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Thermal comfort properties of knitted fabrics produced from bamboo/polyester core-spun yarns

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The influence of polyester content, twist and loop length on the comfort properties of single jersey knitted fabrics produced from 100% bamboo, 80:20 bamboo/polyester and 60:40 bamboo/polyester core-spun yarns has been studied. Comfort properties, such as air permeability, moisture vapour transmission, thermal conductivity and thermal resistance properties have been analyzed with three different twist levels and loop lengths. Box–Behnken, a three level three factorial design software, has been used to study the interactive effect of core-sheath ratio, twist and loop length on the comfort properties of single jersey knitted fabrics, response surface equations are derived and the design variables are optimized. It is found that the increase in bamboo content in the core yarns having high twist and loop length increases the moisture vapour transmission and thermal conductivity of the knitted fabrics. The air permeability and thermal resistance of the knitted fabrics are found to be higher as the polyester component is increased. High twist and loop length increase the thermal comfort properties of knitted fabrics.

Keywords: Bamboo, Comfort, Knitted fabrics, Loop length, Polyester, Thermal comfort

1 Introduction

Consumers are more and more interested in knitted fabrics because of such advantages as good fit and softness. Application of core-spun yarns in knitting is also in a development direction. The market demand for core-spun yarns is continuing to increase. Now core-spun yarns are manufactured on more than ten million spindles of spinning machines all over the world and two or three hundred thousand spindles are expected to be added every year.

Thermal comfort is the condition of the human mind which expresses satisfaction with the thermal environment. Normally body temperature is about 37^0 C, and this value is achieved by balancing the amount of heat produced in the body with the amount lost. If it does not occur, the body core temperature will change. Clothing and textiles need good thermal insulation properties in cold climates as reported by Paul[1]. Zaghouani *et al.*[2] concluded that in knitted fabrics, linear density and twist factor have considerable influence on the air permeability of plain knitted fabrics. Değirmenci and Çoruh[3] and Ogulata and Mavruz[4] opine that an increase in the loop length produces an open structure in the fabric and hence increases air permeability values.

Ozdil[5] reports that when yarn twist increases water vapour permeability of the knitted fabrics also increases. As the twist of yarn increases, thermal resistance values decrease. Kothari[6] opines that natural fibres have lower thermal conductivity than synthetic fibres in dry state; with 8-13% moisture content which increases the thermal conductivity is noticed. Vadicherla and Saravanan[7] found that the recycled polyester ratio, loop length and linear density have a significant influence on the thermal comfort properties of single jersey fabrics. It was observed that with the increase in the recycled polyester ratio, the fabric becomes thinner, lighter and more porous with higher thermal conductivity, air permeability, relative water-vapour permeability, and lesser thermal resistance. Hussain *et al.*[8] opine that the air permeability of P/B and P/C blended fabric increases by increasing bamboo and cotton fibre content in the blend, while thermal resistance of the fabric decreases with an increase in natural and cellulosic fibre content

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in the blends. Prakash *et al*.[9] remarks that decrease in yarn linear density and increase in loop length increases air permeability and relative water-vapour permeability of the knitted fabrics. Ozkan and Meric[10] state that fibre type, spinning technology, yarn linear density, yarn twist and fabric thickness mainly influence the thermal comfort properties of fabrics. Studies on the properties of core-spun knitted fabrics are found scanty and hence an investigation on the effect of polyester content, twist and loop length on the comfort properties of single jersey knitted fabrics has been undertaken.

2 Materials and Methods

2.1 Materials

For this study, regenerated bamboo staple fibres with 38mm fibre length, 1.6 dtex fibre fineness, 20.3g/tex, 0.156 tex linear density, 11.46% moisture regain and 21.4% elongation were used as wrap fibres; and 50 and 65 denier polyester mono filaments were used as core.

2.2 Methods

2.2.1 Yarn Production

The process steps of fibre mixing, lap production, carding, drawing, roving, and spinning were controlled to result in a yarn linear density of 14.76 tex. 100% regenerated bamboo yarns with low, medium and high twist levels were produced in the ring frame. 80:20 bamboo/polyester and 60:40 bamboo/polyester core-spun yarns were produced in the Trytex Core Lycra ring frame with a core spin attachment above the drafting unit. A polyester filament was passed through the front drafting roller with core spin attachment. Regenerated bamboo rovings were drafted at the back and middle drafting rollers with the required core ratio. For 80:20 and 60:40 bamboo/polyester core-spun yarns, 50D and 65D polyester filaments were used respectively.

