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Fabric comfort by modifying yarn structure: Part II—Low-stress mechanical, thermal and transmission characteristics of fabrics

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The present study aims at investigating the influence of yarn structure, modified through process parameters of ring frame (spindle speed, twist multiplier and ring frame draft), on low-stress mechanical, thermal properties and transmission properties of fabric. It is observed that the structural changes influence thermal, transmission and low-stress mechanical characteristics of fabrics due to change in fabric porosity and thickness. In general, the bending and compression properties increase but shear and surface properties of the fabrics decrease with the increase in spindle speed, twist multiplier and draft. The study further reveals that air permeability, thermal absorptivity, thermal diffusivity, heat conductivity and moisture transmission properties increase but thermal resistance decreases with the increase in spinning process parameters.

Keywords: Cotton fibre, Fabric comfort, Low-stress mechanical properties, Packing density, Radial packing density, Thermal properties, Transmission properties, Yarn structure

1 Introduction

Comfort is a subjective response resulting from many characteristics of yarn and fabric. Several researchers studied the fabric comfort considering different approaches[1-10]. Some of them considered the fabric structure as variable to study the fabric comfort [11-13] and others studied the behaviour of different finishes on comfort. Many of them attempted to understand the influence of different spinning technologies on fabric comfort[14-17]. Though there has been consistent development in different spinning technologies, ring spinning still gives the best response. This is perhaps, because of its flexibility and distinct yarn structure. Modifications in the internal structure of yarn can bring required changes in fabric quality from comfort point of view. The internal structure of yarn in terms of packing density and radial packing density, and ultimately overall yarn diameter have direct influence on the fabric structure and its comfort characteristics, as governed by thermal and transmission properties[18-21]. To the best of our knowledge, the possible advantages of internal structure of yarn to govern fabric comfort have not been fully exploited by the researchers. In this context, the present study was aimed at investigating the influence of yarn structure dully modified through the process parameters of ring frame (spindle speed, twist multiplier and ring frame draft)[22] on low-stress mechanical, thermal and transmission properties of fabric.

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2 Materials and Methods

Cotton fibre having tenacity 30.63 g/tex, fineness 1.3 dtex, upper half mean length 29.34 mm, SFI 8.25 and trash content 3.67% has been used for the study.

2.1 Preparation of Sample

The rovings of three different linear densities were prepared to produce yarns of 37.0 tex linear density with different level of drafts. Total seven yarns with different combinations of spindle speed, twist multiplier (TM) and ring frame draft (Table 1) were prepared. Finally, seven fabric samples with 60 × 40 sett using plain weave were prepared on the sample loom.

2.2 Fabric Testing

The fabric low-stress mechanical properties were evaluated on Kawabata evaluation system. Comfort

Table 1 — Process parameters of yarns

Yarn code	Yarn TM	Spindle speed, rpm	Draft
A	4	10,000	20
B	4	13,000	20
C	4	16,000	20
D	3.5	13,000	20
E	4.5	13,000	20
F	4	13,000	30
G	4	13,000	40

related properties were evaluated on different instruments. Thermal properties were evaluated using Alambeta system. Parameters obtained from this instrument were used for the measurement of thermal resistance, thermal diffusivity, thermal absorptivity and thermal conductivity. Air permeability was measured in Textest FX3300 according to the ATSM D737. Moisture management test was carried out on SDL Atlas moisture management tester. Moisture vapor transmission rate (MVTR) was measured in the MVTR cell for measuring the water vapour transmission behaviour of the fabrics.

