIENTED POLYMER FIBROUS MATERIALS AS A FUNCTION OF FIBRE ARRANGEMENT AT MESOSCOPIC LEVEL

***Snežana B. STANKOVIC[1*], Dušan POPOVIĆ[2], Goran B. POPARIĆ[2]***

[1]University of Belgrade, Textile Engineering Department, Faculty of Technology and Metallurgy, Belgrade, Serbia
[2]University of Belgrade, Faculty of Physics, Belgrade, Serbia

*Corresponding author E-mail: stankovic@tmf.bg.ac.rs

*Thermal properties of directionally oriented fibrous materials have been investigated in this research with the purpose of considering the influence of fibre arrangement at mesoscopic level. The range of various distributions of fibres in the fibrous materials was obtained by applying different twist intensity during spinning of cotton fibres. From various twisted cotton yarns the knitted fabrics were produced under controlled conditions, so as to obtain as similar as possible constructions. This made possible to obtain the heterogeneity of the porous fibrous structures coming from the mesoscopic level. Thermal conductivity and heat transfer coefficient of the materials were investigated. The results obtained indicate the arrangement of fibres (or their compactness, orientation and migration), which, in turn, was determined by twist intensity (mesoscopic scale), as the key factor influencing thermal properties. Yarn compactness and fibre migration, determined by lateral forces imposed by the twist inserted in yarn, affected variations in structural parameters of the knitted fabrics, and thus influenced their thermal properties. Fibre orientation manifested itself in surface geometry of the yarn was also proved to have a considerable influence on heat transfer properties.*

*Key words: textile material, thermal conductivity, fibre arrangement, knitted fabric, yarn twist, air permeability*

## 1. Introduction

Textile materials are a type of porous fibrous polymer materials with various purposes such as conventional (decoration, protection and function), and specific applications in various industries, medicine, etc. Conventional textile fabrics are usually planar sheets characterized by a small transverse dimension (thickness). In spite of this fact, the arrangement of fibres in textile structure is hierarchical (multi-layered) whatever the formation techniques (weaving, knitting, braiding and netting) – microscopic level (fibres), mesoscopic level (intermediate) and macroscopic level (fabric). The internal structure of a fabric is responsible to a large extent for its properties. Starting from the fibre packing formats the geometry of the fabric is developed which determines its (energy and mass) transport properties. When fibres are assembled by nonwoven systems, such as needle punching, spinlacing, spunbonding or stitch bonding, a mat or web is formed as an intermediate product consisting of layers with randomly oriented fibres which are bonded together by mechanical, chemical or heat treatments forming the nonwoven fabric-like structure. Such hierarchical structure is similar to the morphology of silk cocoons formed by randomly oriented continuous fibroin fibres bonded by silk gum (sericin) [1, 2]. On the other hand, woven and knitted fabrics are porous fibrous systems with oriented distribution of fibres into yarns (mesoscopic level). Generally, yarn is a single yarn fibre bundle obtained by spinning process. Fibres are directionally oriented with an angle relative to yarn axis coming from a twist that gives cohesion to the yarn. Yarns are incorporated into woven fabric in the way that the warp (lengthwise) and weft (widthwise) yarns are tightly interlaced, or looped continuously to form stitches interlocked together in knitted fabric.

In thermal aspect, textile materials are widely used in protective clothing such as fire-fighters' uniform, in building thermal insulation and various insulating composite materials. In addition, thermal properties of textile materials have always been the focus of numerous studies concerned with clothing comfort, since clothing should ensure appropriate heat transfer between the human body and its environment in order to maintain the physiological thermal balance of the wearer. This investigation deals with the thermal properties of directionally oriented polymer fibrous systems in the form of knitted fabrics.

The heat transfer process in porous fibrous materials is a very complex phenomenon which generally involves all three transport mechanisms: conduction, convection and radiation. The complexity of the phenomena comes from the fact that the heat transfer in porous fibrous material is closely related to the material's porous structure such as the pore numbers, sizes and distributions. The arrangement of fibres in porous fibrous material determines the pore character: open pores (among yarns) and capillaries (among fibres in yarns), thus affecting heat transfer phenomena across the material.