2.2.2 Fabric Production

Box–Behnken (BBD), a three level- three variable factorial design, was used for this study. The input parameters under study were core sheath ratio of bamboo and bamboo/ polyester (100%, 80:20, and 60:40), twists per meter (940 1020, and 1100) and loop length (2.5, 2.7, 2.9 mm). The coded factors were calculated using the following equation:

$$x_c = \frac{(x - \widetilde{x})}{\Delta x} \quad \text{... (1)}$$

where x is the actual value of the factor (low or centre or high level); $\ddot{x}$, the mean value of all levels of the factor; and Δx, the difference between the levels of the factor.

Fifteen single jersey knitted fabrics with a linear density of 14.76tex were knitted as per the combination shown in Table 1. The number of experiment performed as per BBD is $2k\ (k\text{-}1) + c$, where k is number of factors and c is number of centre points. For 3 factors with 3 centre points, 15 experiments were performed using "Design Expert 12" software (Table 2). The fabrics were knitted using Smart mc knitting machine with following specifications: 32 inch gauge, 24 inch diameter, 4 feeders/inch, 35 rpm speed and 1800 needles. Knitted samples were subjected to the dry, wet and full relaxation treatments as per the procedure set out by the 'Starfish' recommendations. The fabrics were then subjected to scouring and then conditioned in the standard atmospheric conditions of 20ºC ± 2 ºC at a relative humidity of 65% ± 2% prior to testing.

2.3 Test Methods

Bamboo/polyester single jersey knitted fabrics were tested for areal density and thickness, evaluated

Table 1 — Variables and levels used in Box-Behnken design

Variables	Levels		
	-1	0	1
Core sheath ratio, %	100:0	80:20	60:40
TPM	940	1020	1100
Loop length, mm	2.5	2.7	2.9

Table 2 — Box-Behnken design sample plan

Standard	Run	Factor 1 Core sheath ratio (*A*)	Factor 2 TPM (*B*)	Factor 3 Loop length (*C*)
2	1	1	-1	0
13	2	1	0	1
10	3	1	0	-1
9	4	1	1	0
3	5	0	-1	1
11	6	0	-1	-1
6	7	0	0	0
15	8	0	1	1
8	9	0	1	-1
5	10	-1	-1	0
4	11	-1	0	1
1	12	-1	0	-1
7	13	-1	1	0
12	14	0	0	0
14	15	0	0	0

in accordance with the standards of ASTM D 3776 and ASTM D 1777-96 respectively. Air permeability of the fabric samples was measured in cm³/cm²/s using Textest FX 3300 tester at a pressure of 100 Pa using ASTM D737 test standard, ten measurements of the samples were carried out and then the average values were reported. Water vapour permeability of fabrics was determined by means of water vapour permeability tester according to ASTM E96-95 OPTION B standard. Alambeta testing instrument was used for measuring the thermal properties of the fabrics, such as thermal conductivity and thermal resistance. The sample was kept between the two plates (one is hot and another is cold) provided in the instrument, according to ISO 11092 standards. The measurement of the samples was done five times and the average values were reported.

Table 3 — Physical properties of bamboo/polyester core-spun knitted fabrics

Sample code[a]	WPcm	CPcm	Fabric weight g/m^2	Fabric thickness mm
100-940-2.7	17	18	95	0.48
100-1020-2.9	16	18	95	0.46
100-1020-2.5	15	17	96	0.48
100-1100-2.7	15	17	96	0.48
80:20-940-2.9	18	19	93	0.46
80:20-940-2.5	17	19	93	0.47
80:20-1020-2.7	16	18	94	0.47
80:20-1020-2.7	16	18	94	0.47
80:20-1020-2.7	16	18	94	0.47
80:20-1100-2.9	17	20	94	0.46
80:20-1100-2.5	16	20	95	0.45
60:40-940-2.7	18	20	93	0.44
60:40-1020-2.9	18	21	92	0.44
60:40-1020-2.5	18	21	93	0.45
60:40-1100-2.7	17	22	91	0.43

[a]Core/shear ratio–TPM–loop length.

