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Thermal Properties of 1×1, 2×2, 3×3 Rib Knit Fabrics

Abstract
The thermal property of fabric is very important for both its thermal comfort and protection against challenging weather conditions. Although some research has reportedly been done on the dimensional and some of the mechanical properties of rib knit fabrics, no detailed study about the thermal properties of rib knit fabric could be seen. In this study, the natural and forced convective heat transfer characteristics of rib knit fabric have been analysed. The effect of rib design and other fabric properties such as fabric density and air permeability on thermal behaviour have been considered. It has been noted that a decrease in rib number of the order of 3×3, 2×2 or 1×1 leads to a decrease in heat loss due to an increase in the amount of air entrapped between the face and the back loop. The results also indicated that as the fabric gets tighter, so the heat loss lessens, due to reduced air permeability, i.e., reduced air circulation within the fabric. Thus, it results that when the fabric design (1×1 rib, 2×2 rib, 3×3 rib, etc.) is taken into consideration, the conductive heat loss due to fibres and air gaps becomes more important than the heat loss due to air circulation (convective heat loss). However, when the fabric density for each fabric design is taken into consideration, the heat loss due to air circulation (convective heat loss) becomes more important than the conductive heat loss due to fibres and air gaps.

Key words: *rib knit fabric, heat transfer, natural convection, forced convection, conductive, thermal comfort.*

Introduction

The comfort provided by clothing depends on several factors. One of them is thermal comfort, together with other factors such as softness, flexibility, moisture diffusion, etc. Heat transfer characteristics are very important for thermal feeling and protection against weather conditions. Heat transfer through most fabrics, especially for woven and knitted fabrics under conditions of low activity, is governed by conductive, convective and radiation heat transfer mechanisms due to temperature differences [5]. If moisture absorption or disorption takes place, evaporative heat transfer will also occur. The basic heat transfer mechanisms (conduction, convection and radiation) are well known to anyone in engineering. However, the heat transfer process from a heated surface to the ambient through a porous medium, a material consisting of a solid matrix with an interconnected void, will be explained briefly. This process is similar to the experimental model of this study.

All three heat transfer mechanisms coexist in the heat transfer process from a heated surface maintained at T_W to the ambient temperature at T_∞ through a porous media (fabric) attached onto it, as shown in Figure 1. In general, heat transfer from the heated body to the porous media takes place by convection, conduction and radiation concurrently. The same mechanism is valid across the porous medium. From the outer surface of the porous medium to the ambient, heat is transferred by convection and radiation simultaneously. If the thermal boundary layer is contained within the porous medium, as indicated in Figure 1 with continuous lines, the heat will be carried away by convection. If, however, the thermal boundary layer fills the thickness of the porous medium and spreads out of it (dashed lines on Figure 1), then both convection and radiation will participate in the heat transfer, since the surface temperature of the porous medium will be higher than that of the ambient. The heat transfer in porous media is well explained in many textbooks, such as Nield & Bejan [13]. However, the effect of radiation will be negligible at temperatures concerning heat transfer through fabric, which is the subject of this study.

Extensive research has been carried out on the thermal behaviour of textile materials. One of the first studies was carried out by Rees [25], who developed an apparatus to measure heat transfer within fabrics. Rees examined the effect of ventilation and humidity on the heat transfer characteristics of several fabrics. Similarly, Niven [14] studied the heat transmission in wind when there is an air gap between the body and the fabric. Recently, several experimental studies related to heat transfer characteristics of fabrics have also been carried out. For example, Lamb et al. [8,9] investigated the heat loss from a ventilated clothed body. They noted that heat transfer depends on air velocity and fabric permeability. Farnworth & Dolhan [2] used a sweating hot plate method to detect the rate of heat loss through cotton and polypropylene underwear. They concluded that the pattern of heat loss for polypropylene and cotton was different, but not sufficiently so, to affect the wearer's thermal state. Schneider et al. [17] worked on the thermal conductivity of textile fabrics containing water. They showed that under moist conditions wool fabric had better insulating properties than porous acrylic, cotton and polypropylene. Gibson [3] examined the influence of air permeability on heat and water vapour transport through woven and nonwoven fabrics. From this study, it has been pointed out that the air permeability of fabric becomes particularly important in the situation of an air space between fabric and sweating skin simulating surface. The study by Woo et al. [27] pointed out that conduction is the dominant heat transfer mechanism for most non-woven fabrics. Fibre fineness-