Thermal properties of porous textile materials have drawn the attention of many scientists from the thirties of the 20th century to nowadays. Most of the investigations refer to the correlation between the structure of textile materials and the heat transfer ability. Their results lead to the general conclusion that heat transfer through a clothing material is affected by numerous factors such as thickness [3-9], porosity [8-11] and surface density [5, 10, 12, 13]. It is also generally agreed that heat transfer characteristics of a textile material are much more influenced by the fabric's structure than the fibre conductivity. The contribution of fibre conductivity to the fabric thermal conductivity is relatively small as a consequence of interconnected air spaces into fabric's structure. Furthermore, some investigations indicated that the thermal properties of fabrics are determined by fibre arrangement [10, 14]. Some other investigations [6, 10, 14-16] demonstrated that fibre properties such as fineness and elastic properties have a great influence on the thermal properties of textile fabrics as these properties of fibres are responsible for their arrangement. The results coming from the investigations [17-27] indicated the packing density of a yarn, which in turn was influenced by fibre geometry and spinning technique as an extremely important parameter influencing thermal behaviour of textile materials. Although fibre arrangement is also dependent on yarn basic characteristics (linear density, twist), there are very few number of investigations concerned with the relationship between the structure heterogeneity at mesoscopic level and heat transfer through the fabric. Majumdar et al. [23], Prakash et al. [24], Afzal et al. [13, 25] and Gupta et al. [26] investigated the influence of yarn linear density on the thermal properties of knitted fabrics. In addition to yarn linear density, Ozdil et al. [27] have also presented some results of the influence of yarn twist on the thermal behaviour of knitted fabrics. To the best of authors' knowledge, this is the only research concerned with the influence of yarn twist on the thermal properties of directionally oriented fibrous materials. Bearing in mind this serious lack of results, in the presented paper the influence of yarn twist on fibre distribution throughout the fabric and consequently, on its thermal properties was investigated. Apart from the arrangement of fibres in the yarn core, their migration and orientation on the yarn surface was also analysed in the study.

### 1.1. Effect of fibre arrangement

The simplest oriented distribution of fibres is that of a continuous-filament yarn where fibres (continuous filaments) are typically arranged in a parallel and straight form. In short-fibre yarn, the fibre arrangement is quite different from the simple arrangement of continuous fibre. The discrete nature of short fibres makes it difficult to control the fibre flow, thus a well-defined fibre arrangement is extremely difficult to obtain. In addition, the spinning of short fibres can result in many modes of fibre mobility influencing their arrangement. The inevitable phenomenon of the short-fibre yarn is the existence of fibre segments protruding from the yarn body, so-called "yarn hairiness". In general, when a woven or knitted porous structure is produced, the directional distribution of fibres (parallel to the fabric surface) still remains with the fibre segments protruding from the fabric surface.

Although all three mechanisms (conduction, convection and radiation) coexist in the heat transfer process through porous fibrous textiles, it is generally accepted that heat transfer by conduction is more significant than others. The effect of radiation through textile material is quite negligible at common ambient temperatures. Whatever the structure of fibrous material (weaved or knitted) its thermal conductivity is a combination of the fibre and air thermal conductivity. The air immobilized into yarn (capillaries) behaves as an insulating medium. Finck [28] demonstrated that the fibres arranged parallel to the direction of heat flow exhibit two- to three-fold greater thermal conductivity than that of perpendicularly arranged fibre assemblies of equal bulk density. For a textile material in which the fibres are arranged parallel to the heat flow, the thermal conductivity is $\lambda = v_f \cdot \lambda_f + v_a \cdot \lambda_a$, where $\lambda_f$ and $\lambda_a$ are the thermal conductivities of fibre and air, respectively, and $v_f$ and $v_a$ are the corresponding volume fractions of each component ($v_f + v_a = 1$). In such an arrangement the fibre thermal conductivity makes the largest contribution to the overall thermal conductivity of the assembly. For short-fibre fabrics, this type of arrangement corresponds to one with the fibres protruding from the fabric surface. However, most fibres are parallel to the plane of the fabric surface i.e. perpendicular to the direction of heat flow. The perpendicular fibres contribute a less amount to the overall thermal conductivity of the fabric because of an insulating air layer between each fibre element. In general, the thermal conductivity of a staple-fibre fabric is given by the eq. (1):

$$\lambda = x\left(\nu_f \cdot \lambda_f + \nu_a \cdot \lambda_a\right) + y\frac{\lambda_f \cdot \lambda_a}{\nu_f \lambda_f + \nu_a \cdot \lambda_a} \qquad (1)$$

where $x$ and $y$ are the effective fractions of fibres parallel and perpendicular to the direction of heat flow, respectively (x+y=1). The second addend of the relation refers to the assembly in which the fibres are arranged perpendicular to the direction of heat flow [14].