3 Results and Discussion

3.1 Fabric Thickness

Table 2 shows the results of fabric thickness. Fabric thickness values (T_0) decrease with the increase in spindle speed, TM and ring frame draft. This is because of the overall reduction in yarn diameter with the increase in spindle speed, TM and draft. It is observed that with the increase in spindle speed from 10,000 rpm to 13,000 rpm and from 13,000 rpm to 16,000 rpm, the reduction in yarn diameter is 4.6% and 8.96% but corresponding reduction in the fabric thickness is 22.04% and 5.39% respectively. Therefore, it can be inferred that at initial increase of spindle speed, the reduction in yarn diameter is lesser but the reduction percentage of fabric thickness is higher in comparison to the further increase of spindle speed. The observed trend can be supported from the corresponding packing density of yarns. A 0.17% increase in packing density is noticed with the increase in spindle speed from 10,000 rpm to 13,000 rpm but 2.40% increase in packing density is noticed with increasing spindle speed from 13,000 rpm to 16,000 rpm. Further, the reduction of fabric thickness with the increase in spindle speed can be supported from the radial packing density in the different zones of the yarn. It is depicted in Table 2 that with the increase of spindle speed, radial packing density on the surface zone of yarn decreases but in the core zone, it increases.

The increase in TM from 3.5 to 4.0 and from 4.0 to 4.5 shows reduction in yarn diameter by 4.25% and 9.24% but corresponding reduction in the fabric thickness is 16.86% and 4.62% respectively. Therefore, it is observed that the influence of TM and spindle speed on reduction in yarn diameter and corresponding reduction in fabric thickness have good resemblance. The corresponding packing density of yarns supports the observed trend. A 5.72% increase in packing density is noticed with the increase of TM from 3.5 to 4.0 but 10.80% increase in packing density is noticed with increase in TM from 4.0 to 4.5. Further, the reduction of fabric thickness with the increase of TM can be supported from the radial packing density of the surface zone. It is noticed from Table 2 that with the increase of TM, radial packing density in the surface zone decreases but in the core zone, it increases.

It is further observed that with the increase in ring frame draft from 20 to 30 and from 30 to 40, the reduction in yarn diameter is 13.41% and 1.87% and the corresponding reduction in fabric thickness is 12.68% and 3.99% respectively. Therefore, it is noticed that the trend of reduction in yarn diameter with the change in draft is quite different from the change in spindle speed and TM. It is observed that

Table 2 — Yarn and fabric properties

Parameter	A	B	C	D	E	F	G
Areal density, g/m^2	198.20	195.68	193.40	195.77	197.75	194.93	192.11
Ends/cm	24.60	24.60	24.40	24.60	24.60	24.60	24.40
Picks/cm	16.90	16.70	16.50	16.90	16.90	16.50	16.40
Fractional cover	0.7941	0.7730	0.7695	0.7889	0.7183	0.6913	0.6478
Fabric porosity	0.5126	0.5370	0.5710	0.5419	0.5543	0.5495	0.5555
Thickness, mm (at 0.5 gf/cm^2 load)	1.284	1.001	0.947	1.204	0.998	0.876	0.841
Thickness, mm (at 50 gf/cm^2 load)	0.550	0.539	0.532	0.539	0.571	0.540	0.549
Yarn diameter, mm	0.2577	0.2456	0.2243	0.2565	0.2229	0.2130	0.2090
Yarn packing density	0.4556	0.4564	0.4676	0.4303	0.4818	0.5145	0.5212
Packing							
Core zone	0.4641	0.4822	0.5037	0.4614	0.5435	0.5496	0.6456
Interim zone	0.4706	0.4747	0.4515	0.5282	0.4803	0.5611	0.6232
Surface zone	0.3686	0.2320	0.1983	0.2591	0.2117	0.3185	0.2861
Surface zone1	0.4753	0.3627	0.3139	0.3864	0.3302	0.4557	0.4337
Surface zone 2	0.2812	0.1266	0.1065	0.1550	0.1177	0.2062	0.1714

the reduction in yarn diameter is found to be higher with initial increase in draft. Accordingly, corresponding reduction in the fabric thickness is also higher in comparison to the increase of draft. The observed trend can be supported from the corresponding packing density of yarns. An 11.30% increase in packing density is noticed with the increase in draft from 3.5 to 4.0 and 1.28% increase in packing density is observed with increasing draft from 4.0 to 4.5. Further, the reduction of fabric thickness with the increase in ring frame draft can be supported from the radial packing density in surface zone. It is depicted in Table 2 that with the increase of draft, radial packing density of the surface zone decreases but in core zone, it increases.

