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# Modulation of cross-sectional structure of air-vortex yarn through process variables

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Influence of process parameters on structural mechanics of air-vortex polyester cotton (65/35) blended yarn has been studied. Box-Behnken three variables design is used to optimize the spindle diameter, nozzle pressure and yarn delivery speed to achieve the required packing density of air vortex yarn. Image processing technique is used to measure the fibre area in different concentric zones. The study confirms that the yarn packing density and radial packing density of yarns are influenced by individual as well as interaction effect of process parameters. The packing density is not found to be maximum near the yarn axis. It is depicted that packing density of core, intermediate and surface zones of the yarn shows an increase with the increase in nozzle pressure, and decrease with the increase in spindle diameter and yarn delivery speed. The packing density of ring-spun yarn is found to be higher than vortex yarns with distinctly higher packing in the core- zone of the yarn.

**Keywords:** Air-vortex yarn, Delivery speed, Nozzle pressure, Packing density, Polyester/Cotton yarn, Radial packing density, Spindle diameter, Yarn structure

## 1 Introduction

The physical and mechanical properties of yarns are not only governed by the properties of constituent fibres and process parameters rather derived by structural changes in the yarn influenced by the properties of constituent fibres and process parameters. Henceforth, the study of internal structure of yarn has attracted the researchesto understand better the mechanics of yarn formation of different spinning systems. Ishtiaque *et al.*[1], Neckář *et al.*[2], Göktepe *et al.*[3], Ishtiaque[4], Zheng *et al.*[5], Punj *et al.*[6], and Ishtiaque *et al.*[7] have conducted several studies related to distribution of fibres in the cross-section of yarn made on different spinning systems.

Zhuan *et al.*[8] concluded that air-vortex spinning technology created a high-level of market acceptance due to its higher production rates and few special yarn characteristics. The research works carried out by Basal & Oxenham[9], Oxenham[10] and Soe *et al.*[11] have established the superiority of air-vortex yarns over ring spun yarns in terms of visual appearance and hairiness. Basal & Oxenham[12], Tyagi *et al.*[13], Tyagi & Sharma[14], Zheng *et al.*[15], Zhuan *et al.*[16], Zou[17], Zou *et al.*[18] and Zou *et al.*[19] studied the influence of air-vortex yarn properties on the performance of fabric. The structure of air-vortex yarn differs significantly from conventional yarns, as it is comprised of wrapper fibres and the core fibres. Kilic *et al.*[20] used image processing approach to compare the packing densities of yarns made on ring, compact systems and vortex systems. Zheng *et al.*[21] analyzed the arrangement of fibres in the cross-section of vortex-spun and ring yarns. Basal & Oxenham[12], Cheng *et al.*[22] and Zou *et al.*[23] studied the trajectory of core and surface fibres of vortex-spun yarn influenced by the process parameters.

However, the influence of machine and process variables on distribution of fibres in the cross-section of vortex-spun yarn has not been much experimentally validated. It is a known fact that information related to distribution of fibres in the cross-section of yarns made on different spinning systems felicitates to engineer the comfort properties of fabrics[24, 25] and the properties of sized and dyed yarns for different applications. Therefore, in present work, an attempt has been made to study the packing density and radial packing density of vortex-spun yarn influenced by process variables. Further, the work has been extended to measure the packing density exclusively in the core, intermediate and surface zones of yarn. Accordingly, Box-Behnken three variables three factors design is used to optimize the spindle diameter, nozzle pressure and yarn delivery speed to achieve the required packing density and radial packing density of air vortex polyester/cotton blended yarn and the results are compared with corresponding ring yarn. The proposed work is expected to provide a

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new direction to engineer the cross-sectional structure of yarns to achieve the required functional properties of fabrics for specific end use by using right combination of process parameters.

## 2 Materials and Methods

Polyester fibre of 1.4 denier, 38 mm length and cotton fibre of 4.0 micronaire were used to prepare 30 Ne polyester/cotton (65/35) blended yarn on MVS 870 model of vortex spinning system. A ring-spun yarn was also prepared for comparison point view. Box Behnken three variables three factors design was used to optimize the spindle diameter, nozzle pressure and yarn delivery speed to achieve the required packing density of yarn. The actual values of variables corresponding to coded levels are shown in Table 1. A three variables three factors design generated is given in Table 2.

