Investigation on Thermal Properties of Double-Layered Weft Knitted Fabrics

Asta BIVAINYTĖ [1], Daiva MIKUČIONIENĖ [1]*, Paulius KERPAUSKAS [2]

[1] *Department of Textile Technology, Kaunas University of Technology, Studentų 56, LT-51424 Kaunas, Lithuania*
[2] *Department of Heat and Biotechnology Engineering, University of Aleksandras Stulginskis, Studentu 15, LT-53362 Akademija, Kaunas d., Lithuania*

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It is known, that fibre type, yarn properties, fabric structure, finishing treatments and clothing conditions are the main factors affecting thermo-physiological comfort. The warmth of a fabric is due to insulation provided by air trapped between fibres and yarns. Fabrics from straight filament yarns remove heat rapidly by conduction when placed next to the skin and in such a way produce a so-called cool feel or handle. The objects of investigation were double-layered weft fabrics knitted from cotton or man-made bamboo yarns and synthetic PA (polyamide), PP (polypropylene), PES (polyester) threads combination in three different knitting patterns. 16 samples variations were used. Thermal conductivity and thermal resistance were determined. It was established that thermal properties of double-layered knitted fabrics depend on raw material, structural parameters and knitting pattern of the fabric. Thermal resistance increases when thickness of the fabric increases, and thermal conductivity coefficient increases when loop length of the fabric increases. The highest influence on thermal properties has the kind of knitting pattern.

Keywords: double-layered knitted fabric, thermal conductivity, thermal resistance.

INTRODUCTION

Consumers of textile and clothing products are becoming increasingly aware of the importance of the comfort. In addition to aesthetic appearance, the comfort is one of the main properties of clothing, which affects the choice of product. The term comfort is a subjective concept, which is recognised by the person experiencing it. It can be defined as a natural state compared to the more active state of pleasure. A state of comfort can only be achieved when the most complex interactions between a range of physiological, psychological and physical factors taken place in a satisfactory manner, i. e. clothing comfort includes three main considerations: thermo-physiological, sensorial and psychological comfort [1, 2]. The comfort provided by clothing depends on several factors, one of them being thermal comfort. It is known, the fibre type, yarn properties, fabric structure, finishing treatments and clothing conditions are the main factors affecting thermo-physiological comfort [2 – 4].

Clothing must assist the body's thermal control function under changing physical loads in such a way that the body's thermal and moisture management is balanced and a microclimate is created next to the skin [5]. This physiological effect is extremely important, especially in the case of clothing for sports and active leisure. Items of clothing with poor thermo-physiological wear characteristics not only detract from well-being of the human but also impair his/her physical performance and may even act as a health hazard. Human produces heat continuously inside his/her body during all his/her activities because of metabolic processes. With greater physical exertion, and thus a greater level of heat generated by the body itself, heat transfer through the clothing is insufficient to compensate for the body's energy balance. In this case, the human begin to sweat, the aim being to cool the body through evaporation of the sweat on the skin [5, 6].

Many researchers have conducted studies to evaluate and analyse thermal comfort of woven fabrics. They examined the effects of the fibre type and the fabric composition on thermal comfort. The fibre composition and the fabric structure were forecasted to affect the heat and moisture transfer properties of textiles. Studies of thermal wearing tests showed that fabric properties influenced the subjective wearing sensations and the microclimate inside the clothing; however, these effects varied with the environmental conditions or physical activity levels. Authors examined the effects of the fibre type and the fabric composition on thermal comfort. They found that thermal comfort of fabric was influenced by the thickness, water absorption properties, and thermal conductivity of the fabric [7]. Comparing knits manufactured from two pure yarns with those made from three pure yarns, it was found [8, 9] that the linear density increases, whereas the thermal resistance varies in different ways: the thermal resistance of pure knits and a combination with textured PA (polyamide) increase, and the thermal resistance of knits from a combination with Lycra thread decreases. Therefore, for a cold season the most comfortable would be knitted garments plated with textured PA thread. For the summer season, it is recommended knitted garments with pure natural yarns [9].

