Indian Journal of Fibre & Textile Research
Vol. 44, December 2019, pp. 424-430

Fabric comfort by modifying yarn structure: Part I – Study on structural changes by cross-sectional microtomy of yarn

S M Ishtiaque[a], Unsanhame Mawkhlieng & V K Yadav
Department of Textile Technology, Indian Institute of Technology Delhi, New Delhi 110 016, India

Received 16 April 2018; revised received and accepted 8 January 2019

A study has been carried out to engineer the fabric comfort by modifying the internal yarn structure through spinning process parameters. The yarn packing density is found to be one of most influential factors of yarn structure, which governs the comfort aspect of the textile material. The work reported here mainly deals with the influence of ring frame process parameters, i.e. spindle speed, twist and draft, on mechanics of yarn structure. It is evident that an increase in spindle speed, twist multiplier and draft decreases the yarn diameter and accordingly increases the packing density. The reduction in yarn diameter is found to be maximum with the increase of draft followed by twist multiplier and spindle speed. The yarn packing density also follows the similar trend. The radial packing density of considered yarns is neither uniform across the yarn cross-section nor maximum near the yarn axis. The maximum packing density is noticed at some distance from the yarn axis and it decreases further towards yarn surface. In general, yarns do not possess maximum packing density near yarn axis. It is observed that considered process parameters significantly influence the packing in core, intermediate and surface zone of the yarns.

Keywords: Fabric comfort, Packing density, Radial packing density, Spindle speed, Twist multiplier, Yarn microtomy, Yarn diameter, Yarn structure

1 Introduction

Clothing, being a primary part of human life, has many functions to perform. Adornment, status, protection, modesty are basically what clothing aims at achieving. Clothing basically forms a layer of barrier that protects the skin and the body against unsuitable environmental conditions. Comfort is perhaps the most important attribute of clothing. Owing to this ever-increasing concern for fabric comfort, researchers all over the world are working for deep understanding about the attributes of clothing. Several researchers tried different approaches to investigate fabric comfort[1-12]. But very few have attempted to study the effect of yarn spinning process parameters on fabric comfort[13-17]. The study of internal structure of yarn provides vital information about yarn characteristics[18-26]. Accordingly, this information can be effectively utilized to improve the fabric characteristics from comfort point of view, but available literature has not addressed this important issue. Engineering of yarn structure can bring some revolutionary changes in fabric quality from comfort point of view. The internal structure of yarn confirms the availability of free space inside the yarn body. The available space is measured in terms of yarn packing density and radial packing density which have direct influence on the fabric structure and its comfort characteristics. In real fabrics, the cross-section of yarn varies considerably for different fabrics. It depends on yarn linear density and packing density of yarn. Accordingly, yarn packing density influences the fabric cover factor. A knowledge of fibre specific volume helps in calculating the packing of fibres in the fabric. The studies on fabrics have shown that the inter-fibre and inter-yarn spaces contribute the most to the fabric porosity and accordingly the flow behaviour is governed by the wide range of pore sizes available in the fabric. Therefore, it generates the possibilities to engineer the fabric comfort by modifying the internal yarn structure. The literature part, however, shows that packing coefficient is one of most influential factors of yarn structure which governs the comfort aspect of the textile material. Realizing the importance, the present work is divided into two parts. Part I of the series (present study) mainly deals with the influence of ring frame process parameters, i.e. spindle speed, twist and draft, on mechanics of yarn structure for better understanding about packing

---

[a]Corresponding author.
E-mail: ishtiaque@iitd.ac.in

density and radial packing of yarns. Part II will address the influence of yarn structure on low-stress mechanical, thermal and transmission properties of fabrics.

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 present 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. Seven different types of yarns were produced from those rovings as per the details given in Table 1.

2.2 Preparation of Yarn Cross-section Cutting

The yarn sample were moulded with paraffin wax to give better support to the yarn while cutting the cross-section on microtome. The yarn cross-sections were cut to thickness of 30 μm using rotary microtome. The images of the yarn cross-sections were captured in camera fitted with microscope at magnification of ×100.

