EFFECT OF FABRIC STRUCTURAL DESIGN ON THE THERMAL PROPERTIES OF WOVEN FABRICS

Khubab Shaker, Muhammad Umair, Madeha Jabbar, Danish Mahmood Baitab, Yasir Nawab, Ali Afzal, Sheraz Ahmad*

[1] Faculty of Engineering & Technology, National Textile University, Faisalabad, Pakistan

Corresponding author: Sheraz AHMAD
Postal address: Department of Materials and Testing, National Textile University, Sheikhupura Road, Faisalabad-37610, Pakistan
Email address: itsadeelnaz@hotmail.com

The thermal properties of a certain fabric govern its end usage. The enhanced thermal resistance can help to use light weight fabric for cold conditions. The aim of this study was the development fabric with a particular structural design having enhanced thermal resistance, without any change in the constituent materials or any extra process. Fabric samples were produced using cotton and core spun elastane yarns along weft, in a specific sequence. The fabrics had either a flat or puckered appearance, depending on the arrangement of weft yarns. It was observed that the percentage of core spun yarns and fabric thickness had a significant effect on the thermal resistance of fabrics. A valuable difference in the thermal resistance of flat and seersucker (puckered) fabrics, having same construction was observed. It was found to be the effect of the characteristic puckered effect of the seersucker fabric. Statistical models were developed to predict the thermal resistance of flat fabrics using core spun yarns percentage and fabric thickness.

Key words: seersucker, core spun, fabric structural design, thermal resistance

1. Introduction

Clothing is the basic need of all human beings, serving the purpose of covering body and also protecting from environment severity. The primary role of clothing is to enable the body to maintain itself in an acceptable physiological state with respect to thermal balance, core and skin temperature, and sweat dissipation for all types of environmental conditions [1]. The heat is transferred from a high temperature zone to a low temperature zone until equilibrium is established between both. The different ways of heat transfer to environment from body are conduction, convection and radiation [2]. The comfort of wearer is another important parameter in the clothing of any type. It is described as a measure of how well clothing assists the functioning of body. The structural parameters have a direct effect on the comfort properties of woven fabric [3], [4].

1.1 Puckered fabrics

The seersucker fabrics are traditionally used as informal summer dressing due its light weight and slack tension weave [5]. These fabrics are produced from cotton or viscose, having puckered surface and a striped pattern [6]. The puckered effect in the fabric results in the formation of air pockets between the body and the fabric, keeping the wearer cool in warm climatic conditions [7]. These stripes run in whole fabric generally along warp. The production of these fabrics requires the warp sheet to be divided into two sets of yarns, one set with higher tension and other set in normal tension [8]. The weft yarns are kept in uniform tension; while combination of slack yarns and tight yarns in warp gives a puckered effect. The production of seersucker fabric can be difficult, if the warp tensions of both beams are not appropriate.

Maqsood *et. al.* [9] produced seersucker effect in the woven fabric on conventional loom using single beam. They used 100% cotton yarn in warp while in weft direction 100% cotton and core spun yarn having elastane in core and cotton in sheath were used. The difference in the contraction of core spun yarn and cotton yarn produced the seersucker effect in weft direction. The seersucker effect has also been produced in the knitted fabrics [10], providing better comfort as compared to the flat knit fabrics.

1.2 Effect of fabric parameters on thermal performance

The textile materials are also used as thermal insulators in buildings and transport [11]. The use of textile fabrics as thermal insulators requires study of their thermal insulating properties at different operating conditions. To enhance the thermal insulation, modes of heat transfer (conduction, convection and radiation) must be controlled. To minimize the convective heat transfer, material must be relatively impermeable to air [12]. The heat transfer through the fabrics is highly related to its capillary structure and surface characteristics of yarns, as well as air volume distribution within the fabrics. This is a complex phenomenon, depending on a number of parameter like fabric geometry, fabric thickness [13], fabric density, yarn structure, weave design [14], the number of fabric layers, etc. The thermal resistance offered by the fabric decreases as the twist in yarn increases. Also, the fabrics woven with carded cotton yarn were found to have better thermal resistance values as compared to those produced with combed cotton yarns. The thermal resistance values of woven fabrics are lower than the fabrics knitted with carded cotton yarns fabrics [15].