In addition to fibre geometry, the arrangement of fibres in yarn is also determined by the spinning technique. It is well known that yarn produced by conventional (ring spinning) technique has a compact core structure and a more or less hairy surface. Unlike ring-spun yarn, that produced by rotor (open-end, OE) spinning technique is characterised by three layer structure: truly twisted core fibres, partially twisted outer layer and belt fibres wrapped around the yarn. The surface of OE yarn is consisted mainly of fibre loops and loose fibres, also having fewer fibre ends than ring-spun yarns, and therefore may sometimes be regarded as having more hairy appearance in relation to ring-spun yarns [29]. Figure 1 represents Scanning electron micrograph (SEM) of the structure of the highest twisted cotton OE yarn used in this investigation. As can be seen in the picture, belt fibres (some of them are indicated in the picture with white arrows) are arranged perpendicular to the yarn axis as well as the knitted fabric surface. Bearing in mind that yarn axis is parallel to the plane of the knitted fabric surface, it is reasonable to believe that wrapped fibres are mainly parallel to the direction of heat flow contributing to an improvement in thermal conductivity. SEM of the OE cotton yarn also illustrates the geometry of fibre loops in which at least some segments are parallel to heat flow.

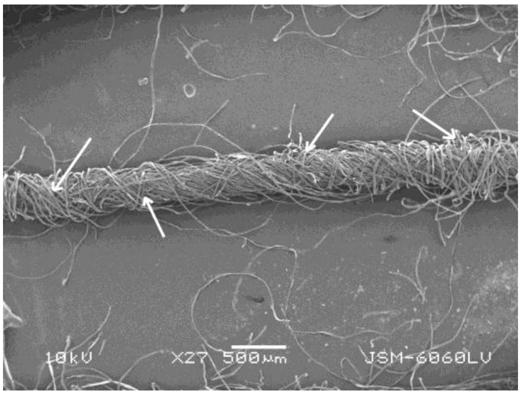


**Figure 1. SEM illustrating structure of cotton OE yarn designated as Co3 (the highest twist level)**

## 2. Experimental

Three variants of yarns, all having the same nominal linear density 50 tex, were produced by OE spinning technique with the same cotton fibre and different twist levels (490, 590 and 690 t/m). From these yarns three plain knitted fabrics were produced on a circular knitting machine under the same knitting conditions in order to obtain identical structures. The arrangement of cotton fibres was indicated by the geometry of both core and surface of the yarns which were characterised by parameters such as factual linear density, yarn diameter, bulk density, packing factor and yarn hairiness. Factual values of linear density of the cotton yarns were determined in accordance with ISO 2060:1994 (Textiles – Yarns from Packages – Determination of Linear Density (mass per unit length) by Skein Method). Diameter of the yarns was determined using Nikon SMZ800 microscope. Since yarn diameter is never uniform, for each yarn 50 readings were taken and average diameter was calculated. Bulk density of the yarns was calculated using their diameter and linear density. Packing density of the yarns, defined as the fibre volume fraction in a unit length of yarn, was calculated by dividing bulk density of the yarns by fibre density. Hairiness (protruding fibres) of the yarns was measured using the Shirley Yarn Hairiness Monitor. The hairiness was registered on travelling yarn samples in 5 second intervals and later was reduced to 1m of yarn length.