It is further evident that at the 50 gf/cm^2 force, the decrease in fabric thickness is 57.16%, 46.15% and 43. 82% at 10,000, 13,000 and 16,000 spindle rpm respectively, however 46.15%, 38.35% and 34.72% reduction in fabric thickness is noticed at 20, 30 and 40 draft respectively. Also, the decrease in fabric thickness is 39.03%, 46.15% and 42.95% at 3.5, 4.0 and 4.5 TM respectively. It is further observed that the decrease in fabric thickness is more prominent with the increase of spindle speed followed by TM and draft. The observed trend can be explained based on radial packing density in different zones of the yarn, as given in Table 2.

3.2 Fabric Low-stress Mechanical Properties

3.2.1 Bending Properties

It is observed from Table 3 that the bending rigidity (B) of the fabric increases with increase in spindle speed, TM and draft both in warp and weft direction. However, in weft direction it reduces with the increase of draft. The values of bending rigidity in warp direction are always higher than in weft direction for all the researched yarns. Bending rigidity (B) of fabrics mainly depends on the flexural rigidity of component yarns and the mobility of the yarn in fabric. An increase in the values of B and 2HB of the fabric will reduce the fabric flexibility and elastic recovery from bending. A relatively low packing density yarn will tend to become more flattened due to the fibre movement in the yarn structure. A high packing density yarn will prevent inter-fibre movement but suffer intra-fibre strain. Therefore, the increase of bending rigidity with the increase of spindle speed, TM and draft can be explained on the basis of yarn packing density with the expected radial packing density. It has been established that the over-all yarn packing density increases with the increase of spindle speed, TM and ring frame draft. However, it decreases towards the surface zone of the yarns [22]. Increase of fibre compactness reduces fibre mobility in the yarn body, which makes the fabric more rigid. The higher bending rigidity in warp direction than in weft direction can be explained on the basis of higher end density in comparison to pick density of the fabric. The measured values of 2HB are found to increase with the increase in spindle speed, TM and draft. The hysteresis of the bending movement and the recoverability of the fabric after bending is represented by 2HB. A more open yarn is likely to recover more than a compact one. The reduction in the hysteresis value again throws some light on the radial packing behaviour of the yarn. It is further noticed that the values of 2HB are lesser in weft direction than in warp direction. The observed trend can be explained on the basis of number of ends and picks of the fabric.

3.2.2 Compression Properties

In general, the values of LC, WC and RC are found to increase with increase in spindle speed, TM and draft, as shown in Table 3. However, the value of RC initially decreases and then increases with increase in TM, whereas increase in draft gives reverse trend.

Table 3 — Bending and compressional properties of fabrics

Fabric	Bending properties				Compressional properties				
	B, gf cm^3		2HB, g.cm/cm		LC	WC gf.cm/cm^2	RC %	To mm	Tm mm
	Warp	Weft	Warp	Weft					
A	0.0802	0.0610	0.1108	0.0883	0.207	0.259	25.49	1.284	0.550
B	0.0803	0.0669	0.1106	0.0977	0.268	0.287	29.33	1.001	0.539
C	0.0852	0.0711	0.1001	0.0907	0.250	0.334	31.10	0.947	0.532
D	0.0755	0.0551	0.0910	0.0717	0.259	0.222	34.04	0.884	0.539
E	0.0958	0.0822	0.1242	0.1031	0.285	0.303	33.41	1.001	0.571
F	0.0791	0.0661	0.0869	0.0717	0.285	0.296	35.63	0.876	0.540
G	0.0919	0.0592	0.1328	0.1090	0.284	0.314	31.04	0.841	0.549