3 Results and Discussion

3.1 Physical Properties of Bamboo/Polyester Core-spun Knitted Fabrics

Table 3 exhibits the physical properties of bamboo/polyester core-spun knitted fabrics. The fabrics were tested for wales per cm, course per cm, GSM and thickness. As the polyester content increases, fabric becomes lighter and thinner which may be attributing to the highest amount of hairiness of bamboo fibres. Low twist and high loop length decrease the areal density and fabric thickness in accordance to the studies[11,12].

3.2 Comfort Properties of Bamboo/Polyester Core-spun Knitted Fabrics

Comfort properties of 100% bamboo, 80:20 and 60:40 bamboo/polyester core-spun knitted fabrics were tabulated in Table 4. The influences of these variables and their response surface equations have been derived and the optimized values are shown in Table 5. Table 6 reveals the statistical significance of ANOVA test model with high F-value and low p-values.

Table 4 — Comfort properties of bamboo/polyester core-spun knitted fabrics

Sample code	Air permeability c.c/cm^2 (Response 1)	Moisture vapour transmission g/m^2/24h (Response 2)	Thermal conductivity W/mK (Response 3)	Thermal resistance×10^{-3} m^{2}K/W (Response 4)
100-940-2.7	103	2188.72	0.0297	14.47
100-1020-2.9	105	2043.72	0.0296	14.86
100-1020-2.5	118	2012.16	0.0291	16.49
100-1100-2.7	128	1861.29	0.0285	16.84
80:20-940-2.9	128	2176.88	0.0289	15.9
80:20-940-2.5	139	2110.79	0.0282	16.36
80:20-1020-2.7	143	2055.93	0.0277	16.96
80:20-1020-2.7	143	2055.93	0.0277	16.96
80:20-1020-2.7	143	2055.93	0.0277	16.96
80:20-1100-2.9	165	1869.14	0.0272	17.56
80:20-1100-2.5	177	1814.89	0.0276	17.07
60:40-940-2.7	172	1932.1	0.0289	16.61
60:40-1020-2.9	203	1956.68	0.0288	15.63
60:40-1020-2.5	216	1819.61	0.0271	17.71
60:40-1100-2.7	235	1696.73	0.0271	17.34

Table 5 — Response surface equation

Property	Response surface equation
Air permeability	$143+46.5*A+20.375*B-6.125*C+9.50*AB+3.57E-14*AC-0.25*BC+12.38*A^2+4.123*B^2+5.125*C^2$
Moisture vapour transmission	$2055.93+87.60*A-145.81*B+36.12*C-23.02*AB-26.38*AC-2.96*BC-85.55*A^2-50.67*B^2-12.34*C^2$
Thermal conductivity	$0.0277+0.000062*A-0.000588*B+0.000075*C-0.000250*AB+0.000625*AC-0.000275*BC+.0000575*A^2+0.000025*B^2+0.000250*C^2$
Thermal resistance	$+16.52667-0.560000*A+0.663750*B-0.461250*C-0.015000*AB+2.30586E-15*AC-0.002500*BC+0.005417*A^2+0.007917*B^2+0.007083*C^2$
Optimized values	A = 65:35, B = 1030, C = 2.5.

Table 6 — Analysis of variance results

Property	F value	P value	Significance
Air permeability	168.72	<0.0001	Significant
Moisture vapour transmission	51.95	0.0002	Significant
Thermal conductivity	1407.74	<0.0001	Significant
Thermal resistance	551.64	0.0500	Significant

3.2.1 Air Permeability

The interactive effects of core ratio and twist, core ratio and loop length and twist and loop length on air permeability of bamboo/polyester core-spun knitted fabrics are shown in Fig. 1. Bamboo/polyester (60:40) core-spun knitted fabrics show the highest air permeability value of 235 c.c/cm^2 with high twist and medium loop length as compared to other fabrics. Fabric weight and thickness values are inversely proportional to the air permeability. As the thickness and fabric weight decrease, air permeability increases due to the passage of more air through the fabric.