Total 15 samples were prepared with a combination of different process parameters as shown in Table 2. The ANOVA technique was applied to study the impact of individual as well as interaction effect of considered process parameters on yarn packing density. Accordingly, response surface equations were obtained for respective structural characteristics of yarn. The results of corresponding ring yarn are also given in Table 2.

Table 1 — Actual values of variables corresponding to coded levels

| Variables | Levels | | |
|---|---|---|---|
| | -1 | 0 | 1 |
| Spindle diameter (A), mm | 1.0 | 1.1 | 1.2 |
| Nozzle pressure (B), MPa | 0.45 | 0.5 | 0.55 |
| Yarn delivery speed (C), m/min | 400 | 450 | 500 |

### 2.1 Preparation of Cross-section Cutting of Yarn

The yarn was first coated with solution of 13 mL acetone and 1.8 g polyvinyl acetate to avoid displacement of fibre while cutting. Micro tip was used to make mould for cutting the cross-section of yarn. The coated yarn was placed vertically straight at the centre of the micro tip. Cyanoacrylate was poured into micro tip with the help of syringe. For each sample 20 micro tip were prepared. The prepared moulds were placed in vacuum oven for 8h at 70°C to harden the resin. The cross-sections of yarn were cut by Leica Ultra Microtome to mere thickness of 25-30 µm. The cross-sections were placed on glass slide and a drop of xylene was put on the cross-section to enhance the optical property and the quality of image. The images were viewed on Leica microscope at × 200 magnification. The selective cross-sections of vortex yarn with different combinations of process parameters as well as cross-section of corresponding ring-spun yarn are given in Fig. 1.

### 2.2 Measurement of Fibre Area in Different Concentric Zones Using Image Processing Technique

The method of equidistance concentric zones as proposed by Neckář *et al*[2], was used to study the cross-section of the yarn. The special purpose software was used to locate the centre of gravity of yarn cross-section by cropping the outermost boundary of yarn cross-section. The width of concentric zone was

Table 2 — Three variables three factors experimental design with corresponding yarn properties

| Sample/ yarn no. | Spindle diameter mm | Nozzle pressure MPa | Yarn delivery speed m/min | Yarn diameter mm | Yarn packing density | Yarn packing density of core zone | Yarn packing density of intermediate zone | Yarn packing density of surface zone |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.0 | 0.45 | 450 | 0.218 | 0.380 | 0.420 | 0.318 | 0.0451 |
| 2 | 1.2 | 0.45 | 450 | 0.240 | 0.335 | 0.381 | 0.315 | 0.0438 |
| 3 | 1.0 | 0.55 | 450 | 0.211 | 0.394 | 0.440 | 0.387 | 0.1110 |
| 4 | 1.2 | 0.55 | 450 | 0.218 | 0.378 | 0.404 | 0.312 | 0.0121 |
| 5 | 1.0 | 0.50 | 400 | 0.209 | 0.421 | 0.444 | 0.398 | 0.0645 |
| 6 | 1.2 | 0.50 | 400 | 0.210 | 0.400 | 0.437 | 0.374 | 0.0341 |
| 7 | 1.0 | 0.50 | 500 | 0.218 | 0.367 | 0.383 | 0.276 | 0.0301 |
| 8 | 1.2 | 0.50 | 500 | 0.232 | 0.330 | 0.364 | 0.267 | 0.0170 |
| 9 | 1.1 | 0.55 | 400 | 0.207 | 0.441 | 0.460 | 0.389 | 0.0315 |
| 10 | 1.1 | 0.45 | 400 | 0.213 | 0.384 | 0.438 | 0.277 | 0.0090 |
| 11 | 1.1 | 0.45 | 500 | 0.230 | 0.338 | 0.365 | 0.285 | 0.0360 |
| 12 | 1.1 | 0.55 | 500 | 0.218 | 0.352 | 0.380 | 0.279 | 0.0280 |
| 13 | 1.1 | 0.50 | 450 | 0.212 | 0.390 | 0.424 | 0.330 | 0.0431 |
| 14 | 1.1 | 0.50 | 450 | 0.208 | 0.433 | 0.428 | 0.347 | 0.0292 |
| 15 | 1.1 | 0.50 | 450 | 0.224 | 0.371 | 0.409 | 0.301 | 0.0365 |
| Ring yarn | | | | 0.196 | 0.468 | 0.478 | 0.303 | 0.205 |

decided by considering that the cross-section of individual fibre should occupy minimum three adjacent concentric zones. Accordingly, a template with 30 equidistance concentric zones was developed in software. Image J analysis software which converts the grouped image into B&W image was used to analyze the images. The area of the black component of image, which represents the fibres, was measured in terms of pixel value. The concentric zones were filed with white colour one after the other starting from inner most zone to $30^{th}$ zone respectively. Respective white-colour filed image was preserved separately and then the total fibre area of respective 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 analyzed by filling the annular ring with black colour and subtracting the pixel of next annular ring. Packing density of yarn is defined as the ratio of total area of fibres as black pixel to the area of yarn which includes both white and black pixel. Diameter of yarn was measured through microscope at ×200 magnification.