Schacher *et. al.* [16] assess the thermal properties of fabrics produced using conventional and microfiber types polyester. The fabrics produced of microfibers show lower heat conductance and higher thermal insulation properties. The garment fit is also reported to have effect on the thermal insulation provided by the clothing [17]. The thermal insulation of clothing increases with the thickness of air gap between the garment and body. The rate of increase in thermal resistance gradually decreases as the air gap becomes wider; and may decrease when the air gap is too large.

Above all, the fiber used to produce fabric has also a strong effect on its thermal comfort [18]. Majumdar *et. al.* [19] investigated the properties of knitted fabrics and concluded that the thermal conductivity of fabrics made from finer yarns was lower as compared to coarse yarns. The textile fabrics made of hemp fibers or their blends were reported to have thermal characteristics comparable to the fabrics produced from cotton or viscose fiber [20]. According to another study, the thermal insulation provided by a fabric may be estimated solely in terms of fabric thickness, irrespective of its chemical composition, diameter, linear density or mesh size. The thermal insulation of clothing, as well as blankets, carpets and quilts, is better attributed to the amount of air contained within them [21].

1.3 Modelling thermal performance of fabric

Afzal *et. al*. [22] developed statistical models to predict the thermal resistance of interlock knitted fabrics. Three different statistical models were developed and compared for the prediction of thermal resistance of polyester/cotton interlock knitted fabrics. The first was based on yarn specific heat, yarn linear density and knitting stitch length. The second model was based on specific heat of the yarn, fabric areal density and fabric thickness. The third model was based on yarn specific heat, yarn linear density, knitting stitch length, fabric areal density and fabric thickness.

The mathematical model for the thermal resistance was presented by Kothari [23]. As the woven fabric has pores between yarns, the conductive heat transfer takes place through the pores; and it was modeled using a lumped method. The radiative heat transfer through the pores and yarns was modeled as an analogy to a system of electrical resistances and in terms of linear anisotropic scattering respectively. While the sum of conductive and radiative heat transfer based on the developed mathematical model predicted the thermal resistance values.

Bhattacharjee and Kothari [24] simulated the convective heat transfer through fabric with the help of computational fluid dynamics (CFD).The fabric was subjected to natural and forced convection during simulation and the coefficients of convective heat transfer were used to find the thermal resistance due to convection. Thermal resistance was also measured experimentally, and a close resemblance was observed with those predicted in forced as well as natural convective mode using CFD. The artificial neural networks (ANN) used to predict the steady-state and transient thermal behavior of the fabrics also provided satisfactory results [25].

The aim of current study is the development of a thermally insulating fabric from by varying its structural appearance. It was achieved using a combination of cotton and core spun elastane yarns along weft in the fabric. Another objective was to model the thermal insulation of the fabric produced.

2. Experimental

2.1. Materials

Two different yarns were used to produce fabrics in this study. One was 37tex (100% cotton) and other was 37tex core spun yarn having 78 dtex elastane in the core and cotton in sheath. The specifications of these yarns are given in Table 1.

Table 1. Properties of yarn material

Sr. #	*Parameters*	*Units*	*100% Cotton*	*Core spun yarn*
1	Yarn linear density	tex	37	37

2	Elastane linear density	dtex	--	78
3	Twist per meter	turns	15.76	20.57
4	Tenacity	cN tex^{-1}	13.03	20.65
5	Elongation	%	3.34	8.31
6	CVm	%	11.23	11.91
7	IPI	No.	8.5	9.5

2.2. Fabric production

The 37 tex (100% cotton) yarn was used as warp to produce eight different fabric samples (Table 2) on the sample weaving machine, using single warp beam. In the weft direction, a combination of 37 tex (100% cotton) and 37 tex core spun yarn was used. The warp and weft thread density were 36 and 24 yarns per cm respectively, while weave design was 3/1 twill for all the samples.