Stitch density, surface density (mass per unit area) and stitch moduli (planar and volume) of the knitted fabrics were determined according to procedure described in the literature [30]. Stitch density refers to the total number of loops in the area of 1 $cm^2$. Planar stitch modulus presents the relationship between the area of a stitch and the area occupied by the yarn within the stitch, and indicates the interstitial pore size. Volume stitch modulus indicates the ratio between the volume of a rectangular solid outlining a stitch and the volume occupied by the yarn within the stitch. Thickness of the knitted fabrics was measured according to ISO 5084:1996 (Textiles – Determination of thickness of textiles and textile products). Bulk density of the knitted fabrics $\rho_k$ [g $cm^{-3}$] was calculated by dividing their surface density (mass per unit area) by thickness. Total porosity of the knitted fabrics, $P$ [%], defined as the portion of all air spaces in knitted fabric both between yarns and inside them, was calculated as $P$=100–($\rho_k/\rho_f$)·100, where $\rho_f$ [g $cm^{-3}$] is the fibre density. Open porosity, $O$ [%], expressing the portion of air spaces between yarns was calculated as $O$=100–($\rho_k/\rho_y$)·100, where $\rho_y$ [g $cm^{-3}$] is the bulk density of the yarn.

Air permeability of the knitted fabrics, defined as the volume of air measured in cubic meters passed per minute through a square meter of fabric at a constant pressure [$m^3/m^2$ min], was measured according to standard procedure (ISO 9273:1995, Textiles – Determination of the permeability of fabrics to air). Thermal properties of the knitted fabrics were determined using the experimental set-up designed to provide measuring of the cooling rate of a solid body heated to a preset temperature and isolated from the ambient medium by the fabric. The method, which is described in detail elsewhere [19], is based on the principle that for two different media in series with respect to the direction of heat flow, the ratio of the temperature drop across the media is equal to the ratio of their thermal resistance. A cylindrical shape glass container is filled with water whose temperature is controlled by a commercial thermostatic system. The fabric is placed around the container and the rate of the system cooling is determined by measuring the temperature change with time. The ambient temperature is registered simultaneously. The same procedure is repeated without the fabric. By linear fitting of the curve obtained with cooling time t [s] along the abscissa and $\ln[(T-T_{amb})/(T_0-T_{amb})]$, were $T$ [K] is the temperature of the system at a particular moment, $T_0$ [K] is the initial temperature of the system and $T_{amb}$ [K] is the ambient temperature, along the ordinate (fig. 2), the cooling constant $K_1$ can be determined as $K_1=1/R_{k+a}\cdot C=1/(R_k+R_a)C$, where $C$ [J $K^{-1}$] is the thermal capacity of the system (glass container with water), $R_{k+a}$ [K $W^{-1}$] is the thermal resistance of both the fabric medium and the air medium around the fabric sample, $R_k$ [K $W^{-1}$] is the thermal resistance of the fabric layer, $R_a$ [K $W^{-1}$] is the thermal resistance of the air layer. The absolute thermal resistance of the fabric was calculated as $R_k=(1/C)\cdot(1/K_1-1/K_0)$, where $K_0$ is the cooling constant of the system without fabric. Knowing the absolute thermal resistance $R_k$ as well as the fabric sample area $S_k$ [$m^2$] and fabric thickness $t_f$ [m], the fabric thermal conductivity $\lambda_k$ [$Wm^{-1}K^{-1}$] is calculated as $\lambda_k=t_f/R_k\cdot S_k$.

Although the heat transfer coefficient, $h$ [$Wm^{-2}$ $K^{-1}$], refers to conduction, convection and radiation mechanisms, in general, the thermal parameter range applied in this experiment caused this parameter to cover heat transfer by conduction and convection through the knitted fabrics. The heat transfer coefficient was calculated as $h=(1/S_k\cdot\Delta T)\cdot dQ/dt$, where $dQ/dt$ [W] is the heat flow, and $\Delta T$

[K] is the difference between the average temperature of the system and the ambient temperature. Both yarn and knitted fabric specimens were conditioned and all tests were performed under the standard atmospheric conditions.

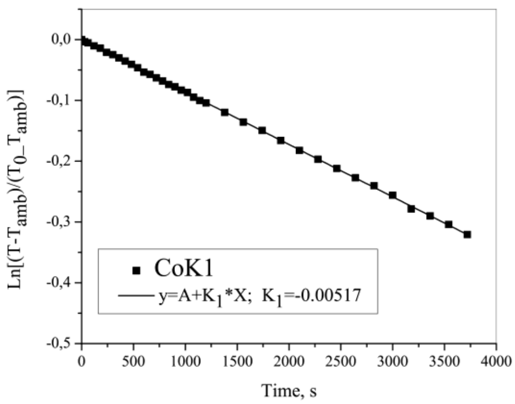


**Figure 2. Cooling line and cooling constant ($K_1$) of the CoK1 knitted fabric**

The influence of twist level on air permeability and thermal conductivity of the knitted fabrics was assessed for significance using ANOVA analysis. In ANOVA, the F-ratio is the statistic used to test the hypothesis that the effects are real.