Air permeability of knitted fabrics increases with the decrease in bamboo content due to the increased hairiness of bamboo staple fibres. Unrestricted air passage through inter-yarn pores and correspondingly high air permeability is found in manmade yarn due to the absence of hairs. As the twist increases, fibres bind compactly to the yarn body that reduces the hairiness which brings high air permeability. As the loop length increases porosity of the knitted fabrics increases, and hence the air permeability is found to be higher because of the looser structure, which correlates with earlier findings[13,14].

3.2.2 Moisture Vapour Transmission

Figure 2 shows the interactive effects of core ratio, twist and loop length on the moisture vapour transmission property of bamboo/polyester core-spun knitted fabrics. 100% bamboo fabrics show highest moisture vapour transmission rate followed by 80:20 and 60:40 bamboo/polyester core-spun knitted fabrics.

It is observed that the moisture vapour transmission rate increases with the increase in bamboo content. Moisture vapour permeability of bamboo is high and the cross-section of bamboo is filled with micro pockets that provide amazing absorption and ventilation. Thus, bamboo fabrics absorb and evaporate human sweat quickly with this unique microstructure. Increase in twist and loop length makes the fabric more porous that result in increased water vapour transmission rate. The higher water vapour transmission value of the knitted fabrics is due to the lower values of fabric weight and thickness. Moisture vapour transmission rate is strongly correlated with fabric thickness, and fibre-related factors, such as cross-sectional shape and moisture absorbing properties which agrees with the earlier findings[15-17].

3.2.3 Thermal Conductivity

Thermal conductivity is the ability of fabricsto conduct heat and it depends much more on the air entrapped within fabric. The thermal conductivity provided by a fabric depends on the fibre type, fabric thickness, fibre arrangement and the compressibility of the fabric structure.

From the response surface equations and Fig. 3, it is clear that the thermal conductivity of the knitted fabrics increases with the increase in bamboo content since 100% bamboo fabrics are the good conductor of heat. Increase in polyester core ratio decreases the fabric weight and thickness, which makes the fabric more porous, resulting in lower thermal conductivity of the fabric. Increased twist and lower loop length, increases the thermal conductivity of the knitted