Table 2. List of samples produced

Sr. #	*Sample ID*	*Weft sequence*		*Core spun yarns (%)*
		Cotton yarns	Core spun yarns	
1	S1	5	0	0
2	S2	4	1	20
3	S3	2	1	33
4	S4	1	1	50
5	S5	1	2	66
6	S6	1	4	80
7	S7	0	5	100
8	S8	16	4	20

In the sample S1, only 100 % cotton yarn was used as weft. The samples S2-S6 had both the cotton and core spun yarns, with varying numbers. For example, S5 had 1 cotton yarn and 2 consecutive core spun lycra yarns. In sample S7, only core spun lycra yarn was used as weft yarn. All these seven samples had a flat appearance. In sample S8, the weft yarns were used in a way to produce two stripes, A and B. The stripe A had 12 consecutive yarns of cotton, while stripe B had 8 alternate yarns of cotton and core spun yarn producing seersucker effect (Table 3).

Table 3. Sample produced with weft stripes

Sample ID	*Stripe A threads*	*Stripe B threads*	*Arrangement of threads in stripe B*
S8	12 C	8	(1L + 1C) × 4

Where, C and L represent cotton and core spun lycra yarns respectively

2.3. Fabric processing

The fabric samples were desized and bleached before measuring the thermal insulation. Enzymatic desizing was performed using Bectosol enzyme at a temperature of 60-65° C for 30 min. It was preferred over acid desizing as acid could affect the properties of core spun yarn used. The fabrics were then bleached with a 50% solution of hydrogen peroxide at temperature of85 °C for 20 min, followed by rinsing with tap water. The fabric samples were then dried in a heating oven for 20 min.

2.4. Fabric testing

Prior to the testing, fabric samples were preconditioned at 20% relative humidity (R.H.) and 47 °C temperature for four hours. The samples were conditioned further under standard atmospheric conditions (R.H.65±2%, Temperature 20±2 °C) according to ASTM D 1776. The SDL Atlas M259B sweating guarded hotplate instrument was used for the measurement of thermal insulation. This instrument is based on the standard test method ISO 11092:2014. The samples were placed on the thermal plate enclosed in a controlled environment (Air temperature 20±0.1°C, R.H. 65±3%, thermal plate temperature 35±0.1°C, air speed 1.00±0.05 m/s and measuring unit temperature 35±0.1°C. Five readings were recorded for each fabric sample and thermal resistance was recorded in terms of m^2 K/mW.
Fabric thickness testing was performed using a digital precision thickness tester according to the ASTM D1777. Its working principle is based on the precise measurement of distance between two plane plates (anvil and press foot) separated by the fabric under a known pressure. Five readings were noted for each fabric sample and average value was reported in mm.

3. Results and Discussions

The results of fabric thickness, appearance and thermal resistance are shown in Table 4. As discussed in the introduction section, seersucker effect is produced by the combination of cotton and core spun yarns in weft. But any random combination of these yarns will not produce the seersucker effect as evident from Table 4. Although the sample S2 and S8 have same percentage of core spun yarns (i.e. 20%), but the appearance of both fabrics is different; the S2 is a flat fabric while S8 has seersucker appearance. Therefore, it can be concluded that the effect is only produced for the fabric samples with weft stripes, of cotton and core spun yarns, for example the one mentioned in Table 3. Varying the sequence of cotton and core spun yarns in stripes, seersucker effect may be obtained with different percentage of core spun yarns.