Human thermal comfort depends on a combination of clothing, climate, and physical activity. The basic heat transfer mechanisms (conduction, convection and radiation) are well known to anyone in engineering. All three heat transfer mechanisms coexist in the heat transfer process from a heated surface through a porous fabric attached onto it. In general, heat transfer from the heated

*Corresponding author. Tel.: +370-37-300219; fax.: +370-37-353989.
E-mail address: *daiva.mikucioniene@ktu.lt* (D. Mikučionienė)

body to the fabric takes place by convection, conduction and radiation concurrently [10].

The thermal resistance of clothing as a set of textile materials depends on the thickness and porosity of particular layer. Because changes in the porosity of standard textile materials used in clothing are not large, the total thermal resistance of clothing is influenced by the material thickness [10, 11]. The warmth of a fabric is due to insulation provided by air trapped between fibres and yarns. Fabrics from strain filament yarns remove heat rapidly by conduction when placed next to the skin. Fabrics from hairy yarns feel warm on contact with the skin due to the insulating air held between the fabric fibres and the skin [6].

However, investigations in the field of the thermal properties of double-layered weft knitted fabrics from combination of natural or man-made yarns in one layer with the synthetic threads in the other layer are very low.

The main goal of this work was to investigate the thermal properties, such as thermal conductivity coefficient and thermal resistance, of double-layered weft knitted fabrics from combination of cotton or man-made bamboo yarns in one layer with the PA (polyamide), PES (polyester), Coolmax® (tetra-channel fibres by DuPont), or PP (polypropylene) threads in other layer.

EXPERIMENTAL

Materials and methods. Investigations were carried out on the double-layered fabrics knitted in plain plating pattern and two types combined structure on a circular knitting machines in a gauge E 22 from cotton and man-made bamboo yarns in outer layer and PP, PA, PES, and Coolmax® (tetra-channel fibres by DuPont) threads in inner layer. Overall, 16 particular variants of knits were investigated. The characteristics of tested knitted fabrics are presented in Table 1, and the knitting structure – in Fig. 1.

All experiments were carried out in a standard atmosphere for testing according to the standard ISO 139:2005. Structure parameters of knitted samples were analysed according to the British Standard BS 5441:1998.

Table 1. Characteristics of tested knitted fabrics

Sample code	Pattern	Linear density of yarns and percentage composition	Course density, P_v, cm^{-1}	Wale density, P_h, cm^{-1}	Loop length, l, mm	Thickness, b, mm	Air permeability, dm^3/(m^2·s)
SJI-1	Plain plating	Cotton, 20 tex, 71 % PA, 7.8; 29 %	24.5	12.5	2.84	0.617	860
SJI-2	Plain plating	Cotton, 20 tex, 71 % Coolmax®, 7.8; 29 %	24.5	12.5	2.79	0.692	852
SJI-3	Plain plating	Cotton, 20 tex, 71 % PES, 8.3; 29 %	24.5	12.5	2.79	0.646	855
SJI-4	Plain plating	Cotton, 20 tex, 71 % PP, 8.4; 29%	25	12	2.88	0.661	899
SJII-1	Plain plating	Bamboo, 20 tex, 71% PA, 7.8; 29 %	24	12.5	2.85	0.524	896
SJII–2	Plain plating	Bamboo, 20 tex, 71 % Coolmax®, 7.8; 29 %	24	12.5	2.81	0.658	871
SJII–3	Plain plating	Bamboo, 20 tex, 71 % PES, 8.3; 29 %	24	12.5	2.81	0.566	881
SJII-4	Plain plating	Bamboo, 20 tex, 71 % PP, 8.4; 29 %	24.5	12	2.93	0.590	927
KI-1	Combined I (piquè)	Cotton, 20 tex, 71 % PA, 7.8; 29 %	16	12	3.11	0.908	863
KI-2	Combined I (piquè)	Cotton, 20 tex, 71 % Coolmax®, 7.8; 29 %	16	12	3.10	1.142	882
KI-3	Combined I (piquè)	Cotton, 20 tex, 71 % PES, 8.3; 29 %	16	12	3.10	0.988	877
KI-4	Combined I (piquè)	Cotton, 20 tex, 71 % PP, 8.4; 29 %	16	11	3.21	1.028	920
KII-1	Combined II	Cotton, 20 tex, 76 % PA, 7.8; 24 %	15	11.5	3.24	1.243	788
KII-2	Combined II	Cotton, 20 tex, 76 % Coolmax®, 7.8; 24 %	15	11.5	3.26	1.474	779
KII-3	Combined II	Cotton, 20 tex, 76 % PES, 8.3; 24 %	15	11.5	3.26	1.268	772
KII-4	Combined II	Cotton, 20 tex, 76 % PP, 8.4; 24 %	15	11	3.35	1.392	876