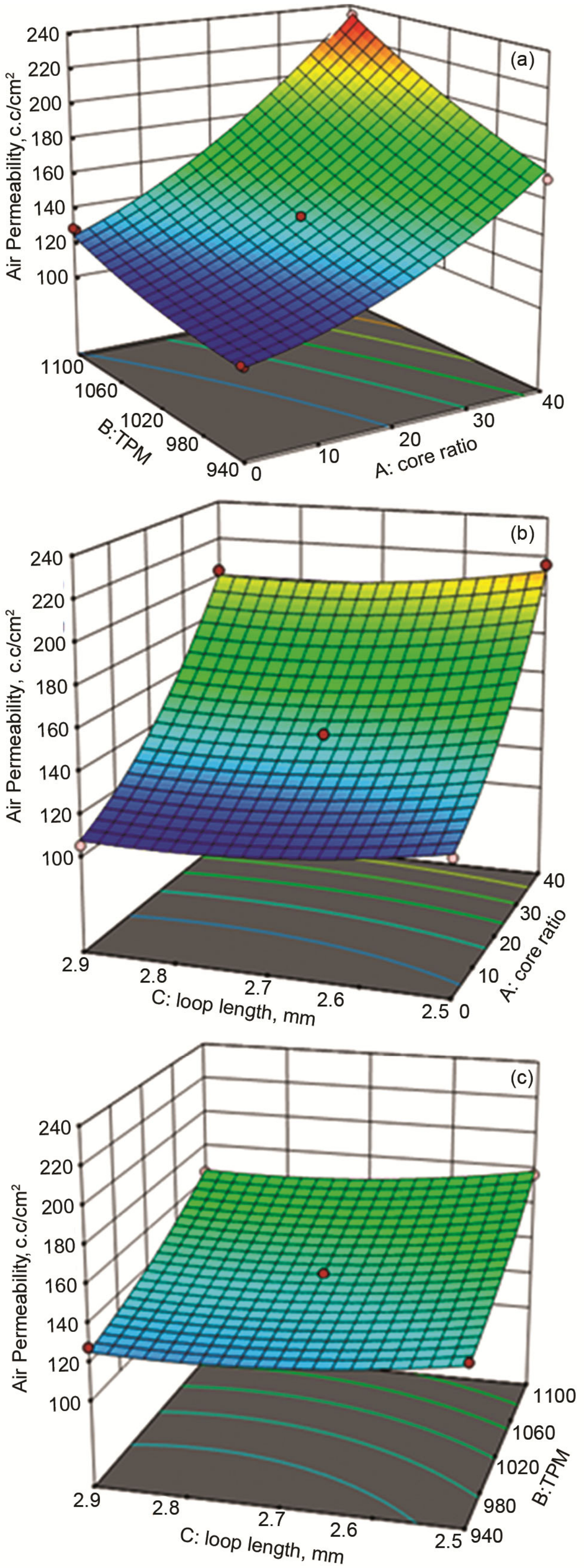

Fig. 1 — Interactive effect of (a) core ratio (b) twist and (c) loop length on air permeability of bamboo/polyester core-spun fabrics

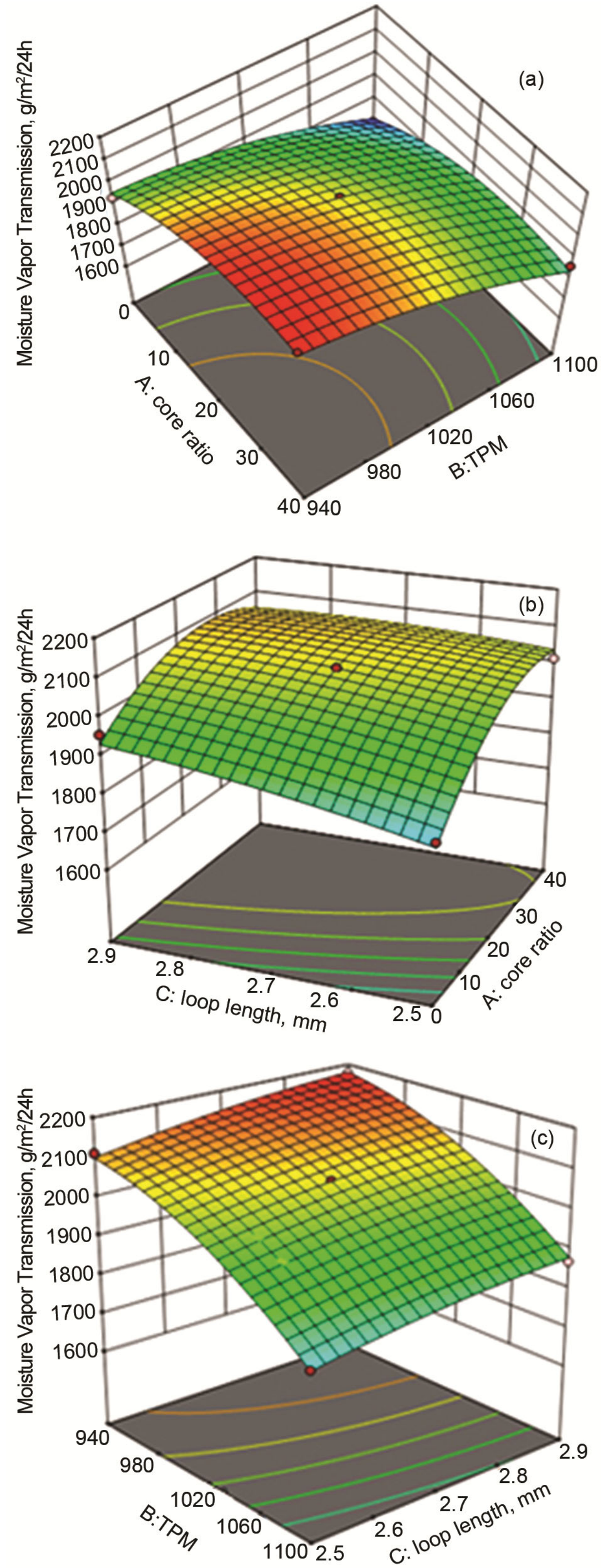

Fig. 2 — Interactive effect of (a) core ratio (b) twist and (c) loop length on moisture vapour transmission of bamboo/ polyester core-spun fabrics