Table 4. **Thermal resistance of all fabric samples**

Sr. #	*Sample ID*	*Thickness (mm)*		*Thermal Resistance (Clo)*		*Appearance*
		Average	*SD*	*Average*	*SD*	
1	S1	0.6714	0.011	0.0362	0.016	Flat
2	S2	0.6886	0.016	0.0473	0.011	Flat
3	S3	0.7200	0.016	0.0524	0.016	Flat
4	S4	0.7629	0.014	0.0614	0.002	Flat
5	S5	0.7943	0.015	0.0627	0.011	Flat
6	S6	0.8114	0.016	0.0637	0.003	Flat
7	S7	0.8543	0.022	0.0844	0.016	Flat
8	S8	4.4000	0.018	0.1511	0.021	Seersucker

It can be observed from the Table 4 that the thermal insulation of pure cotton based fabric sample (S1) is very small as compared to the seersucker fabric sample (S8). The construction and weave design of both the S1 and S8 samples is same. The only difference is the material; S1 has no core spun yarns, while S8 has 20% core spun yarns in the weft, resulting in a puckered appearance. As the seersucker fabric is produced using some percentage of core spun yarns, therefore the increase in thermal resistance may be attributed either due to the material or structure of fabric. If we consider it to be the effect of material, then the fabric S2 having same percentage of core spun yarns has a remarkably small value of thermal resistance as compared to the fabric S8.

Comparing the thermal resistance of fabrics S1 and S2, the increase of 0.0111 clo may be attributed to the change in the material (20% core spun yarns), as both the fabrics are flat. Therefore, the increase in the thermal resistance (0.1149clo) of the seersucker fabric S8 as compared to S1 is the result of both the material and structure of the fabric. The effect of material on increase in the thermal resistance is very small (0.0111 clo); major contribution is made by the seersucker structure of fabric (0.1038 clo). Owing to the puckered effect in seersucker fabric, some air is trapped in the pockets between body and skin, as shown in Figure 1. As the air is a good insulator of heat, this puckered effect fabric gives a higher value of thermal resistance.

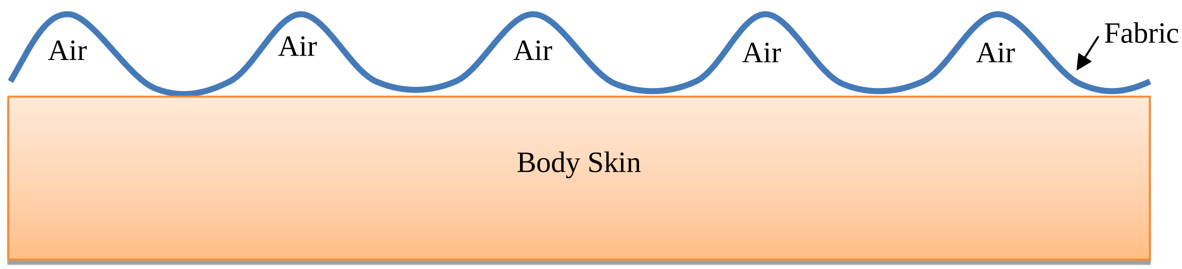

Figure 1. Schematic of higher thermal insulation for seersucker fabrics

The thermal resistance results of samples S1 to S7 were used to develop the statistical model for fabrics with different percentages of core spun yarns. Minitab 17 was used to analyze the results, and fitted mean graphs were plotted. It can be observed from the Figure 2 that with the increase in the percentage of core spun yarns, the thermal resistance of the fabric is also increasing. This is because the thermal conductivity of lycra in the core spun yarn is less (0.03 W/m.K), as compared to cotton (0.04 W/m.K). This lower value of thermal conductivity will resist the flow of heat through the fabric, giving a higher value of thermal resistance. Therefore, as the percentage of core spun yarn increases, the value of thermal resistance also increases. The trend is linear giving an inclined straight line.