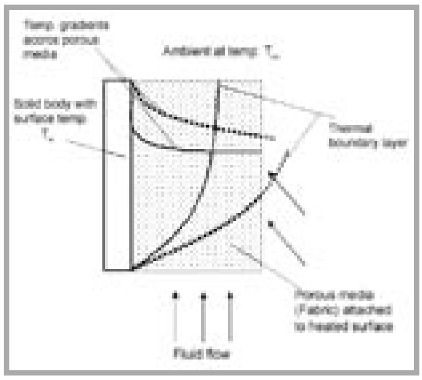

***Figure 1.** Heat transfer process from a surface through a porous medium to the ambient.*

es and fabric thickness have a significant influence on thermal conductivity, especially for low-density nonwoven fabrics. Jirsak et al. [6] developed dynamic and static methods for measuring the thermal conductive properties of textile materials. They pointed out that thermal conductivity measured by the dynamic method is generally higher and more unstable than that of the static method, probably because of the thermal convection due to the thermal gradient within the fabric. They recommended static methods for porous media such as textile materials.

As seen from the literature, most thermal studies have been carried out on either non-woven or woven fabrics. However, a limited number of studies have been carried out on knitted fabrics, such as those by Holcombe et al. and Hatch et al. [5,4]. The general conclusion of these studies is that the contribution of fibre to thermal conductivity is relatively small compared to the effect of entrapped air. The heat transfer characteristics of fabric are more influenced by the fabric's structural features such as thickness, air volume fraction and bulk density of fabric, rather than fibre type. Most of the studies done on knitted fabric have been carried out for conductive heat transfer, rather than convective heat transfer. However, most of the knit fabrics preferred for outer apparel, such as rib knit fabric, present a more open structure than woven fabric and they are used in different environmental conditions, such as windy conditions. Therefore, forced convection heat transfer mechanisms are also especially important, as is conductive heat transfer. Thus in this study, in contrast to most previous studies, convective heat transfer media rather than conductive heat transfer media has been set up to analyse the thermal properties of rib knit fabrics. Although most rib knit fabrics are preferred for outer apparel, this type of design has been subjected to relatively little investigation. Most of the investigations have been carried out on the shape, dimensional, relaxation properties and mechanical characteristics of rib fabrics [7,11,12,15,18-24,26]. Due to the lack of information on the thermal properties of rib knitted fabrics under convective heat transfer conditions, this study investigated the effect of rib fabric design 1×1, 2×2, 3×3 and other fabric properties such as air permeability and fabric density on natural and forced convection heat transfer coefficients.

Experimental Set-up

1×1, 2×2 and 3×3 rib fabrics were knitted on a flat knitting machine with Ne 8 acrylic yarn (3 feed into knitting machine, Ne 2.77), 374 turns/metre in Z-direction twist. The samples were knitted in three different tightnesses (slack, medium and tight) in order to show the effect of fabric density and air permeability. They were conditioned for 48 hours in the atmospheric conditions of temperature 20±2°C and relative humidity 65±2% RH, before the measurements on the samples were taken. The thickness was measured according to standard ASTM D 1777-64 (1975) under 20 g/cm^2 pressure with 0.01 mm accuracy. Air permeability was measured according to standard TS 391 [1]. The concept of fabric density used in this study indicates the ratio of fabric weight to unit volume.

Experiments were conducted for both natural and forced convection heat transfer measurements through the fabric samples. The environmental parameters were the same as the conditioning parameters. The rig used in this study for the natural convection heat transfer experiments is shown schematically in Figure 2 [16]. The cross-section of the experimental set-up is presented in Figure 3. The same rig was used for forced convection heat transfer with slight modification.