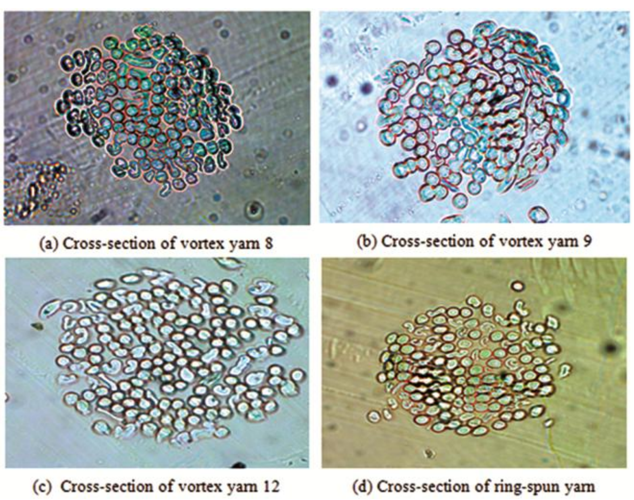


Fig. 1 — Yarn cross-sections of vortex and ring-spun yarns

## 3 Results and Discussion

### 3.1 Influence of Process Parameters on Yarn Packing Density

The experimental results of yarn diameter and packing density of yarns, as per experimental plan, are given in Table 2. The yarn diameters have been measured optically. The ANOVA analysis is conducted to find out the impact of individual as well as interaction effect of considered process parameters on packing density of yarn and the results are given in Table 3.

The response surface equation for packing density of yarn in terms of coded factors and significant model terms is represented in following equation :

$$\text{Yarn packing density} = 0.3792 - 0.0148^{*} A + 0.0023875^{*} B - 0.03175^{*} C \quad \dots (1)$$

Very strong correlation was observed between packing density of yarn and machine parameters with a $R^2$ value 0.823. It is observed from Eq. (1) that the packing density of yarn registers a decrease with increase in spindle diameter (A) and yarn delivery speed (C), but it increases with the increase in nozzle pressure (B). Further, it is noticed that yarn delivery speed plays a major role followed by spindle diameter and nozzle pressure to reduce the yarn packing density. A reduction in yarn packing density is observed with increase in spindle diameter, nozzle pressure and yarn delivery speed together. Therefore, it can be inferred that the increase in spindle diameter and yarn delivery speed dominates over nozzle pressure to reduce the packing density of yarn.

The yarn packing density has been plotted in a 3-D graphs against two variable as machine parameters keeping one of the parameter constant. The obtained trends of packing density influenced by spindle diameter, nozzle pressure and yarn delivery speed are discussed in subsequent sections. Thereafter, process parameters are optimized for minimum or maximum values of packing density.

Table 3 — ANOVA analysis for response surface linear model
[Partial sum of squares - Type III]

| Source | Sum of Squares | Df | Mean Square | F-Value | p-value Prob> F | |
|---|---|---|---|---|---|---|
| Model | 0.009877 | 3 | 0.003292 | 4.86819 | 0.0216 | Significant |
| Spindle diameter (A) | 0.001767 | 1 | 0.001767 | 2.612921 | 0.1343 | |
| Nozzle pressure (B) | 4.56E-05 | 1 | 4.56E-05 | 0.067426 | 0.7999 | |
| Delivery speed (C) | 0.008065 | 1 | 0.008065 | 11.92422 | 0.0054 | |
| Residual | 0.007439 | 11 | 0.000676 | | | |
| Lack of fit | 0.003655 | 9 | 0.000406 | 0.214595 | 0.9592 | not significant |
| Pure error | 0.003785 | 2 | 0.001892 | | | |
| Cor total | 0.017317 | 14 | | | | |