Note: the relative error of all measurements is less than 5 %.

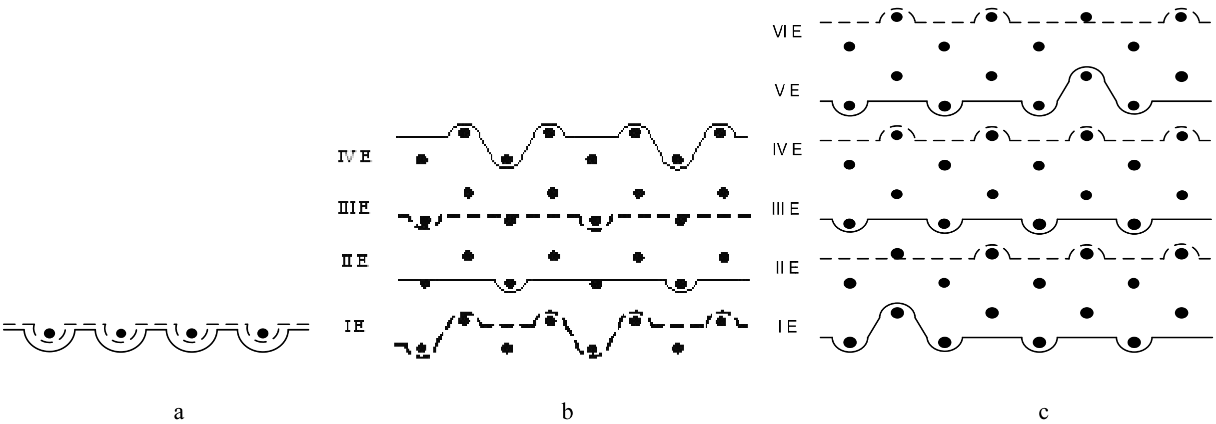

Fig. 1. The pattern of investigated knitted fabrics: a – plain plated single jersey; b – combined I (piqué); c – combined II; ——— cotton C or bamboo B yarn, - - - - - - PP, PA, PES, or Coolmax® thread