The rig consisted of a heater plate, a variable AC power supply, a power meter, a temperature measurement system and a blower for the forced convection heat transfer experiments. The heater plate was fabricated by sandwiching five plane electric heaters between 5 mm-thick aluminium plates, measuring 0.18 m wide and 0.32 m high. The thickness of the heater plate was 11 mm. Twenty-four K-type thermocouples were embedded on the back of the aluminium plates. Thermocouples were distributed on both plates symmetrically, but not with the same spatial resolution, in order to monitor the temperature of the plate at its centreline and also at points positioned sidewise. The thermocouple leads were taken from one side of the heater plate, while the power leads of the electric heaters were taken from the other side. The heater plate was attached to the square section GRP (Glass Reinforced Plastic) bars of the same thickness at the bottom and top, and then fastened on a steel frame via the GRP bars. The purpose of the GRP bars was to reduce heat-bridge effects. The heater plate was level with the top of the frame. The frame had the following dimensions: 1.2 m height, 0.8 m width and 0.8 m depth. The sides of the frame were covered with cardboard, leaving the top open in order to minimise the effect of draughts inside the laboratory.

Power to the heater plate was supplied via a variable AC power supply. A power meter consisting of an ampere meter and a voltmeter was fitted to the power supply line in order to measure the power drawn by the heater plate. Since the electric heaters are assumed to be ohmic, and the losses from the sides of the heaters were negligible, the power measured was taken as the heat transferred through the fabric to the environment.

The temperature measurement system consisted of K-type thermocouples embedded in the heater plate, a multi-

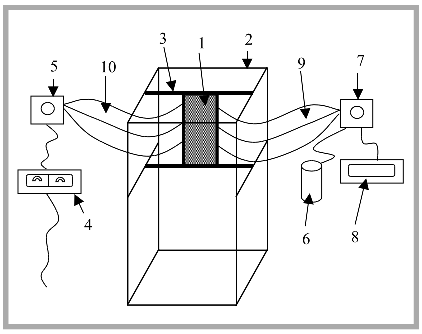

Figure 2. Schematic diagram of the experimental rig; 1 - heater plate, 2 - steel frame, 3 - thermoplastic bar, 4 - power meter, 5 - AC variac, 6 - cold junction, 7 - multiplexing device, 8 - multimetre, 9 - thermocouple leads, 10 - powerline leads

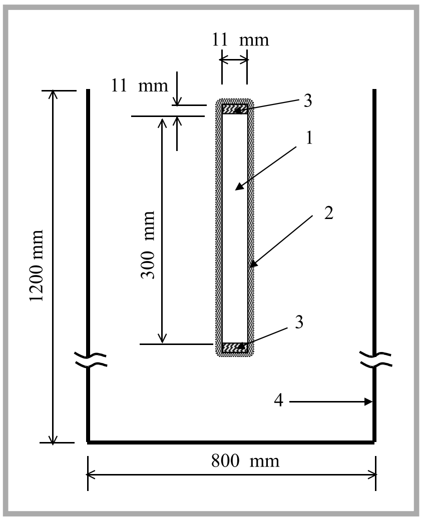

Figure 3. Cross-sectional view of the experimental set-up; 1 - heater plate, 2 - fabric, 3 - GRP bar, 4 - cardboard paravan.

plexing device, an ice-point flask and a multimeter. Thermocouples were connected to the multiplexing device, and its output to the voltmeter with 0.1mV resolution. A reference junction for the thermocouples was provided via a thermocouple inserted into a flask filled with ice. End-to-end calibration of the thermocouples was carried out with respect to the ice point and boiling point of water. Readings from the voltmeter were converted to temperature calibration data and using conversion tables for K-type thermocouples.

Fabric samples were cut to the width of the heater and to a length longer then twice the heater height (0.18 m wide and 0.67 m high). It was wrapped to the heater, so that the ends would meet at the trailing edge of the heater assembly. The ends of the samples were then sewn together to completely wrap the heater, as shown in Figure 3. Care was taken to keep the samples in good contact with the heater. Care was also taken not to stretch the samples excessively when they are wrapped around the heater.

A blower assembly was placed below the heater for forced convection heat transfer experiments. This consisted of a fan, its controls and a diffuser at the output of the fan. The downstream end of the diffuser was fitted with a honeycomb matrix to provide uniform velocity at the outlet. The distance between the end of the diffuser and the heater was 0.2 m. The blower was set to provide a uniform velocity field of 1.5 m/s. The cardboard covering around the steel frame of the rig was partly removed at the bottom to provide for the blower to intake air from the environment.