The contour diagram in Fig. 2(a) illustrates the influence of nozzle pressure v/s spindle diameter at 450 m/min delivery speed. The increase in nozzle pressure shows an increase in yarn packing density but depicts a decrease with the increase in spindle diameter. The observed trends are applicable for all considered yarn delivery speeds. The increase in nozzle pressure increases whirling force of nozzle air flow. Hence, core fibres are tightly held together by wrapper fibres. Further, the increase in nozzle pressure provides more twist in fibre bundle due to increase in both tangential and axial velocity. These factors provide better wrapping intensity of fibres on the body of the yarn with the increase in nozzle pressure, and hence show higher packing density of yarn. Spindle with lower diameter provides lesser freedom for the expansion of fibre bundle when it enters hollow spindle. This provides higher friction between the fibres and is responsible for higher twist, tighter wrapping and denser yarn. It is inferred from Eq. (1) that the increase in both nozzle pressure and spindle diameter has noticed a moderate reduction in the yarn packing density at respective yarn delivery speeds. But the increase in yarn delivery speed depicts high reduction in packing density. Following two reasons justify the observed trend. Firstly, the increase in delivery speed reduces residence time for free trailing end of fibres in the spindle chamber in order to get wrapped over the yarn core. This provides insufficient wrapping intensity of fibre over the core of the yarn. Secondly, the number of wrapper loops per unit length also decreases with the increase in delivery speed. Both the reasons are responsible for lowering the packing density of yarn. But a reduction in the yarn packing density is observed with the increase of nozzle pressure, spindle diameter and yarn delivery speed together.

The influence of nozzle pressure and yarn delivery speed at 1.1mm spindle diameter is shown in Fig. 2(b). The results from Eq.(1) of different spindle diameters depict an increase in yarn packing density with the increase in nozzle pressure but shows a reduction with the increase in yarn delivery speed. The yarn packing density infer a moderate decrease with the increase in both nozzle pressure and delivery speed at respective spindle diameter but a moderate reduction in packing density is observed with the increase in spindle speed. The simultaneous increase in nozzle pressure, spindle diameter and yarn delivery speed notices a reduction in the yarn packing density. The obtained trends can be justified as discussed above.

The contour diagram [Fig. 2(c)] shows the influence of yarn delivery speed and spindle diameter at 0.5 MPa nozzle pressure. Equation (1) depicts a decreasing trend of yarn packing density with the increase in spindle diameter and yarn delivery speed at different nozzle pressures. Once both spindle diameter and yarn delivery speed are increased simultaneously, a high decrease in yarn packing density is noticed at respective nozzle pressure but yarn packing density depicts an small increase with the increase in nozzle pressure. The simultaneous increase of nozzle pressure, spindle speed and yarn delivery notices a reduction in the yarn packing density. Explanations given above are equally applicable for the obtained trends.

The above discussions have reported a reduction in packing density of the yarn with the simultaneous increase in spindle diameter, nozzle pressure and yarn

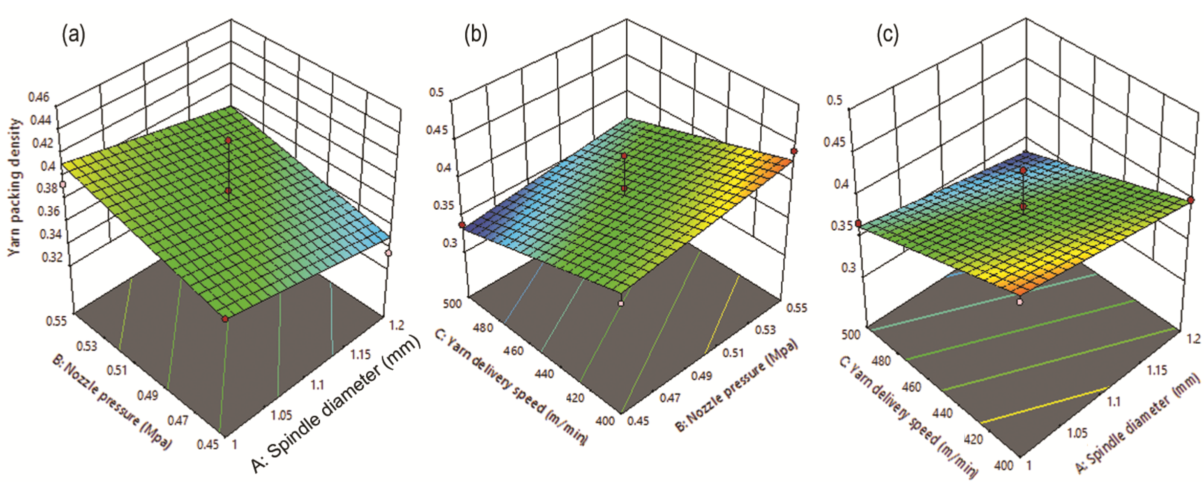


Fig. 2 — Effect of process variables on yarn packing density (a) yarn delivery speed 450 mm/min, (b) spindle diameter 1.1 mm and (c) nozzle pressure 0.5 MPa