2.3 Analysis of Yarn Cross-section

The method of equidistance concentric zones as proposed earlier[18,20] was used to study the cross-section of the yarn. The yarn cross-section was divided in 30 concentric zones of equal width. The MS office messenger software was used to identify the centre of gravity of yarn cross-section. Firstly, the outermost boundary of captured image of yarn cross-section was cropped. By cropping the modified image to quarter image in term of pixel values, the centre of the cropped image was identified. Secondly, a template with 30 equidistance concentric zones was developed in MS office messenger software. The template was superimposed to yarn cross-sections as shown in Fig. 1. Finally, the template and yarn cross-section were grouped and saved as picture. ImageJ analysis software[27] was used to analyse the grouped images. The software converts the grouped image into B&W image. The area of the black component of image, which represent the fibres, was measured in terms of pixel value. The captured grouped images of yarn cross-sections were processed with MS office messenger software. The concentric zones were filled with white colour one after the other starting from inner most zone to 30th zone respectively. The white-colour filled image was preserved separately and then the total fibre area of respective preserved image was measured. The area of fibre possessed in the respective concentric zone is defined as the difference between the total area of the fibres in concentric zones to the next subsequent zones. The total area of the respective concentric zone was analysed by filling the annular ring with black colour and subtracting the pixel of next annular ring.

3 Results and Discussion

The photographs of selected cross-sections of different yarns are shown in Fig. 2.

3.1 Diameter and Packing Density of Yarns

The influence of spindle speed, twist multiplier and ring frame draft on yarn diameter and packing density of all researched yarns is discussed in the subsequent sections.

3.1.1 Influence of Spindle Speed

It is evident from Table 2 that an increase in spindle speed from 10,000 rpm to 16,000 rpm at a

Table 1 — Process parameters of yarns

Yarn code	A	B	C	D	E	F	G
Yarn TM	4	4	4	3.5	4.5	4	4
Spindle speed rpm	10000	13000	16000	13000	13000	13000	13000
Draft of ring frame	20	20	20	20	20	30	40