The observed trends of compressional behaviour of the fabrics are mainly due to the increase in fibre packing density and radial distribution of fibre in the yarn [22]. LC represents the linearity of compression curve and the value of LC is governed by the compressional behaviour of yarns and fabric thickness. The observed trend of LC can be supported from the obtained results of yarn packing density and fabric thickness. The value of WC is controlled by the extent of compression of fabric. The compression of fabric is governed by the extent of fibre compacting in the yarn body which restricts the mobility of fibres within yarn structure. However, the compressional resilience (RC) which is a measure of recoverability of the fabric after deformation, depends on the compressional behaviour of the yarns and overall fabric thickness. This again reflects that the internal structure of the yarn has much role to play, indicating that more open structure of yarn increases the likelihood of fabrics flattening.

3.2.3 Surface Properties

The results of surface properties of the fabrics are given in Table 4. A decrease in mean coefficient of friction (MIU) and surface roughness (SMD) is observed with the increase in spindle speed and ring frame draft. MIU and SMD initially increase and then decrease with the increase of TM. The mean deviation of frictional coefficient (MMD) does not show any trend with the increase of spindle speed, TM and draft. The fabric surface properties, such as MIU and SMD, are a measure of smoothness of the fabric. These properties are governed by surface properties of fibre & yarn, and fabric construction, such as thread density and weave. In the present situation, the values of MIU and SMD depend on the contact area, i.e. geometrical roughness. The contour of the yarn in the fabric decides the contact area, which in turn is decided by the resultant impact of diameter, packing density and bending rigidity of the yarn in the fabric.

3.2.4 Shear Properties

The results of shear properties of fabrics are also given in Table 4. The values of G and 2HG decrease with the increase in spindle speed and TM. The value of 2HG5 initially increases and then decreases with the increase of spindle speed, and it continuously decreases with the increase of TM. Further, it is noticed that the values of all three shear properties initially decrease and then increase with the increase of draft. Shear strain in continuum mechanism defines the deformation of material in which parallel internal surfaces slide over each other. Shear rigidity (G) depends on the mobility of the yarns in the fabric and

Table 4 — Surface and shear properties of fabrics

Fabric		Surface properties			Shear properties		
		MIU	MMD	SMD, µm	G, gf/cm.deg	2HG, gf/cm	2HG5, gf/cm
A	Warp	0.218	0.0218	11.137	1.58	4.55	6.71
	Weft	0.217	0.0202	7.755	0.91	4.1	3.58
	Average	0.2175	0.025	9.446	1.245	4.325	5.145
B	Warp	0.2	0.0295	10.468	1.51	4.49	7.14
	Weft	0.19	0.0205	6.075	0.85	3.14	3.85
	Average	0.195	0.025	8.2715	1.18	3.815	5.495
C	Warp	0.182	0.0143	6.047	1.53	4.38	6.66
	Weft	0.195	0.0237	6.603	0.17	3.04	0.81
	Average	0.1885	0.019	6.325	0.85	3.71	3.735
D	Warp	0.178	0.0232	10.407	1.84	4.94	7.84
	Weft	0.183	0.0257	7.86	0.96	4.14	4.6
	Average	0.1805	0.02445	9.1335	1.4	4.54	6.22
E	Warp	1.75	0.0279	11.343	0.86	3.66	3.3
	Weft	1.83	0.0233	6.99	0.76	3.1	3.21
	Average	1.79	0.0256	9.1665	0.81	3.38	3.255
F	Warp	0.179	0.0286	9.007	0.2	3.6	-2.13
	Weft	0.196	0.023	5.8	0.9	3.2	-0.81
	Average	0.1875	0.0258	7.4035	0.55	3.4	-1.47
G	Warp	0.191	0.0279	9.553	1.42	3.34	1.11
	Weft	0.212	0.0228	6.15	1.74	5.38	3.17
	Average	0.2015	0.02535	7.8515	1.58	4.36	2.14