In this study, the natural convection heat transfer concept refers to the heat transfer taking place from the heater (simulating the body) through the fabric sample to the atmosphere without any external velocity field such as windy conditions. The forced convection heat transfer concept refers to the overall heat transfer as in natural convection, with the difference that an external velocity field is created over the fabric to simulate windy conditions. In fact, since fabrics are a porous medium, convective, conductive and radiation heat transfer mechanisms take place concurrently within the fabric. The term 'natural convection' refers to heat transfer through the fabric to a quiescent ambient with the combined effect of all three mechanisms. Similarly, the term 'forced convection' refers to heat transfer through the fabric to a windy ambient with the combined effect of all three mechanisms. Thus, the heat transfer coefficient is an effective heat transfer coefficient covering conductive, convective and radiative heat transfer. Within the thermal parameter range of this study, it is expected that heat transfer across the fabric would be governed mainly by convection and conduction, since radiation would be negligible.

Natural and forced convection heat transfer experiments were conducted for 1×1, 2×2 and 3×3 rib fabrics at three different tightnesses (slack, medium, tight). Heat transfer coefficients were calculated from the experimental data for both natural and forced convection heat transfer. The heat transfer coefficient is calculated using equation 1:

$$h = \frac{Q}{A\Delta T} \qquad (1)$$

where:

- Q - the measured heat transfer rate from the surface of the heater through the fabric to the atmosphere, in W,
- A - the surface area of the sample fabric in m^2,
- ΔT - difference between the average of heater surface temperature and the temperature of the atmosphere, in °C,
- h - the heat transfer coefficient in W/m^2 °C,

h_n and h_f refer to natural and forced co nvection heat transfer coefficients respectively.

Theoretically, the heat transfer coefficient h can be written as:

$$h = 1/[g/\lambda + 1/\alpha + 1/\alpha_r],\ W/m^2\ °C$$

where:

- g - the thickness of the fabric,
- λ - effective thermal conductivity of the fabric,
- α - convective heat transfer coefficient within the fabric,
- α_r - convection heat transfer coefficient equivalent of radiation heat transfer.

Measurements were carried out to determine the overall heat transfer coefficient only. With this measurement system, it was not possible to measure each quantity (such as effective thermal conductivity λ) of every sample, which would have allowed the determination of the contribution of each heat transfer mechanism. Thus, no mention of the contribution of different mechanisms is made in this study.

Some preliminary experiments were made before making any measurements. After the sample was wrapped on the heater, the power supply was switched on. Since one of the main purposes of this study was to obtain experimental data on the heat transfer behaviour of different rib knit fabrics, the experiments of this study were carried out using a constant heat flux (power rate), rather than applying a constant surface temperature on the heater. Thus, the average surface temperatures were measured for each case of the fabric sample for use in the calculation of heat transfer coefficient, h. The same power rate was used for all the cases of both natural and forced convection heat transfer experiments. As a result, the average temperatures reached on the surface of the heater were different for each experimental case. The power rate used in all cases was 40±1.3 W. The average surface temperatures developed on the heater were 60 to 63°C for the natural convection experiments depending on the fabric sample, and 43 to 45°C for the forced convection cases.

It took almost three hours to reach steady-state conditions, i.e., to obtain no noticeable change in the surface temperatures for the given power rate. To check the repeatability of the measurements, experiments for one sample were repeated ten times. It was seen that the coefficient of variation between measurements were not more than 2%. An uncertainty analysis was carried out, and it was found that the uncertainty of heat transfer coefficient was less than 10% for all the cases considered. The content of moisture is important for the thermal behaviour of fabrics (an increase in moisture content leads to an increase in heat transfer coefficient, i.e. an increase in heat loss). Thus, the change in the samples' moisture content has been checked. No important disorption or absorption has been observed, due to the hydrophobic properties of the fabric. The experimental procedure for forced convection experiments was the same, with the addition of switching on the blower at the start of experiment.

The results are presented in Table 1 under the columns h_n and h_f for natural and forced convection respectively, along with other properties of the samples. To ensure the accuracy of the measurement results, the data obtained from the measurements was checked with the data of Hatch et al. [4] simulated dry and wet skin model at low air velocity conditions. In their studies, polyester and cotton knit fabrics were used, and thermal resistance for 0.05 m/s and 0.275 m/s air velocity (dry skin model) were

Table 1 Properties of fabrics.