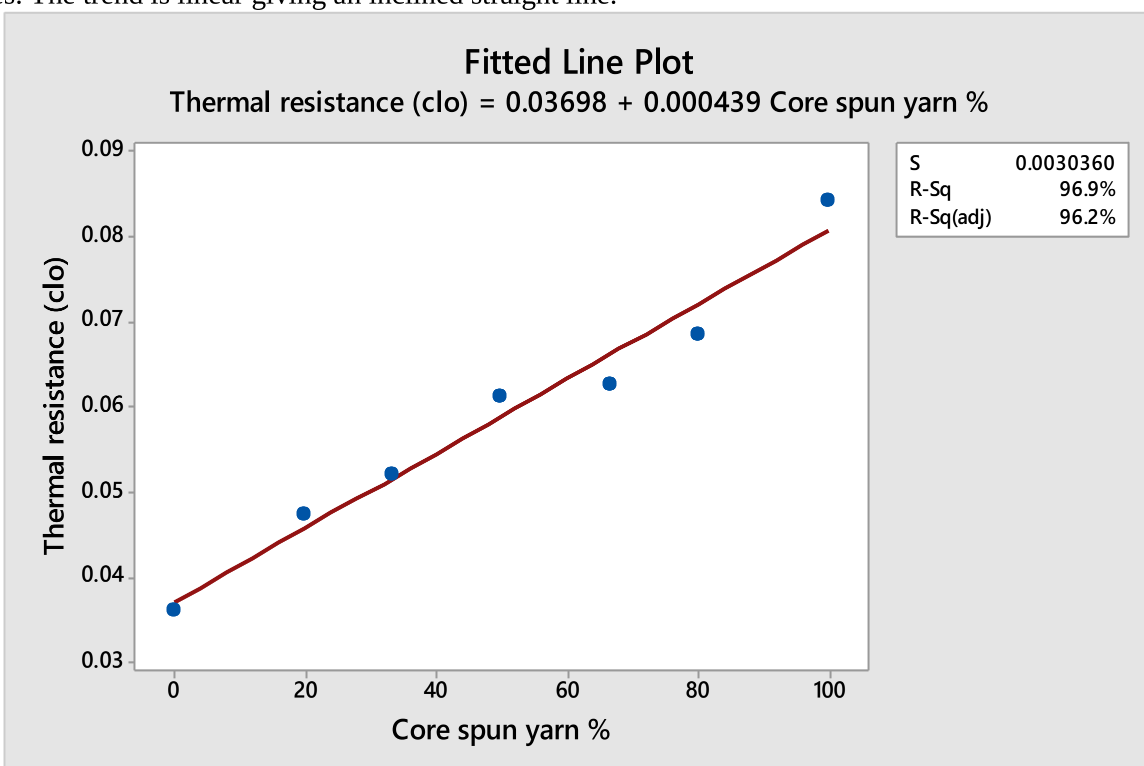

Figure 2. Trend of thermal resistance as a function of core spun yarn %

The slope of this inclined line can be calculated by using the Equation 1:

$$\text{Thermal resistance (clo)} = 0.03698 + 0.000439x \qquad \text{Equation 1}$$

Where, x is the core spun yarn %.

The coefficient of determination (R-squared) for this equation is 0.969, which means 96.9% variation in the results of thermal resistance can be explained by this equation.

As given in Table 4, the thickness of all the fabric samples is not the same. So, the thickness may also be a possible factor for the variation in the thermal resistance of samples S1-S7. A keen look into the results will show that there is an increasing trend in the thermal resistance of the fabric with increase in the fabric thickness (Figure 3).