By comparing the obtained F-ratio with the F-ratio predicted by the model of no effects, a decision on the reality of effects can be made. When the obtained F-ratio was greater than the critical F-ratio, provided the probability value was less than 0.05 (confidence level 95%), the decision is that the effect is real. Two-sample student's t-test procedure is used to compare the means of the absolute thermal resistance for the three comparisons (CoK1 vs. CoK2, CoK2 vs. CoK3 and CoK1 vs. CoK3). Generally, when the probability value (p) is less than 0.05, the evidence to reject the null hypothesis of equal means is provided.

## 3. Results and discussion

### 3.1. Properties of the cotton yarns and knitted fabrics

As a consequence of different twist intensity applied on the cotton yarns, they exhibited slight differences in linear density (tab. 1.). However, the differences in their diameters are more distinct as it is expected since the increase of twist intensity always means the reduction of air spaces among fibres or the increase of yarn compactness manifested itself in a lower diameter. In addition to the diameter reduction, bulk density and packing factor of the yarns were increased with twist intensity, also indicating closer arrangement of the fibres (tab. 1.). Besides the core compactness, yarn surface geometry is also influenced by introduced twist level [31-32]. Among the cotton yarns used, Co2 yarn having medium twist intensity was characterised by the highest hairiness (protruding fibres) (tab. 1.).

It is known that the heterogeneity of weaved or knitted porous fibrous material comes from fibre variability, especially natural fibre variability, specific yarn structure and material structure. The diversity of geometry (length, fineness) and morphology, even if the fibres are from the same bale is inevitable, and therefore slight non-uniformity in textile structures can be expected. Since the knitted fabrics were produced with constant machine settings, some differences in their construction characteristics (tab. 2.) originated from different fibre aggregation at mesoscopic level (yarn structure). The increased stitch density of CoK2 knit was the consequence of distortion which resulted from the residual torque in the yarn due to an increase in twist. The further increase in twist caused an increase in bending stiffness of the highest twisted cotton yarn (Co3). This resulted in a decrease in knitting barrier and the knit made of the highest twisted yarn (CoK3) was characterised by less stitch density in relation to CoK2 knit. The highest diameter of Co1 yarn should lead to the highest thickness of the CoK1 knit, however, due to the loops' distortion in the CoK2 and CoK3 knits they were characterized by slightly increased thickness (tab. 2.). Surface density of the knitted fabrics was in accordance with their stitch density.

**Table 1. Characteristics of the cotton yarns**

| Parameter, unit | Co1 | Co2 | Co3 |
|---|---|---|---|
| Linear density (tex) | 48.94 | 48.08 | 49.06 |
| Twist (t/m) | 490 | 590 | 690 |
| Diameter (mm) | 0.340 | 0.295 | 0.248 |
| Bulk density (g/cm$^3$) | 0.539 | 0.703 | 1.016 |
| Packing factor | 0.36 | 0.47 | 0.68 |
| Hairiness (m$^{-1}$) | 14.8 | 19.3 | 13.2 |

Fibre aggregation within a more compact structure of Co2 and Co3 yarns, which means less space filled with air, caused the increase of bulk density of the CoK2 and CoK3 knitted fabrics (tab. 2.). In addition to differences in bulk density of the knits, the yarn aggregation into a highly packed knitted structure resulted in lower porosity of the CoK2 and CoK3 knits. On the other hand, the effectiveness of fibre packing in the yarns, which in turn was influenced by twist intensity, influenced the air volume distribution within the knitted fabrics. The highest packing density of Co3 yarn having the lowest diameter caused the CoK3 knit to be by far the most open (tab. 2.). The lowest twisted cotton yarn, which was characterised by the highest diameter and the lowest packing factor, influenced the lowest open porosity of the CoK1 knit.