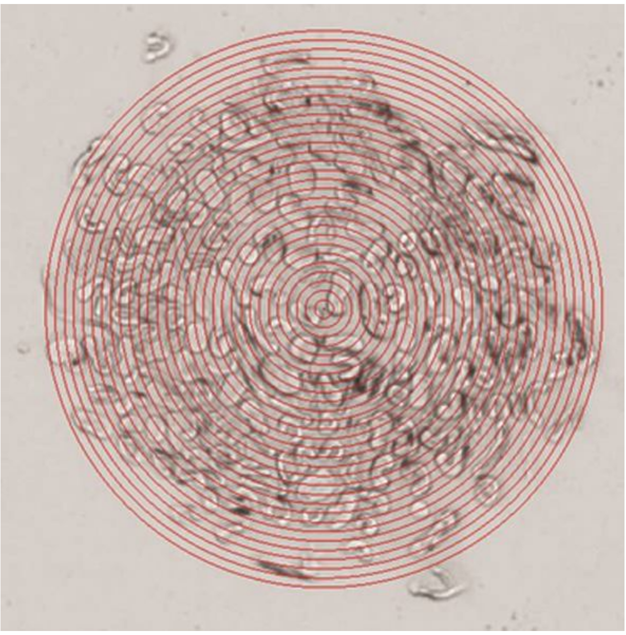

Fig.1 — A template with 30 equidistance concentric zones

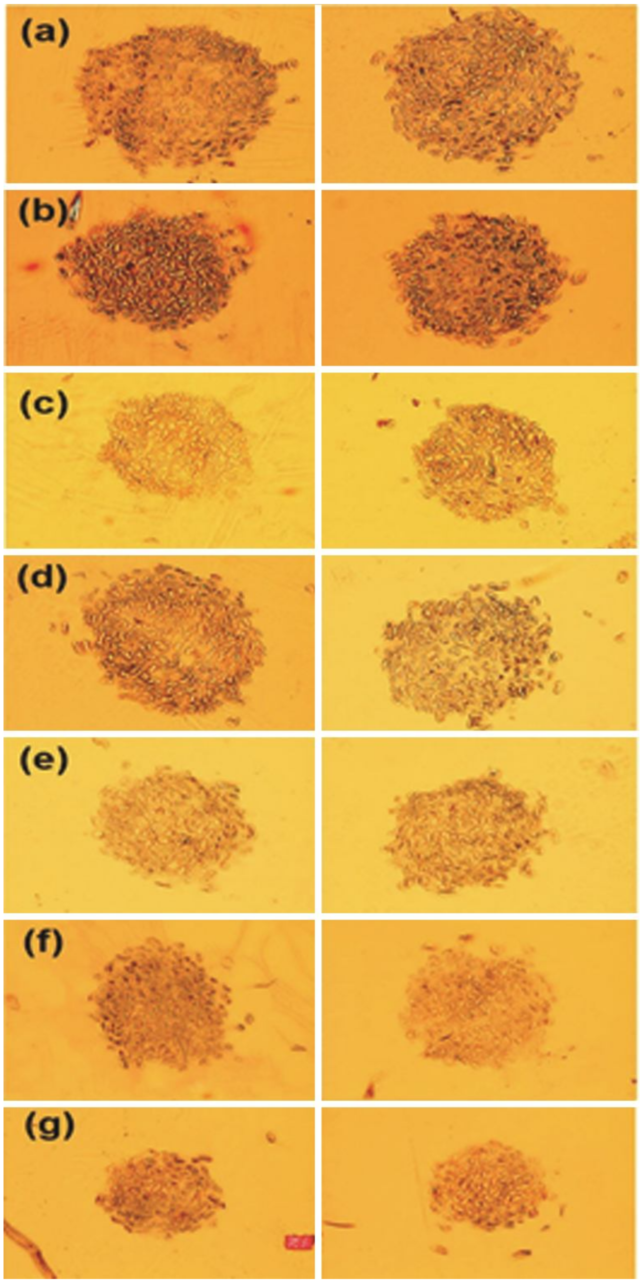

Fig. 2 — Cross-sectional images of (a) yarn A, (b) yarn B, (c) yarn C, (d) yarn D, (e) yarn E, (f) yarn F, and (g) yarn G

Table 2 — Yarn diameter and packing density

Yarn	Diameter obtained from graph, mm	Optically measured diameter, mm	Yarn packing density
A	0.269	0.2577	0.4556
B	0.230	0.2456	0.4564
C	0.208	0.2243	0.4676
D	0.250	0.2565	0.4303
E	0.189	0.2229	0.5117
F	0.215	0.2130	0.5145
G	0.210	0.2090	0.5212

constant twist multiplier 4.0 and draft 20 decreases the yarn diameter. The decrease in yarn diameter with the increase in spindle speed is significant at $\alpha = 0.01$. The decrease in yarn diameter with the increase of spindle speed from 10,000 rpm to 16,000 rpm is found to be 14.89%. But the increase in spindle speed from 10,000 rpm to 13,000 rpm brings greater reduction in yarn diameter than spindle speed from 13,000 rpm to 16,000 rpm.

The increase in spindle speed increases spinning tension which improves the fibre orientation in the spinning triangle due to the straightening and straining of fibres. The increase of tension in selvedge fibre of spinning triangle effectively improves the fibre orientation. Owing to this, a higher compaction of fibre at the conversion point of the spinning triangle is expected which can be confirmed from the results of yarn packing density given in Table 2. It is evident that an increase in spindle speed at a constant twist multiplier and draft, increases yarn packing density. The increase in yarn packing density with the increase in spindle speed is significant at $\alpha = 0.01$. It is evident from the results that due to an increase of spindle speed from 10,000 rpm to 16,000 rpm, the yarn packing density increases up to 2.66%. But the increase in spindle speed up to 13,000 rpm brings lesser increase in yarn packing density than that observed while increase in spindle speed from 13,000 rpm to 16,000 rpm.