Fabric design	Stitch density	Tightness factor	Fabric weight	Thickness	Air permeability	Fabric density	Natural convection heat transfer coefficient h_n	Forced convection heat transfer coefficient h_f
	loop/cm^2	$\sqrt{Tex}$ cm^{-1}	g m^{-2}	mm	l dm^{-2} min^{-1}	g cm^{-3}	W m^{-2} °C^{-1}	W m^{-2} °C^{-1}
1x1 rib, slack	12	11	364	3.2	1007	0.1362	9.50	17.3
1x1 rib, medium	20	12	414	2.8	880	0.1478	9.44	16.87
1x1 rib, tight	24	13	436	2.1	754	0.1733	8.81	16.22
2x2 rib, slack	16	12.5	415	2.5	822	0.1660	10.25	19.55
2x2 rib, medium	20	14	431	2.4	675	0.1795	9.88	19.1
2x2 rib, tight	28	15.5	493	2.4	453	0.2054	9.45	18.93
3x3 rib, slack	20	12.5	390	2.2	619	0.1772	11.13	20.4
3x3 rib, medium	24	14	413	2.0	509	0.2065	11.06	19.88
3x3 rib, tight	40	16	690	2.1	420	0.3052	10.48	19.33

established as 0.67 and 0.52 clo, respectively, (1 clo=0.155 m^2 °C/W; thermal resistance indicates the resistance of fabric against the heat flow. An increase in thermal resistance means a decrease in heat flow). In our study, for natural convection, the thermal resistance (R) lies between 0.579 and 0.73 clo ($R_n=1/h_n$ or $R_f=1/h_f$). Of course, there will be some differences between the results due to differences originating in the environmental effect and the material, such as fibre type, design type, bulk density, etc. However, as seen from the results, the ranges in both studies are close to each other. Thus, it may be said that the results obtained in this study are reliable.

Results and Discussion

Fabric density, air permeability, the natural convection heat transfer coefficient and the forced convection heat transfer coefficient of the samples are presented in tabulated form in Table 1, and in graphic form in Figures 4 to 7 respectively. Judging from these figures and variance analyses, the following conclusions were made.

- As the fabric gets tighter (more fabric density), two situations are expected: one, heat loss decreases because of decreased convective heat loss due to a decrease in air circulation through the fabric; the other, heat loss increases because of increased conductive heat loss due to increased conductivity (less air entrapped in the fabric, and more fibre contact). As seen from Figures 6 and 7, the natural and forced convection heat transfer coefficients h_n and h_f decrease with the increase in fabric tightness for each type of design (1×1, 2×2, 3×3), in the order of slack, medium and tight. This means that for each fabric design, the heat lost through the fabric will decrease as the fabric becomes tighter, due to less air permeability (Figure 4). Thus, it may be said that when the fabric tightness for each fabric design is taken into consideration, heat loss due to air circulation (convective heat loss) becomes more important than conductive heat loss, due to the fibres and air gaps. Since most knit fabrics fall within the range of low or medium fabric density compared to most woven fabrics, the convective heat loss from knitted fabric can become more important than that of most woven fabric.