**Table 2. Construction characteristics and physical properties of the plain knitted fabrics**

| Parameter, unit | CoK1 | CoK2 | CoK3 |
|---|---|---|---|
| Stitch density (cm$^{-2}$) | 72 | 81 | 78 |
| Thickness (mm) | 1.183 | 1.191 | 1.211 |
| Surface density (g/m$^2$) | 387.3 | 430.0 | 423.6 |
| Bulk density (g/cm$^3$) | 0.327 | 0.361 | 0.350 |
| Porosity (%) | 78.2 | 75.9 | 76.6 |
| Open porosity (%) | 39.3 | 48.6 | 67.0 |

It has been reported that the air permeability is one of the most important property of both randomly and directionally oriented fibrous materials. The key parameter influencing this property is porosity of the fabric. In nonwoven fabric, it is about the micro-pores arranged in random manner through the individual layers during their consolidation. Fibre diameter, and thickness and density of nonwoven structure are to the most extent responsible for the micro-pore distribution across the fabric [33, 34]. In woven and knitted fabrics, a governing factor for air permeability is the macro-porosity since the passage of air through a fabric mainly takes place between yarn interstices. In addition to macro or open porosity, the size of the pores and the number of pores per unit area has a significant influence on air permeability of the fabric [10, 35]. These parameters of fabric geometry are correlated to diameter of yarn and its length in the fabric unit area [36].

Open porosity of the knitted fabrics given in tab. 2 expresses the total amount of interstitial space (air spaces between yarns) but does not indicate the distribution of interstitial space within the fabric. Therefore, the air permeability of the knitted fabrics was determined to assess the interstitial space distribution. According to the results presented in fig. 3, the CoK3 knitted fabric was the most permeable. Knitted fabric produced from the medium twisted cotton yarn, although having medium open porosity (tab. 2.), was characterised by the lowest air permeability. It should be noted here that ANOVA test results confirmed a significant difference among the knitted fabrics with respect to air permeability [$F(24.64) > F_{crit}(3.88)$; $P(5.6E\text{-}05) < \alpha(0.05)$]. Bearing in mind the fact that smaller open pores are more resistant to air flow [35], the lowest air permeability of CoK2 knit is an indication of the reduced size of its interstitial pores. To quantify this, the planar stitch modulus was chosen to calculate. The lower value of planar stitch modulus expresses more compact fabric structure i.e. the reduced size of the interstitial pores. The values of planar stitch modulus for the knitted fabrics are presented in fig. 3. The analogy between the planar stitch modulus and air permeability of the knitted fabrics was confirmed by extremely high correlation coefficient ($r$ = 0.97). Apart from to the lowest air permeability, CoK2 knitted fabric was characterised by the lowest planar stitch modulus. The highest planar stitch modulus of CoK3 knitted fabric together with its highest air permeability indicated the highest size of open pores within this knit.

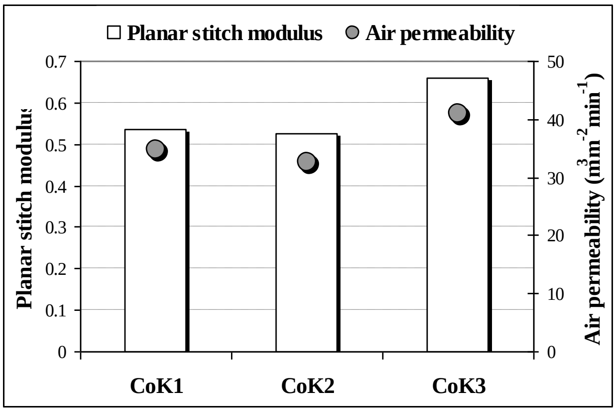


**Figure 3. Planar stitch modulus and air permeability of the knitted fabrics**

## 3.2. Thermal properties of the knitted fabrics

Since knitted fabrics generally characterised by more open structure than woven fabrics, convective heat transfer through knitted fabrics can be important. However, in spite of a loose structure of OE cotton yarn from which the knitted fabrics were produced, the conduction by fibres was considered to be a dominant heat transfer mode for at least two reasons. High covering power of OE yarns prevents heat transfer through the open pores by convection mechanism. In addition, the belt fibres typical for OE yarns (fig. 1.) were expected to make a large contribution to the heat transfer by conduction due to their parallel arrangement to the heat flow. Even in the case of CoK3 knitted fabric with the largest open pores, which was proved by planar stitch modulus and air permeability, the conduction of heat was believed to be predominant due to the highest bulk density and numerous belt fibres of the highest twisted cotton yarn (fig. 1.).