3.1.2 Influence of Twist Multiplier

Table 2 shows that the increase in yarn twist multiplier decreases the yarn diameter and this decrease is significant at $\alpha = 0.01$. The increase of twist multiplier from 3.5 to 4.5 decreases yarn diameter up to 15.07%. But the reduction in yarn diameter is lower for twist multiplier from 3.5 to 4.0 in comparison to that from 4.0 to 4.5.

The observed trend can be explained on the basis of increase in lateral forces with the increase in yarn twist. This causes the fibres to move closer to each other in the yarn body and increases the packing density of yarns. It is noticed from Table 2 that the increase in twist multiplier at a constant spindle speed and draft, increases yarn packing density which is significant at $\alpha = 0.01$. The results confirm 12.12% increase in yarn packing density with the increase of twist multiplier from 3.5 to 4.5. The increase in twist multiplier from 3.5 to 4.0 shows lesser increase in the yarn packing density than that shown in twist multiplier from 4.0 to 4.5.

3.1.3 Influence of Draft

The results of Table 2 depict the increase of yarn diameter with the increase in ring frame draft. The observed change is significant at α = 0.01. The increase of ring frame draft from 20 to 40 decreases the yarn diameter up to 17.5%. The reduction in yarn diameter is noticed to be higher for draft value from 20 to 30 than that from 30 to 40 draft value.

The increase in ring frame draft increases the drafting force per unit mass of fibre, which, in turn, de-crimp the fibres during drafting and align the fibres along the yarn axis. The results of yarn packing density confirm the hypothesis that the increase of draft increases yarn packing density. The increase in yarn packing density is significant at α = 0.01. The increase of ring frame draft from 20 to 30 at constant spindle speed and twist multiplier increases the yarn packing density up to 14.2%. But initial increase of draft from 20 to 30 shows higher increase in yarn packing density than that observed in case of draft from 30 to 40.

On the basis of above findings, it can be concluded that the reduction of yarn diameter is found to be maximum with the increase of draft followed by twist multiplier and spindle speed. The yarn packing density also follows the similar trend.

The changes in yarn diameter and packing density due to considered process parameter are likely to influence thermal, transmission and low-stress mechanical characteristics of fabrics, leading to affect (i) fabric porosity due to yarn spacing and yarn packing density; and (ii) fabric thickness due to radial distribution of fibres within the yarn. The influence of these aspects will be dealt in the subsequent sections.

3.2 Radial Packing Density of Yarns

Study related to radial packing density of yarn further strengthen the knowledge about the mechanics of yarn structure. Table 3 shows the results of fibre packing density in the respective concentric zones of seven researched yarns. The fibre packing density in the respective zone is defined as the ratio of fibre area in the zone to the total area of the respective zone. Accordingly, the radial packing density curves of the respective yarn have been drawn and results are