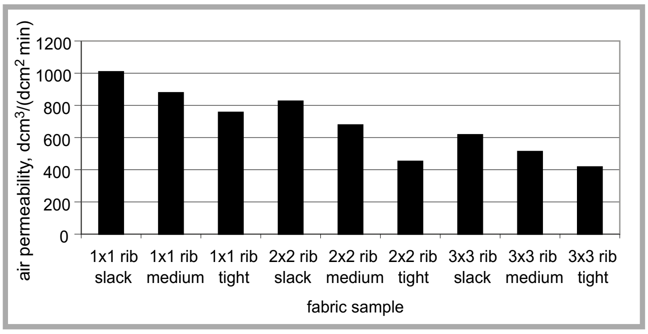

***Figure 4.** Air permeability with respect to fabric sample.*

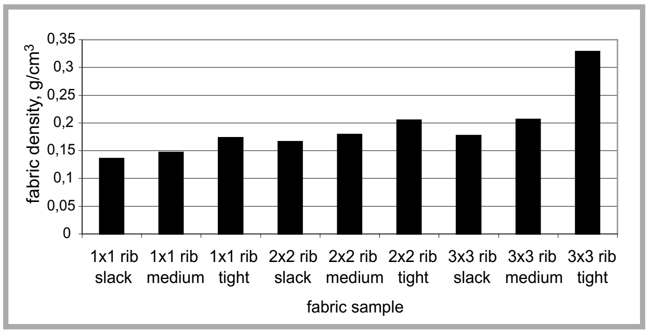

***Figure 5.** Bulk density with respect to fabric sample.*

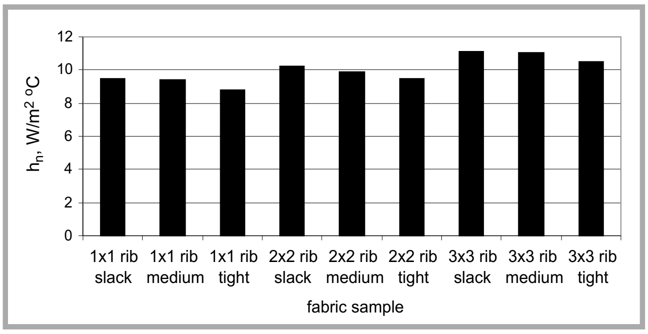

***Figure 6.** Natural convection heat transfer coefficient with respect to fabric sample.*

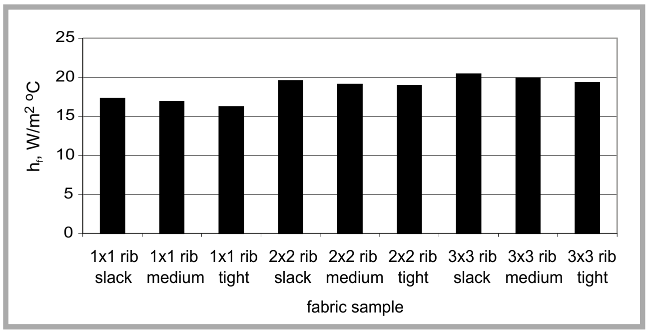

***Figure 7.** Forced convection heat transfer coefficient with respect to fabric sample.*

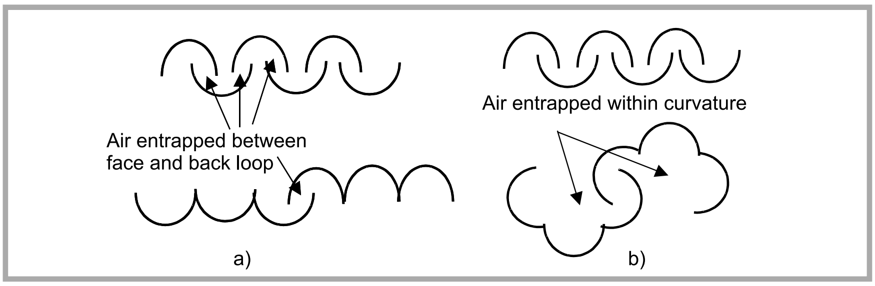

Figure 8. *The rib structures: a - top illustrates the 1×1 rib and the bottom the 3×3 rib, b - top illustrates the 1×1 rib and the bottom the 3×3 rib, increase in curvature with the increase in rib number.*

- The heat loss decreases with the decrease in rib number, i.e. in the order of 3×3, 2×2 and 1×1. This may be due to an increase in the air entrapped in the fabric, i.e. a bulkier structure. As is known, an increase in air entrapped in the fabric (a bulkier structure) decreases the conductive heat loss. As seen from Figure 8a, the air entrapped area between the face and back loop in the 1×1 decreases as the rib number increase towards 3×3, 4×4, 5×5, etc. In this study, no increase of curvature due to an increase of rib number was observed [23], as shown in Figure 8a. If the curvature of the rib structure as shown in Figure 8b increased, the heat lost could decrease with the increase in rib number, due to the increase in air entrapped within the curvature (a bulkier structure). Thus, it can be said that when the fabric design (1×1 rib, 2×2 rib, 3×3 rib, etc.) is taken into consideration, the conductive heat loss due to fibres and air gaps becomes more important than the heat loss due to air circulation (convective heat loss). If the structure between rib knit stitch (front and back stitch) has a flat shape (Figure 8a), as in the case of this study, the use of 1×1 rib and a tight structure will provide better insulation against cold weather.
- From analyses of variance, it is seen that the effects of each level of fabric density (slack, medium, tight) and fabric design (1×1, 2×2, 3×3) on the thermal coefficient are statistically important to 90% and 99% respectively. This means that each set of data obtained for the thermal coefficient differs statistically from each other.

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