The results of thermal properties of the knitted fabrics are presented in tab. 3. CoK1 knitted fabric exhibited the lowest thermal conductivity, as we expected, since the lowest twisted cotton yarn (Co1) was characterised by the highest amount of air immobilized among fibres (the lowest bulk density and packing factor). The close structure of CoK1 knit due to the lowest packing density of Co1 yarn, manifesting itself through the lowest air permeability, could not have increased heat transfer by convection, therefore the CoK1 knitted fabric was characterised by the lowest heat transfer coefficient (tab. 3).

**Table 3. Thermal properties of the plain knitted fabrics**

| Parameter, unit | CoK1 | CoK2 | CoK3 |
|---|---|---|---|
| Absolute thermal resistance ($KW^{-1}$) | 0.81±0.08 | 0.39±0.04 | 0.42±0.04 |
| Thermal conductivity (W/m K) | 0.026±0.002 | 0.054±0.004 | 0.052±0.004 |
| Heat transfer coefficient ($W/m^2$ K) | 22±1 | 45±3 | 43±3 |

An increase in bulk density of the cotton yarns with an increase in twist intensity should lead to an increase in thermal conductivity as a consequence of more intimate contact between fibres. With the increase of about 30% in bulk density of the cotton yarn (Co2 yarn in relation to Co1 yarn), the thermal conductivity of the knitted fabric (CoK2) was doubled. However, the thermal conductivity of CoK3 knitted fabric produced from the highest twisted cotton yarn does not differ from the previous one (CoK2) despite Co3 yarn being denser (about 44%) than Co2 yarn. Although the ANOVA statistics confirmed a real effect of yarn twist on the measured values of absolute thermal resistance of the knits [$F(47.1) > F_{crit}(5.14)$; $P(2.2E\text{-}04) < \alpha(0.05)$], it is confirmed by two-sample student's t-test computed for the three comparisons (CoK1 vs. CoK2, CoK2 vs. CoK3 and CoK1 vs. CoK3) that the difference came from the values of absolute thermal resistance of CoK1 knit. T-test results (tab. 4.) proved that there was no difference between CoK2 and CoK3 knitted fabrics.

**Table 4**. Two-sample student's t-test results.

| Parameter | CoK1 vs.CoK2 | CoK1 vs.CoK3 | CoK2 vs.CoK3 |
|---|---|---|---|
| p two-tail | 0.001* | 0.004* | 0.547 |
| T Stat | 7.814 | 7.849 | 0.657 |
| T Critical | 2.776 | 3.182 | 2.776 |

*Statistically significant ($p < 0.05$)

In order to analyse such thermal behaviour of the knits, the volume stitch modulus was calculated. A higher value of volume stitch modulus indicates the structure with less volume within one stitch filled with yarn. In addition to the construction of a knitted fabric, the volume stitch modulus is a direct consequence of the yarn diameter. Due to the lowest diameter of the highest twisted cotton yarn, CoK3 knitted fabrics was characterised by the highest volume stitch modulus (fig. 4.). The highest volume stitch modulus of CoK3 knit together with the highest bulk density of Co3 yarn is in accordance with the thermal conductivity which is higher than that of CoK1 knit (fig.

4.). Bearing this in mind, the thermal conductivity of CoK2 knitted fabric seems to be surprisingly high. With the volume stitch modulus of CoK2 knit and bulk density of the medium twisted cotton yarn, the thermal conductivity of CoK2 knit should be between the two other knits rather than being similar to CoK3 knitted fabric. We believe that this can be explained by the higher stitch density of the CoK2 knit, which in turn was affected by Co2 yarn twist. The highest stitch density of the CoK2 knit means the highest number of interlocking points (where the yarn segments are flattened) per unit area of the knit due to which the amount of air between the fibres in Co2 yarn is reduced. The effect of yarn flattening was more pronounced in CoK2 knit in relation to CoK3 knit due to the lower packing density of the Co2 yarn. It seems reasonable to believe that the reduced amount of air immobilized in the Co2 yarn contributed to an increase in thermal conductivity of the CoK2 knitted fabric.