Table 3 — Packing density of yarn in different concentric zones

Zone	Yarn						
	A	B	C	D	E	F	G
1	0.500	0.499	0.495	0.437	0.602	0.552	0.600
2	0.512	0.513	0.580	0.478	0.612	0.570	0.635
3	0.475	0.484	0.519	0.456	0.593	0.550	0.667
4	0.455	0.477	0.502	0.435	0.603	0.527	0.664
5	0.461	0.473	0.472	0.458	0.575	0.560	0.628
6	0.451	0.486	0.484	0.481	0.576	0.572	0.642
7	0.451	0.494	0.481	0.481	0.555	0.570	0.646
8	0.446	0.477	0.445	0.513	0.544	0.568	0.625
9	0.458	0.478	0.442	0.510	0.490	0.558	0.592
10	0.489	0.474	0.426	0.543	0.444	0.546	0.530
11	0.468	0.453	0.383	0.560	0.328	0.512	0.448
12	0.494	0.425	0.328	0.537	0.221	0.454	0.341
13	0.499	0.373	0.243	0.484	0.123	0.355	0.256
14	0.487	0.300	0.153	0.393	0.069	0.234	0.174
15	0.444	0.206	0.098	0.296	0.033	0.118	0.096
16	0.385	0.119	0.074	0.218	0.009	0.051	0.053
17	0.289	0.064	0.059	0.150	0.003	0.024	0.030
18	0.182	0.027	0.046	0.104	0.001	0.008	0.016
19	0.093	0.014	0.035	0.068	0	0.003	0.007
20	0.036	0.007	0.023	0.048	0	0.003	0.004
21	0.015	0.003	0.015	0.039	0	0.001	0.002
22	0.011	0	0.008	0.024	0	0.002	0.001
23	0.004	0	0.004	0.013	0	0	0.001
24	0.003	0	0.002	0.011	0	0	0
25	0.003	0	0.001	0.007	0	0	0
26	0.003	0	0	0.004	0	0	0
27	0.001	0	0	0.002	0	0	0
28	0	0	0	0.001	0	0	0
29	0	0	0	0.001	0	0	0
30	0	0	0	0	0	0	0

shown in Fig. 3. It is well depicted that the radial packing density curves of all researched yarns have good resemblance. The radial packing density of yarns is neither uniform across the yarn cross-section nor maximum near the yarn axis. This strengthens the concept of non-linear compactness of fibres in the yarn body. The maximum packing density is noticed at some distance from the yarn axis and decreases further towards yarn surface. In general, all yarns do not possess maximum packing density near yarn axis. The observed trend can be explained on the basis of ribbon-twist hypothesis proposed by Hickie and Chaikin[19] and further confirmed by Necker[18] and Ishtiaque[25]. Drafted small width fibres ribbon during twisting get converted to roughly circular shape at the convergence point of the spinning triangle. The positioning of fibres in the spinning triangle decides the level of strain in the fibres. The selvedge fibres get strain more due to higher yarn tension but the fibres in the middle are likely to buckle due to lesser tension. Hence, the stress on the selvedge fibre is increased by lengthening the fibre path and stress on the middle fibre is released by shortening it. The fibres get longitudinally strained, due to twist insertion in the yarn. But fibres try to get reoriented, which highly depend on the physical states of competing fibre, to reach the position of minimum strain near the yarn axis under minimum energy state condition. Therefore, due to such dependable movement of fibres in the spinning triangle, it increases the possibilities of not having maximum packing density near the yarn axis.

All researched yarns confirm maximum packing density at some distance from the yarn axis. The earlier works of Hickie and Chaikin [19] and Ishtiaque [25] also confirmed the above trend. But the findings of Soni[21] and Kumar *et al.*[22] showed that the helix twist of yarn is not maximum near the yarn axis, rather it is maximum at some distance from the yarn axis. Maximum helix twist was observed in the intermediate zone followed by core and surface zone of the yarn[22]. Therefore, it can be concluded that the trends of radial distribution of fibre and twist in the yarn are having very good resemblance. Therefore, it can be concluded that the radial twist distribution inside the yarn governs the behaviour of radial packing density of the yarn.

3.2.1 Influence of Spindle Speed

It can be observed from Table 3 and Fig. 3(a) that an increase in spindle speed increases the packing density towards yarn core but reduces towards yarn surface. For better understanding, the yarn cross-section is divided into three equal width zones to represent core, intermediate and surface zone, as shown in Fig. 4. It is evident from Table 4 that yarn C