depends on the cover factor of the fabric. It is observed from Table 2 that fractional cover of the fabric decreases with the increase of spindle speed, TM and draft. Accordingly, the decrease of fractional cover reduces shear rigidity and shear hysteresis of the fabric. The increase of shear rigidity with increase of draft from 30 to 40 can be explained on the basis of bending behaviour of the fabric. 2HG and 2HG5 are the shear hysteresis of shear force at 0.5º and 5º respectively. The shear hysteresis is a measure of frictional restraints arising during rotation of the yarn at the intersecting points of the fabric. The observed trends of shear hysteresis can be supported from the fractional cover of the fabric and packing density of yarn with expected differential radial packing density of yarn. Shear property has good correlation with the bending behaviour of the fabric.

3.3 Thermal Insulation Properties

3.3.1 Air Permeability

The results of air permeability of fabrics made of different spindle speeds, TM and draft are shown in Table 5. The increase in spindle speed, TM and draft show an increase in the air permeability of the fabric. The air permeability of the fabric is largely decided by the fabric structure, fabric tightness factor, yarn packing density, yarn radial packing density and yarn deformation properties in the fabric. Hence, the air permeability of the fabric is derived from the access of open space available for the passage of air in the fabric structure. The reduction in yarn diameter leads to decreased fabric fractional cover and accordingly increases the fabric porosity, which results in higher air permeability of the fabric. However, the yarn in the fabric with lower packing density as well as lower packing density towards surface zone result in more flattening of yarns, thereby covering more inter-yarn space in the fabric. It is further noticed that air permeability values are found to be maximum with increase of draft followed by TM and spindle speed.

3.3.2 Thermal Absorptivity

The effect of spindle speed, TM and draft on thermal absorptivity are shown in Table 5. The results show an increase in thermal absorptivity with the increase of spindle speed, TM and draft, except at 4.0 TM. It is further noticed that the thermal absorptivity values are found to be maximum with increase of draft followed by TM and spindle speed. The property of thermal absorptivity depends largely on the area of contact available to the heated body. This depends on the degree of curvature of the individual yarns in the fabric. Yarns with lesser diameter will curve less due to more fibre compactness and hence increase the surface area of contact. Therefore, the increase in the area of contact between the heated body and the fabric increases thermal absorption.

3.3.3 Thermal Diffusivity

It is observed from Table 5 that thermal diffusivity of the fabrics increases with the increase in spindle speed, TM and draft. Further, it is noticed that the considered process variables are not much influencing the thermal diffusivity of the fabrics. The thermal diffusivity is basically the rate at which a temperature disturbance at one point in a body travels to another point. It is a measure related to the heat flow through the fabric structure and depends on fabric density, specific heat of fabric and thermal conductivity. The thermal diffusivity of a fabric from a specific type of fibre increases with the increase in thermal conductivity but reduces with the increase in fabric density. The results depict that with the increase of spindle speed, TM and draft, the fabric density decreases.

3.3.4 Thermal Resistance

It is observed from Table 5 that the thermal resistance of the fabric decreases with the increase in spindle speed, TM and draft. The thermal resistance of the fabric is found to be maximum for spindle speed followed by TM and ring frame draft. Thermal

Table 5 — Thermal and transmission properties of fabrics

Parameter	A	B	C	D	E	F	G
Air permeability, $cm^3/cm^2/s$	17.821	22.21	22.40	18.91	22.73	22.71	22.842
Thermal absorptivity, $Ws^{1/2}/m^2.K$	86.20	86.95	87.88	88.28	101.52	86.95	87.88
Thermal diffusivity, m^2/s	0.122	0.122	0.124	0.121	0.124	0.121	0.124
Thermal resistance, m^2K/W	24.18	24.05	24.05	24.17	22.27	21.27	21.50
Heat conductivity, W/m.K	30.12	30.25	30.37	30.22	32.78	33.12	32.87
Moisture ttransmission							
MVTR, $g/in^2/day$	4.10	4.76	5.20	4.33	4.94	5.07	5.34
MMT (OWTC)	262.60	344.77	796.08	319.85	1084.70	741.01	874.50