The fact that CoK2 knitted fabric exhibited thermal conductivity at the level of CoK3 knit may also be explained by the surface geometry of the cotton yarns. The hairiest surface of Co2 cotton yarn (or the largest number of protruding fibres, tab. 1.) could also be a factor responsible for conducting heat more efficiently according to the eq. (1). This is in accordance with the finding of Kawabata that the thermal conductivity of a single fibre along its axis is about ten times higher than the conductivity across the fibre width [37]. Therefore, it seems reasonable to believe that fibre segments protruding from the hairiest surface of the medium twisted cotton yarn, which are parallel to the heat flux, certainly contribute to the overall thermal conductivity of CoK2 knitted fabric. It should be noted that when commercially available devices for measuring thermal properties of textile fabrics, which are based on the principle that a textile sample is positioned between two plates (one of which is heated), are applied, the fibres protruding from the surface bend under even very low pressure changing their orientation. Being previously arranged parallel to the direction of heat flow, the fibres become perpendicularly oriented to the direction of heat flow resulting in an overall thermal conductivity reduction. Since the experimental set-up used in this investigation is based on the principle of heated plate with a textile sample added, the protruding fibres bend only on one side of the sample, whereas the fibres protruding from the other sample's side can contribute greatly to the conduction of heat.

Although CoK2 and CoK3 knitted fabrics differed in planar stitch modulus and air permeability, indicating the different size of open pores, the overall heat transfer coefficient for both knits was at the same level (tab. 3.). These facts indicated the conduction mechanism as the main heat transfer mode. Our hypothesis about the efficiency of thermal conductance of the highest twisted cotton yarn seems to be confirmed.

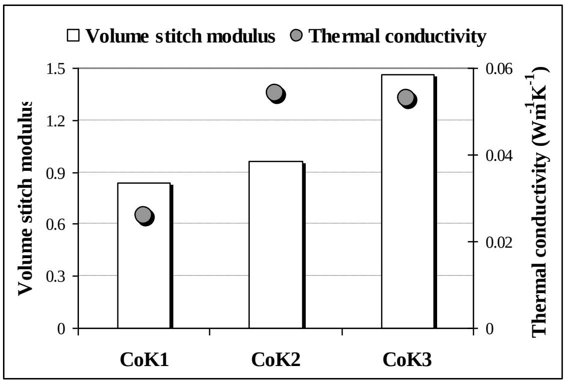


**Figure 4. Volume stitch modulus and thermal conductivity of the knitted fabrics**

## 4. Conclusion

Thanks to the fact that the knitted structures were produced under controlled conditions so as to obtain as similar as possible construction characteristics, it was possible to investigate the impact of heterogeneity coming from the fibre aggregation at the mesoscopic level (yarn structure) on their heat transfer properties. Thanks to the specific structure of rotor - spun yarn (high covering power of the yarn with belt fibres arranged parallel to the heat flow), the conduction mechanism is hastened making it easier to analyse the thermal behaviour of knitted fabrics. The effectiveness of fibre aggregation (arrangement, compactness and migration) in a yarn, which resulted from the twist level and manifested itself in yarn's diameter and bulk density values (packing factor), influenced thermal behaviour of the fabric through the determination of its primary (thickness, stitch density, surface density) and secondary (bulk density, porosity, open porosity, planar stitch modulus, volume stitch modulus) structural parameters. The geometry of yarn surface was also developed as a consequence of twist level introduced, thus determining the specific fibre orientation, i.e. the yarn hairiness, responsible for an increase in thermal conductivity of the fabric.

In conclusion, it can be said with certainty that fibre arrangement, which is the consequence of twist intensity in this research, is the parameter of great importance in terms of the engineering of directionally oriented textile materials (woven and knitted fabrics) in order to achieve desired thermal properties according to end use requirements (clothing textiles, thermal isolation materials, fabric-reinforced composite materials or other applications). Further research will include different yarn types with a wider range of twist intensity in order to obtain explicit guidelines for adequate design.

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