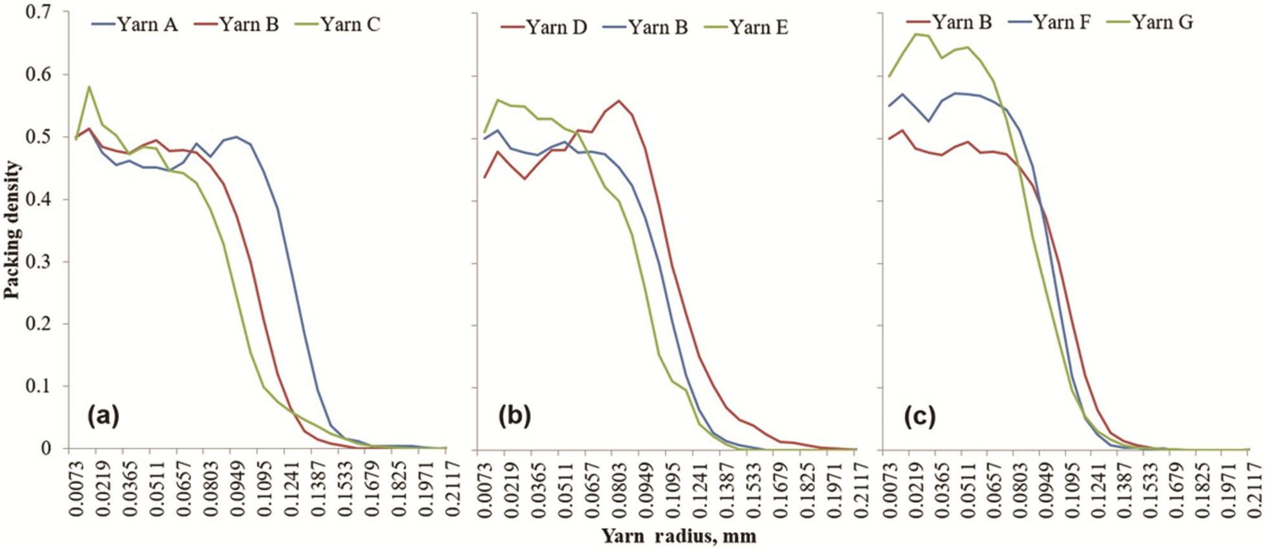

Fig. 3 — Influence of (a) spindle speed, (b) TM and (c) draft on radial packing density of yarns

Table 4 — Packing density of yarns in three concentric zones

Zone	A	B	C	D	E	F	G
Core	0.46405	0.48216	0.50368	0.46136	0.59196	0.54964	0.64560
Intermediate	0.47055	0.47466	0.45146	0.52820	0.51302	0.56109	0.62319
Surface	0.36856	0.23199	019826	0.25913	0.11631	0.31847	0.28613

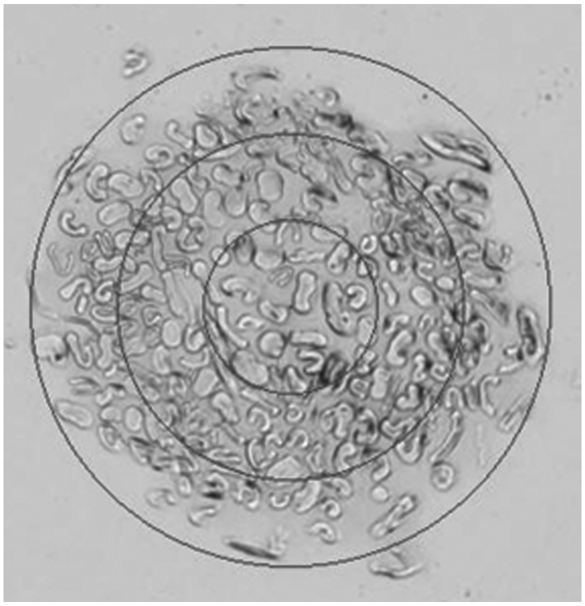

Fig. 4 — Yarn cross-section divided into three zones of equal width

gives maximum packing density in the core zone followed by yarn B and yarn A, but yarn A gives maximum packing density in the surface zone followed by yarn B and yarn C with the increase of spindle speed.