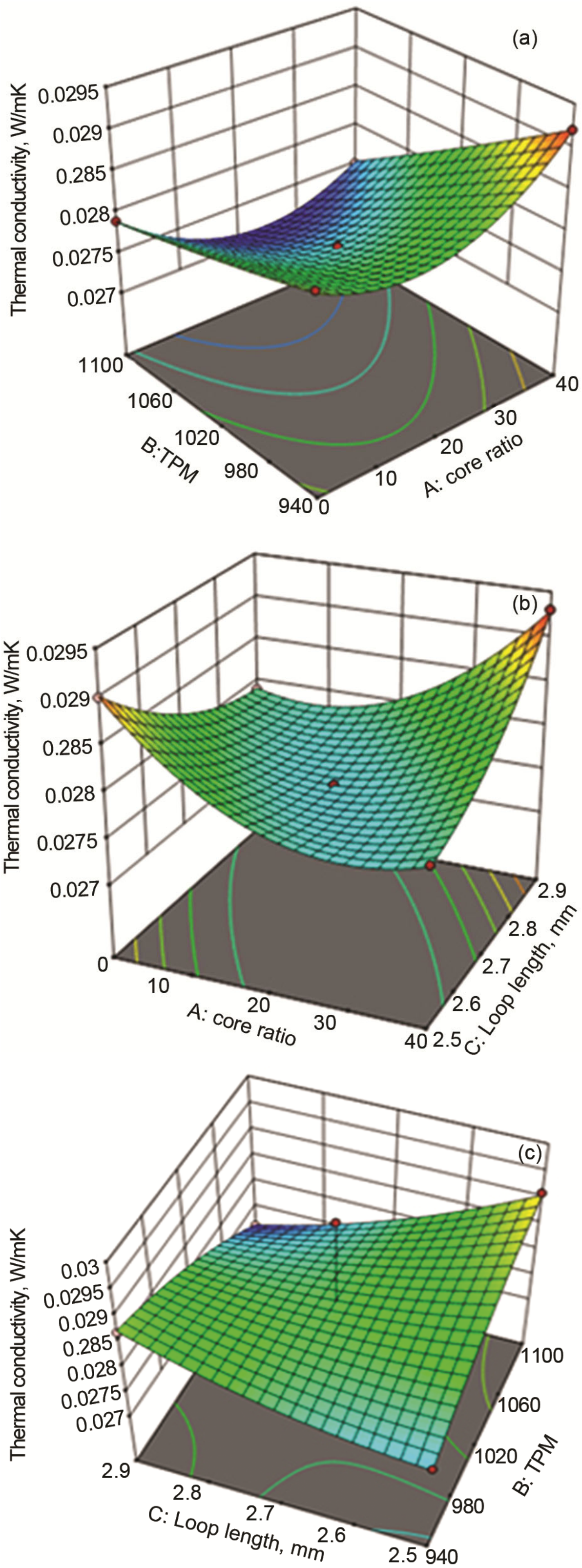

Fig. 3 — Interactive effect of (a) core ratio (b) twist and (c) loop length on thermal conductivity of bamboo/polyester core-spun fabrics