delivery speed. But reduction in packing density is observed with the increase in spindle diameter and yarn delivery speed, and increase in packing density is found with the increase in nozzle pressure. Hence, it can be inferred that yarn delivery speed and spindle diameter have dominance over nozzle pressure to govern the packing density of the yarn. It is to be noted from Table 2 that packing density of air-vortex yarn is found to be lower than corresponding ring yarn.

### 3.2 Radial Packing Density of Yarn

The information related to yarn packing density limits to know only whether fibres are loosely or tightly packed in the yarn. But it does not reveal how fibres are radially distributed in the yarn cross-section. Study related to radial packing density of yarn provides an insight mechanics of yarn formation, hence internal structure of yarn. The information related to radial distribution of fibres in yarn becomes more relevant to optimize the sizing and dyeing processes of yarn, fabric comfort[24, 25] and some other applications. Accordingly, it is decided to study the radial packing density of vortex-spun yarn influenced by process variables.The graphs of radial packing density of few selective vortex yarns and corresponding ring yarn are shown in Fig. 3. The results confirmed the non-uniformity of radial packing density across the yarn cross sections. The packing density is not found to be maximum near the yarn axis. The maximum packing density is noticed at some distance from yarn axis and shows a decrease towards the surface of the yarn after this point. In general, the maximum packing density is observed between 1/4th or 1/3rd of yarn radius from yarn axis. The results of corresponding ring yarn have also confirmed the pattern of radial packing density of air-vortex yarn. The observed trends are also noticed by Ishtiaque[4], Ishtiaque *et al.*[1], and Punj *et al.*[6] for yarns made on different spinning systems. But Kumar *et al.*[26] observed that radial twist distribution inside the yarn governs the behavior of radial packing density of the yarn.

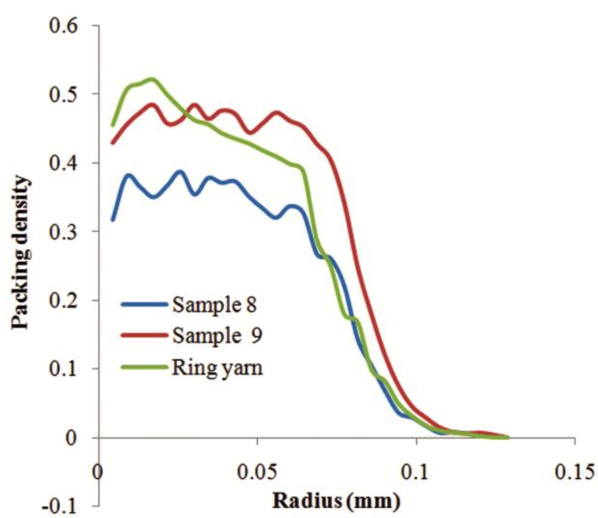


Fig. 3 — Radial packing density curves of vortex and ring yarn

In order to realize the importance of yarn structure influenced by process parameters, two air vortex yarns having minimum and maximum packing density are considered for present discussion. It is depicted from Table 2 that Yarn 9, prepared at a combination of highest nozzle pressure, lowest yarn delivery speed and moderate spindle diameter, shows maximum 0.441 packing density. However, Yarn 8 with highest yarn delivery speed and spindle diameter and moderate nozzle pressure provides the minimum 0.330 packing density. The radial packing density graphs of both the yarns are shown in Fig. 3.

Figure 3 clearly shows a significant difference in the pattern of radial packing density curves of these two yarns. Yarn 9 provides higher packing density in core, intermediate and surface zones in comparison to Yarn 8. Therefore, it can be concluded that cross-sectional structure of yarn can be modulated with right combination of process parameters. A comparative study of radial packing density of yarns made on different spinning systems can be visualized from Fig. 3.