The increase in spindle speed increases tension in selvedge fibres of the spinning triangle. The fibres located in the core of yarn take the axial force and the fibres positioned on the yarn surface take the force radially. The radial force developed on the surface fibres tries to push the fibres of intermediate and core zones towards yarn axis. During this process, the fibres get aligned along the yarn axis due to the fibre straightening and straining, and thus results in more compactness towards core zone of the yarn. It is evident that yarn C possesses maximum packing density in the core zone followed by yarn B and yarn A with the increase in the spindle speed. But the surface fibres under tension, after pushing the fibres towards yarn axis, try to come under minimum energy state. During this process, it releases tension of the surface fibres and creates open structure towards surface zone of the yarn. Further, the length of spinning triangle reduces with the increase of spindle speed. In the case of spinning triangle with shorter length, the selvedge fibres are strongly deflected to bind them in the yarn body. But some selvedge fibres get escaped the twist effect and the trailing end of the fibre comes out from the yarn body and create hair. On the other hand, a long spinning triangle has advantage that the selvedge fibres are better bound into the yarn, which gives smoother and more compactness towards surface zone. The proposed hypothesis is visualized from our results that yarn C gives lowest packing density on the surface zone followed by yarn B and yarn A with the increase of spindle speed.

3.2.2 Influence of Twist Multiplier

It is evident from Table 4 and Fig. 3(b) that the increase of twist multiplier increases the packing density in the core zone but decreases packing in the intermediate and surface zone. But the decrease of packing density with the increase of twist multiplier from 4.0 to 4.5 in the intermediate zone is not noticed.

The increase in yarn twist increases the lateral force acting on the fibre assembly which makes the fibre bundle highly compressed and causes reduction of yarn diameter. The insertion of twist causes longitudinal strain in the fibres and these fibres compete to reach minimum stress. The extent of this re-orientation depends on physical state of competing fibres. The developed lateral force pushed the outer layer fibres to inner layer towards the yarn axis and fibres get aligned due to straightening and straining. This leads to increased fibre compactness towards core zone of the yarn. It is evident from our results that yarn E gives maximum packing density in the core zone followed by yarn B and yarn D with the increase in twist. But the longitudinally strained surface fibres try to come under minimum energy state and release the tension, which makes surface structure of yarn more open. The proposed hypothesis can further be realized that the surface zone of yarn E provides lowest packing density followed by yarn B and yarn D with the increase of twist. It is observed from our results that yarn D gives maximum packing density in the intermediate zone followed by yarn E and yarn B with the increase in twist. The trend of intermediate zone can be explained on the basis of interlocking of fibres of in different zones, they get lesser opportunities to come under minimum energy state. Further, subsequent insertion of twist maintains the physical state of fibres.

3.2.3 Influence of Draft

It is depicted from Table 4 and Fig. 3(c) that the increase in ring frame draft significantly increases the packing density in the core and intermediate zone, but in the surface zone the packing increases up to draft 30 and further increase of draft reduces the packing density.

The drafting force per unit mass of fibre increases with the increase of ring frame draft. Drafting force further increases due to the flattening of roving because bulk of the feed material decides the flattening of roving. Therefore, the feeding of coarsest roving is likely to give maximum flattening at the nip point of the back rollers. Hence, the fibre ribbon follows the highest convergence angle while feeding the coarsest roving to the drafting system. Further, the increase of draft increases compactness of fibre ribbon in the drafting zones due to the de-crimping and straightening of fibre before twisting. The proposed hypothesis can be verified from our results. It is evident from our results that yarn G gives the maximum packing density in the core and intermediate zone of yarn followed by yarn F and yarn B with the increase of draft. Further, amount of draft also decides the width of the spinning triangle, i.e. higher the draft, lower will be the width of the spinning triangle. Due to spinning tension, the selvedge fibres of spinning triangle are under greater strain. Therefore, increase of convergence angle and draft are responsible to bring changes in the spinning triangle geometry. But feeding roving of different fineness is responsible to increase the packing density in the surface zone of the yarn. But the results show the reduction in packing density with the increase of draft from 30 to 40. The noticed trend can be explained on the basis of proposed hypothesis of spinning triangle geometry as discussed above in section **3.2.1**.