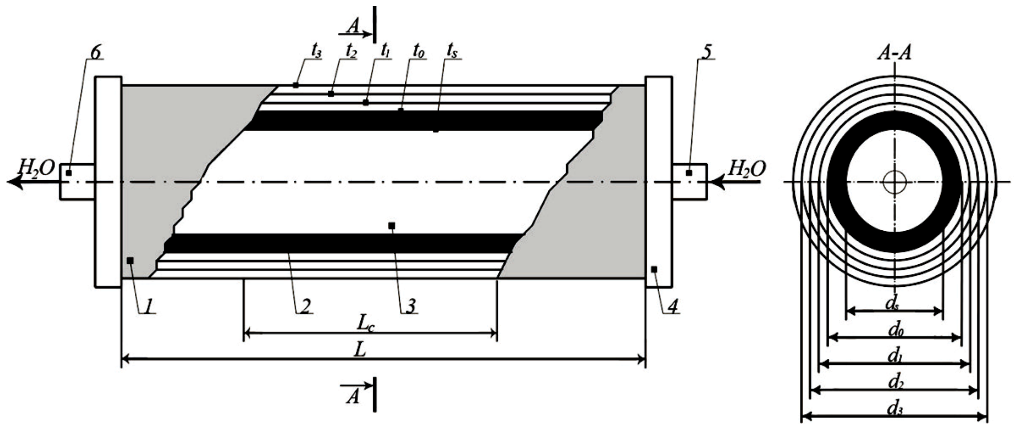

Fig. 2. Principle scheme of the temperature measurement device: 1 – multilayer fabric, 2 – glass tube, 3 – distilled water, 4 – thermo insulation material, 5, 6 – incoming and outgoing water pipes, L – width of sample, L_c – part of constant temperature of glass tube, t_s – temperature of inner layer of glass tube, t_0 – temperature of inner layer of fabric, t_1 – temperature of first layer of fabric, t_2 – temperature of middle layer of fabric, t_3 – temperature of outer layer of fabric, A-A – cross-section of glass tube and three layers of samples: d_s – diameter of inner layer of glass tube, d_0 – diameter of inner layer of fabric, d_1 – diameter of first layer of fabric, d_2 – diameter of middle layer of fabric , d_3 – diameter of outer layer of fabric

The thickness of knitted samples was measured in accordance with ISO 5084:1996 standard.

Thermal conductivity was determined with a measuring device described in [12]. The basic scheme of this device is presented in Fig. 2. The principal element of this device is glass tube 2, whose ends are insulated with a thermo-insulation material so that the temperature field created by the device would remain unaffected. Inside the glass tube distilled water of 40 °C temperature flows. An impulse thermostat accurately maintains the temperature of the water. Sample 1 was wound on the glass tube in three layers. Temperature measurements were then carried out with thermocouples, which were located in five places – on the inside and outside of the glass tube and between every layer of the sample i. e. at points t_s, t_0, t_1, t_2, t_3. The thermocouples were located according to methodology of temperature measurement [13]. When the temperature became constant, measurement was registered. Temperatures were registered using an ALMEMO 2590–9 device with microprocessor data processing and accumulation system. The resolving power of the device is 0.1 °C. The variation coefficient of the temperature measurements did not exceed 3.7 %.

The thermal conductivity coefficient of the fabric (λ in W/mK) can be found using the following equation [12]:

$$\lambda = \lambda_s \frac{(t_s - t_0)\ln\left(\frac{d_3}{d_0}\right)}{(t_0 - t_3)\ln\left(\frac{d_0}{d_s}\right)}; \quad (1)$$

where: λ_s is the thermal conductivity coefficient of the glass tube; t_s is the temperature of the inner layer of the glass tube in °C; t_0 is the temperature of the inner layer of the sample in °C; t_3 is the temperature of the outer layer of the sample in °C; d_s is the diameter of the inner layer of the glass tube in m; d_0 is the diameter of the inner layer of the sample in m; d_3 is the diameter of the outer layer of the sample in m.

By using an indirect method of determining the thermal conductivity coefficient, it is possible to calculate the thermal conductivity coefficient of separate layers of multilayer fabric when the thermal conductivity coefficient of the first layer is known, i. e. $\lambda_i = \lambda_s$ (determined by equation (1)). In this case, the thermal conductivity coefficient of any layer of the fabric (λ_i) is found from the equation (2) [12]:

$$\lambda_i = \frac{(t_{i-1} - t_i) h \left(\frac{d_{i+1}}{d_i} \right)}{(t_i - t_{i+1}) h \left(\frac{d_i}{d_{i-1}} \right)}, \quad (2)$$

where: $i = 2,\ldots.n$.

Thermal resistance R (m^2K/W) is calculated as a quotient of thickness b (mm) and thermal conductivity parameters from following equation:

$$R = \frac{b}{\lambda}, \quad (3)$$

where: b is the thickness of the sample, mm; λ – thermal conductivity coefficient, W/mK.

All measurements were repeated six times at randomly chosen parts of the samples. Relative error values of the thermal conductivity coefficient were calculated and found to range from 3.5 % – 11.8 %.