Figure 3 distinctly confirms the higher packing density in the core of ring yarn as compared to vortex Yarn 8. But intermediate and surface zones of both the yarns do not show much difference. Similarly, the radial packing density graphs of vortex Yarn 9 having maximum packing density and ring-spun yarn provides quite different radial fibre distribution in the intermediate and surface zones, as shown in Fig. 3.

Therefore, it can be concluded that process parameters and fibre consolidation mechanism used in different spinning systems have played a significant role to modulate the structure of yarn. Hence, the gained knowledge will provide great help to the fabric manufacturers to engineer the comfort properties of fabrics and the properties of sized and dyed yarns for different applications.

### 3.3 Influence of Process Parameters on Packing Density in Different cross-sectional Zones of Yarn

In order to enhance the further applicability of the present work, the cross-section of yarns are divided into three zones only, viz. core, intermediate and surface zones of equal width. The obtained information's about packing density in three different zones of yarn might be useful to better optimize the sizing and dyeing processes. Further, these information can be utilized to modulate the comfort properties of the fabrics. The measured packing density in the respective zones is shown in Table 2 and radial packing density plots are given in Fig. 4.

It is noticed from Fig. 4 that packing density in the core-zone of all the yarns is found to be maximum followed by intermediate and surface zones. The observed trends are also applicable for corresponding ring yarn.

The ANOVA analysis is also carried out to find out the impact of individual as well as interaction effect of considered process parameters on packing density in different zones of yarns. The response surface equations for packing density in respective zones of

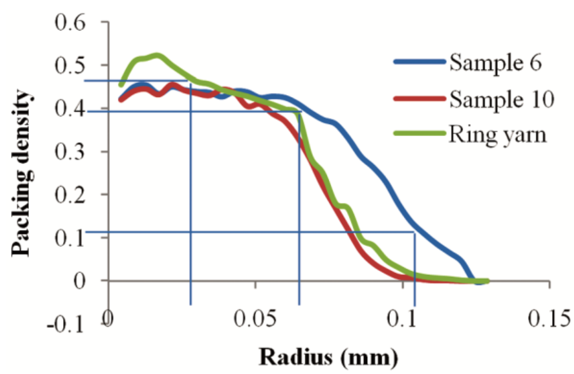


Fig. 4 — Packing density of yarn in core, intermediate and surface zones

yarn in terms of coded factors and significant model terms are given below:

Core-zone = 0.4126 - 0.0125 * A+ 0.003375* B - 0.037125* C … (2)

Intermediate- zone = 0.3236 - 0.013875* A - 0.0065* B - 0.041375* C … (3)

Surface-zone = 0.038 - 0.0179625 * A + 0.000462* B - 0.0035*C - 0.0244 *A*B + 0.004325 *A*C+0.003625* B*C … (4)

Very good correlations are observed among core-zone, intermediate-zone and surface-zone packing density of yarn and machine parameters with a $R^2$ value 0.8629, 0.5401 and 0.6180 respectively.

#### *3.3.1 Packing Density in Core-zone of Yarn*

Figure 5(a) demonstrates the 3D surface plots of spindle diameter *vs* nozzle pressure at yarn delivery speed of 450m/min. A decrease in packing density in the core-zone of yarn is noticed with the increase in spindle diameter but an increase in packing density is recorded with the increase of nozzle pressure at respective yarn delivery speed, as inferred by Eq.(2). A small reduction in packing density in core-zone of the yarn is observed with the increase in both spindle diameter and nozzle pressure at respective yarn delivery speed but it depicts a high decrease in packing density with the increase in yarn delivery speed. Further, the increase in spindle diameter, nozzle pressure and yarn delivery speed shows a reduction in packing density in core-zone of the yarn.

The 3D surface plot of spindle diameter *vs* yarn delivery speed at 0.5MPa nozzle pressure is shown in