resistance is a function of fabric thickness, cover factor, surface roughness and thermal conductivity. The higher the fabric thickness, the more is the resistance. The lower the thermal conductivity, the more is the resistance. The observed trend can be supported from the results of fabric thickness, cover factor and thermal conductivity, as discussed above. It has been established that the fabric thickness reduces with the increase in spindle speed, TM and draft. Hence, it can be concluded that with the increase in spindle speed, TM and draft, the thermal resistance of the fabric reduces due to the reduction in fabric thickness. Further, it has been established above that the thermal conductivity of the fabric increases with the increase in spindle speed, TM and draft due to the reduction in cover factor of the fabric. Therefore, it can be concluded that with the increase in spindle speed, TM and draft, reduction in fabric thickness and increase in thermal conductivity are responsible for the reduction in thermal resistance of the fabric.

3.3.5 Thermal Conductivity

Table 5 shows the influence of change in spindle speed, TM and ring frame draft on thermal conductivity of fabric. It is observed that with the increase in spindle speed, TM and draft, the thermal conductivity of the fabrics increases, except for draft of 40. It is further noticed that the thermal conductivity of the fabric is found to be maximum in case of draft followed by TM and spindle speed. The thermal properties of the fabric are decided by the type of fibre, yarn compactness, fabric cover, fabric thickness and bulk density of the fabric. The availability of more space within the fabrics makes the transmission of heat easier and this can further be supported from the results of fabric porosity. However, the increase in yarn packing density reduces the air pockets within the yarn, which results in higher thermal conductivity through the yarn body.

3.4 Moisture Transmission Properties

3.4.1 Moisture Vapour Transfer Rate (MVTR)

The results of air MVTR of fabrics made of different spindle speeds, TM and draft are shown in Table 5. The data confirms the increase of MVTR values with the increase in spindle speed, TM and draft. It is observed from the results that the influence of draft on MVTR is found to be highest followed by spindle speed and TM. The moisture transmission properties depend on the availability of open space within the yarn and between yarns in the fabric. Reduction in yarn diameter decreases the cover factor of the fabric, and hence increases the available space in the fabric, but increase in packing density of yarn reduces the chances of moisture transmission. Hence, in a given time, the amount of moisture vapours reaching the other side of the fabric increases with the increase of fabric porosity.

3.5 Moisture Management Test (MMT)

3.5.1 One Way Transport Capability (OWTC)

The results of one-way transport capability (OWTC) are given in Table 5. The value of OWTC is found to be increased with the increase in spindle speed, TM and ring frame draft. It is further noticed that the value of OWTC is maximum with change in draft followed by TM and spindle speed. The MMT measures the liquid moisture transfer quantitatively in single step of a fabric in multiple directions, where liquid moisture spreads on both surfaces of the fabric and transfers from one surface to the opposite surface. The above observed trends can be explained from the fabric porosity and fractional cover given in Table 2. It is observed that the fabric porosity increases but fractional cover of the fabric decreases with the increases of spindle speed, TM and draft.

4 Conclusion

A strong evidence has been established that by changing some of the considered ring frame process parameters like spindle speed, twist multiplier and draft, the packing density and radial packing density of yarn can be manipulated. The modified yarn structure has direct impact on the low stress mechanical, thermal and transmission characteristics of the fabrics. The study on low-stress mechanical properties of the fabrics reveals that, in general, the bending and compression properties increase, but shear and surface properties of the fabrics decrease with the increase of spindle speed, TM and draft. The study further reveals that air permeability, thermal absorptivity, thermal diffusivity, heat conductivity and moisture transmission properties increase but thermal resistance decreases with the increase of spinning process parameters.

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