4 Conclusion

The considered ring frame process parameters, i.e. spindle speed, twist multiplier and draft, have an inverse effect on yarn diameter. The yarn diameter decreases but the packing density increases with the increase in one of the process parameters while maintaining the other two parameters constant. Impact of draft on increase in packing density is maximum followed by twist multiplier and spindle speed. The radial packing density curves of all researched yarns have good resemblance. The radial packing density of yarns is neither uniform across the yarn cross-section nor maximum near the yarn axis. The maximum packing density is observed at some distance from the yarn axis and decreases further towards yarn surface. In general, the researched yarns do not possess maximum packing density near yarn axis. The increase of spindle speed, twist multiplier and draft, increases packing density in the core zone but gives reverse trend at the surface zone except for draft where packing density initially increases and then decreases. The intermediate zone does not follow any particular trend. The impact of draft on packing density in the different zones is found to be maximum. The observed structural changes are likely to influence thermal, transmission and low-stress mechanical characteristics of fabrics due to change in fabric porosity and thickness.

References

1 Behera B K, Ishtiaque S M & Chand S, *J Text Inst*, 88 (1997) 255.
2 Das A & Yadav S, *J Text Inst*, 103 (2012) 1244.
3 Das A & Ishtiaque S M, *J Text Apparel, Technol Management*, 3 (2004) 1.
4 Das A, Kothari V K & Balaji M, *J Text Inst*, 98 (2007) 261.
5 Das A, Kothari V K & Balaji M, *J Text Inst*, 98 (2007) 363.
6 Das A, Ishtiaque S M & Singh R P, *J Text Inst*, 100 (2009) 207.
7 Ishtiaque S M, Das A & Singh R P, *J Text Inst*, 99 (2008) 147.
8 Mukhopadhyay A, Ishtiaque S M & Uttam D, *J Text Inst*, 102 (2011) 700.
9 Kawabata S & Niwa M, *Int J Cloth Sci Tech*, 4 (1992) 34.
10 Kawabata S & Niwa M, *Int J Cloth Sci Tech*, 3 (1991) 7.
11 Özdil N, Marmaralı A & Kretzschmar S D, *Int J Therm Sci*, 46 (2007) 1318.
12 Holmér I, *Ergonomics*, 38 (1995) 166.
13 Ishtiaque S M, Sen K & Kumar A, *J Text Inst*, 107 (2016) 683.
14 Ishtiaque S, Sen K & Kumar A, *J Ind Text*, 44 (2015) 625.
15 Ishtiaque S M, Sen K & Kumar A, *J Text Inst*, 106 (2014) 1190.
16 Ishtiaque S M, Das A & Kundu A K, *J Text Inst*, 105 (2014) 736.
17 Ishtiaque S M, Das A & Kundu A K, *J Text Inst*, 105 (2014) 348.
18 Neckář B, *Text Res J*, 46 (1976) 545.
19 Hickie T & Chaikin M, *J Text Inst*, 65 (1974) 433.
20 Ishtiaque S & Neckar B, *Indian J Fibre Text Res*, 11 (1986) 26.
21 Soni M, *Internal Structure of Yarn*, PhD thesis, University of Mechanical and Textile Engineering, Liberec, Czechoslovakia, 1979.
22 Kumar A, Ishtiaque S & Das A, *Fiber Polym*, 13 (2012) 1071.
23 Van Langenhove L, *Text Res J*, 67 (1997) 342.
24 Ishtiaque S M, Sharma I C & Sharma S, *Indian J Fibre Text Res*, 18 (1993) 116.
25 Ishtiaque S, *Indian J Text Res*, 11 (1986) 208.
26 Ishiaque S M, *Indian J Fibre Text Res*, 11 (1986) 215.
27 *Imagej-Image Processing and Analysis in Java* (National Institutes of Health), 2016. https://imagej.nih.gov/ij/index.html (accessed on 2016).