RESULTS AND DISCUSSION

In this work the thermal conductivity coefficient of double-layered fabrics knitted of cotton or man-made bamboo yarns and four types synthetic threads (PA, PES, tetra-channel polyester fibres Coolmax®, an PP) in three different knitting patterns; overall sixteen variants of knits.

The results of investigation of thermal conductivity coefficient of double-layered weft knitted fabrics are presented in Fig. 3.

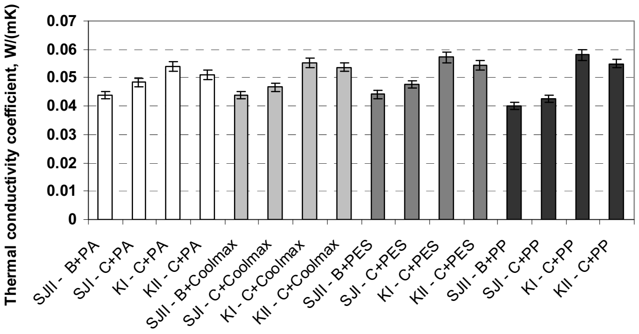

Fig. 3. Thermal conductivity coefficient λ_i of knits manufactured of cotton *C* or bamboo *B* yarns and PA, Coolmax®, PES, or PP threads combination in single platted *SJ* and two types combined *KI* and *KII* patterns

It is found that thermal conductivity coefficient depends on the raw material and knitting structure of the fabric. Fabrics knitted from the man-made bamboo yarns and synthetic threads combination have lower thermal conductivity coefficient as fabrics knitted from cotton yarns and corresponding synthetic threads combination (as was found by other researchers [8]). The influence of synthetic threads on thermal conductivity coefficient is very low. It is interesting that fabrics knitted in combined pattern (*KI* and *KII*) have higher thermal conductivity coefficient as fabrics knitted in plain plated pattern. This is because of combined structure is not so tight, loops in such structure fabric are ranged in two separate layers connected just in some points, whereas in plain plaited fabrics all loops are knitted from two yarns and densely arranged in one line (as is shown in Fig. 1).

The dependence of thermal conductivity coefficient on loop length of knitted fabric is presented in Figure 4. The results are described by a linear equation with sufficiently high determination coefficient.

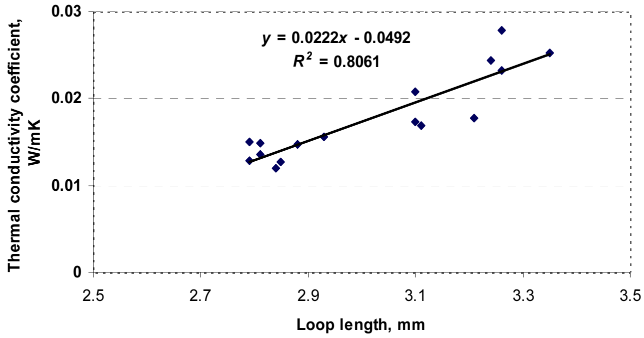

Fig. 4. The dependence of thermal conductivity coefficient of investigated double-layered knitted fabrics on loop length of the fabric

According to the results presented in Fig. 4, when loop length increases thermal conductivity coefficient increases also as stated in [8, 14]. Therefore, knitted garment with low wale and course density gives more cool sense.

The results of investigation of thermal resistance of double-layered weft knitted fabrics are presented in Fig. 5. In contradistinction to thermal conductivity coefficient, thermal resistance depends more on synthetic thread type than on natural fiber yarns. Fabrics knitted from Coolmax® threads combination with cotton or bamboo yarns show highest thermal resistance.