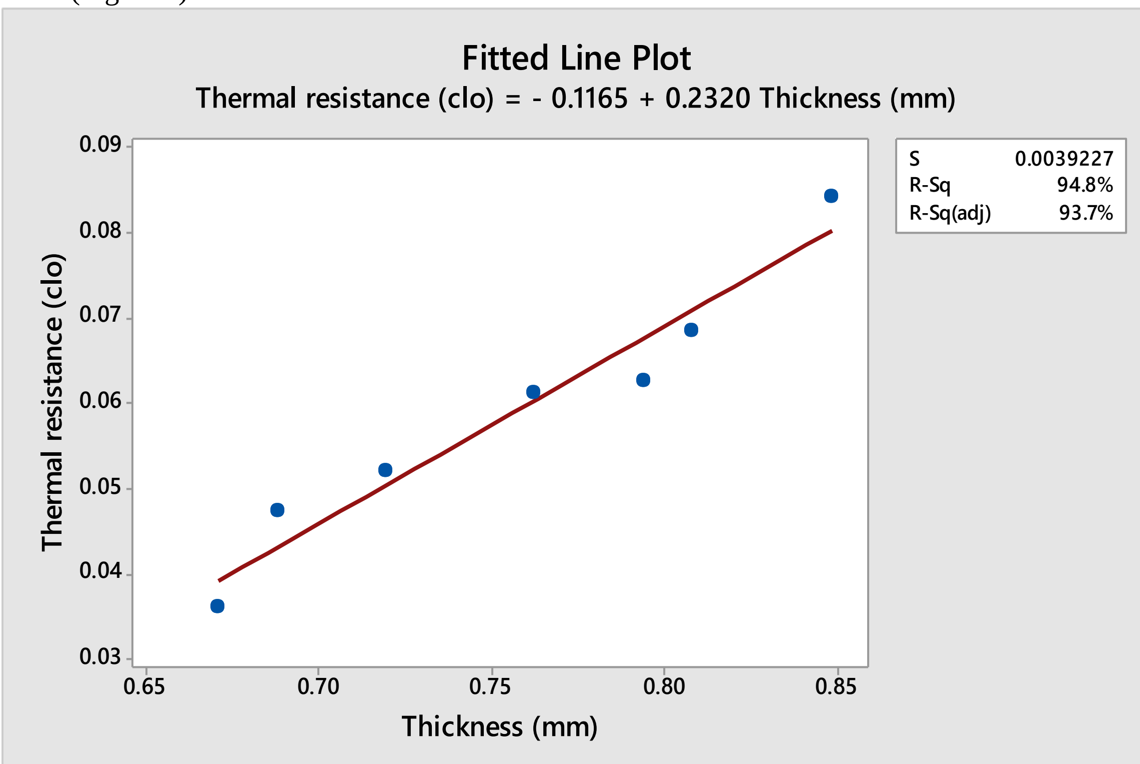

Figure 3. Trend of thermal resistance as a function of fabric thickness

The trend between fabric thickness and its thermal resistance is an inclined straight line; and the slope of this line can be calculated using Equation 2:

$$\text{Thermal resistance (clo)} = -0.1165+0.2320x \qquad \text{Equation 2}$$

Where, x is the fabric thickness in mm.

The coefficient of determination (R-square) for this equation is 0.948, which means 94.8% results of thermal resistance due to thickness can be explained by this equation.

The percentage of core spun yarns is not the only contributing factor to the enhanced thermal resistance of the samples, but the fabric thickness is also playing its role. Both can be used as the predictor to calculate the value of thermal resistance of cotton fabric, with the condition that the fabric is flat, i.e. does not have a puckered appearance. In a puckered fabric, the presence of air is also involved as an additional factor.

The amount of air trapped depends on the size of the puckered stripe; its width and height. These fabrics may find their use in home textiles applications including curtains for thermal insulation, with a novel aesthetic appearance. Additionally, the puckered fabrics woven in high areal weight (with more thread density) may also be used as thermal blankets.

4. Conclusions

The current study concludes that the fabric structural design has significant effect on its thermal resistance. Comparing the thermal resistance of flat fabrics, it is evident that increasing the % of core spun yarns in the weft direction results in a higher thermal insulation. The highest value of thermal resistance (0.0844 clo) was obtained for the fabric with 100% core spun yarn and lowest (0.0362 clo) for fabric without core spun yarns. Moreover, the puckered fabrics offered better thermal resistance (0.1511 clo) as compared to the flat fabrics. This enhanced thermal resistance may be attributed to the presence of air pockets between the fabric and skin. Air being good insulator of heat helps to enhance the thermal insulation. Moreover, the fabric thickness was also found to have a significant effect on thermal resistance (increasing with increase in thickness of fabrics). Statistical models were developed to predict the thermal resistance of flat fabrics using core spun yarns percentage and fabric thickness. The values of coefficient of determination for these models were 96.9% and 94.8% respectively, showing good accuracy of models.

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