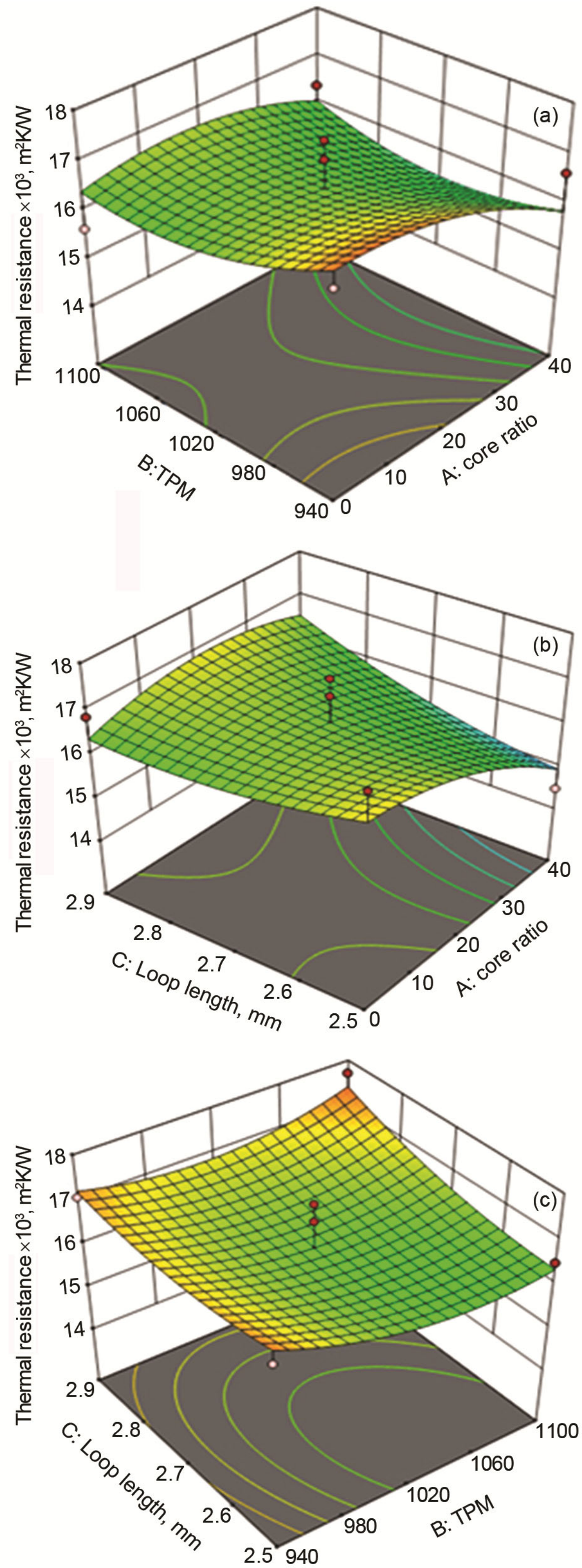

Fig. 4 — Interactive effect of (a) core ratio (b) twist and (c) loop length on thermal resistance of bamboo/polyester core-spun fabrics

fabrics, which also agrees with the earlier observations[18-20].

3.2.4 Thermal Resistance

Thermal resistance expresses the thermal insulation of fabrics and is inversely proportional to thermal conductivity and proportional to the fabric thickness. From Fig. 4, it is observed that the thermal resistance increases with the decrease in bamboo sheath ratio due to the poor insulating property of bamboo fibres consisting of cellulose. As the fabric thickness decreases, the thermal resistance values decrease. The loop length is found to be in direct proportion with the thermal resistance of the fabric.

The thermal resistance increases with the increase in loop length of the fabric. This is due to increase in air gaps generated by increase in loop length of the fabric. As air is a good thermal insulator, increase in air gaps results in improved thermal resistance. However, the results reveal that as thermal conductivity decreases, thermal resistance increases as well. Fabrics knitted from lower loop length will have high thermal resistance which agrees with the findings of the previous workers[21-23].

4 Conclusion

The thermal comfort properties of 100% bamboo, and 80:20 & 60:40 bamboo/polyester core-spun knitted fabrics (single jersey) have been investigated. It is found that the core sheath ratio, twist and loop length have significant influence on thermal comfort properties. Air permeability of the knitted fabrics decreases with the increased bamboo content. Increased bamboo content also increases the hairiness that resists the air flow and hence decreases the air permeability. Moisture vapour transmission rate of the 100% bamboo fabrics is found to be higher, because the cross-section of the bamboo fibre is filled with micro pockets which provide amazing absorption and ventilation. Increased twist and loop length make the fabric more porous, which increases the air permeability and moisture vapour transmission rate. Thermal conductivity of the knitted fabrics increases with the increase in the bamboo component, and thermal resistance decreases due to the poor insulating property of bamboo fibres. High twist and tight loop structure increase the thermal properties of knitted fabrics.

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