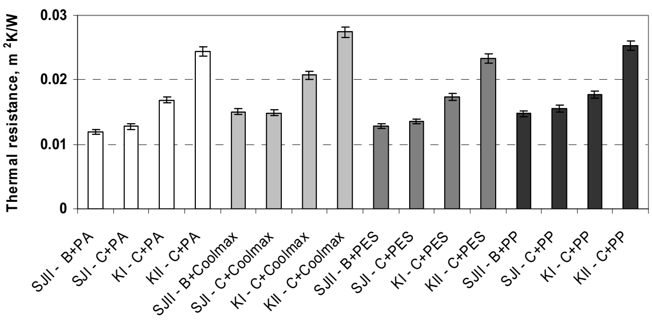

Fig. 5. Thermal resistance of knits manufactured of cotton *C* or bamboo *B* yarns and PA, Coolmax®, PES, or PP threads combination in single platted *SJ* and two types combined *KI* and *KII* patterns

The results presented in Fig. 3 demonstrate the influence of knitting structure on thermal resistance (ability to keep the warmth [9, 12]). The fabrics knitted in combined patterns, especially in *KII* pattern, have the higher thermal resistance than plain plated fabrics. It is because of higher thickness of combined structures.

The measured values of thickness of investigated double-layered weft knitted fabrics are presented in Fig. 6. It is apparently seen in this figure that thickness of the knitted fabric particularly depends on the knitting pattern.

The dependence of thermal resistance on thickness of investigated knitted fabrics is presented in Fig. 7 and good described by linear equation with very high coefficient of determination ($R^2 = 0.9418$). The results presented in this figure demonstrate that by increasing of fabric thickness thermal resistance increases also (differently as is found by [9]). It means that more thick knitted fabric gives warmer sense.

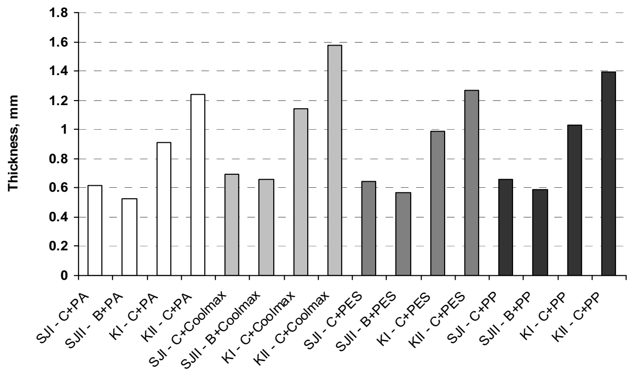

Fig. 6. The values of thickness of investigated double-layered weft knitted fabrics

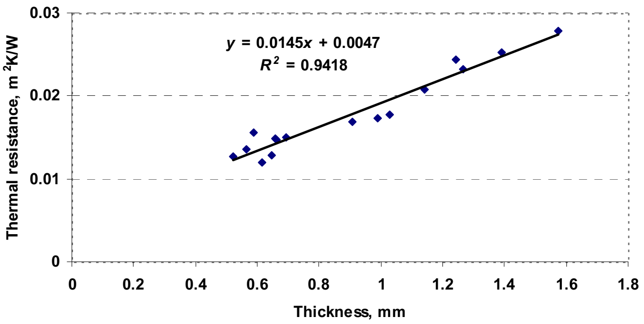

Fig. 7. The dependence of thermal resistance of investigated double-layered knitted fabrics on thickness of the fabric

CONCLUSIONS

The fabrics knitted from man-made bamboo yarns and synthetic threads combination have lower thermal conductivity coefficient as fabrics knitted from cotton yarns and corresponding synthetic threads combination.

The fabrics knitted in combined patterns have higher thermal conductivity coefficient as fabrics knitted in plain plated pattern.

When loop length increases thermal conductivity coefficient increases also, therefore, knitted garment with low wale and course density gives more cool sense.

In contradistinction to thermal conductivity coefficient, thermal resistance depends more on synthetic thread type than on natural fiber yarns. Fabrics knitted from Coolmax® threads combination with cotton or bamboo yarns show highest thermal resistance.

The fabrics knitted in combined patterns have the higher thermal resistance than plain plated fabrics because of higher thickness of combined structures.

By increasing of fabric thickness thermal resistance increases also, it means that more thick knitted fabric gives warmer sense.

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