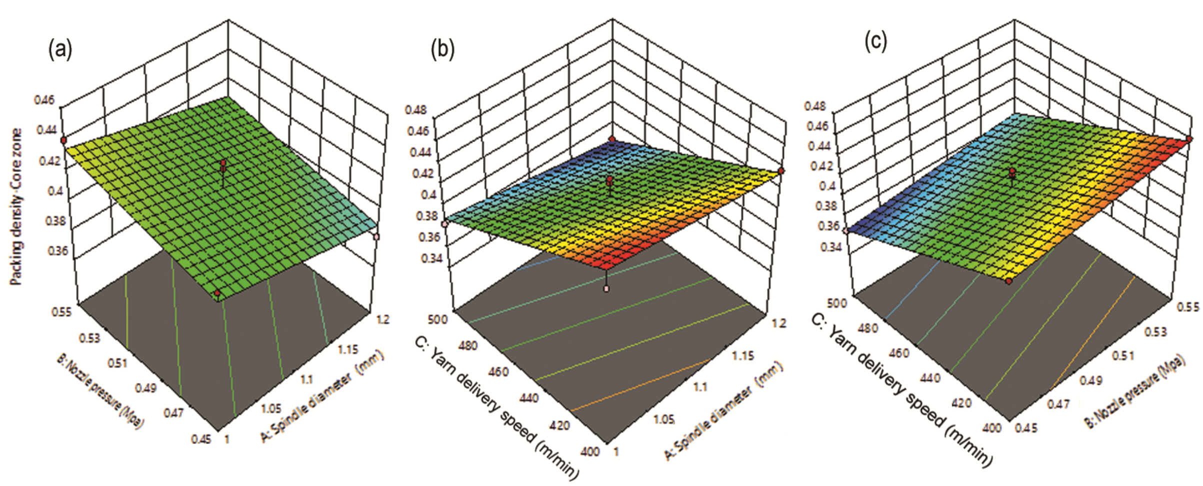


Fig. 5 — Effect of process parameters on packing density in core-zone of yarn (a) yarn delivery speed 450 mm/min, (b) nozzle pressure 0.5 MPa and (c) spindle diameter 1.1 mm

Fig. 5(b). The Eq.(2) depicts that the packing density in core-zone of the yarn shows an increase with the increase in spindle diameter, but a decrease is noticed with the increase in yarn delivery speed at respective nozzle pressure. The increase in both spindle diameter and yarn delivery speed notices a high decrease in packing density in core-zone of the yarn at respective nozzle pressure but a lesser reduction in the packing density is observed with the increase in nozzle pressure. The simultaneous increase in spindle diameter, nozzle pressure and yarn delivery speed registers a reduction in the packing density in core-zone of the yarn.

The 3D surface plot of nozzle pressure *vs* yarn delivery speed at spindle diameter of 1.1mm is shown in Fig. 5(c). Packing density in the core-zone of yarn notices an increase with the increase in nozzle pressure, but a decrease is observed with the increase in yarn delivery speed at respective spindle diameter. At respective spindle diameter, increase in both nozzle pressure, and yarn delivery speed observed a high decrease in packing density in the core-zone of yarn but core-zone packing density notices a lesser reduction with the increase in spindle diameter. The increase in spindle diameter, nozzle pressure and yarn delivery speed together depicts a reduction in the packing density in the core-zone of yarn.

The above results confirm the reduction in packing density in the core-zone of yarn with the increase in spindle diameter, nozzle pressure and yarn delivery speed. The increase in nozzle pressure depicts an increase in packing density but a decrease in packing density is noticed with the increase of spindle diameter and yarn delivery speed. Therefore, it can be concluded that the positive influence of nozzle pressure to increase the packing density in the core-zone of yarn is being nullified by yarn delivery speed and spindle diameter. The similar trends are also noticed in case of intermediate and surface zones

The maximum packing density of 0.46 in the core-zone of yarn is achieved with a combination of 1.1 mm spindle diameter, 0.45 MPa nozzle pressure and 400 m/min yarn delivery speed. But minimum packing density of 0.364 is achieved with a combination of 1.2 mm spindle diameter, 0.5 MPa nozzle pressure and 500 m/min yarn delivery speed. Therefore, it can be concluded here that packing density in the core-zone of yarn can be modulated as required by choosing right combinations of considered variables.

#### *3.3.2 Packing Density in Intermediate-zone of Yarn*

Figure 6 (a) provides the 3D surface plot of spindle diameter *vs* nozzle pressure at yarn delivery speed of 450m/min. Equation (3) provides a decreasing trend of packing density in the intermediate-zone of yarn with the increase in spindle diameter but increase in nozzle pressure notices an increase in packing density at respective yarn delivery speed. The increase in both spindle diameter and nozzle diameter reveals a moderate decrease in packing density in the intermediate-zone of yarn at different yarn delivery speeds. But the packing density in the intermediate-zone of yarn follows a high decrease with the increase in yarn delivery speed. It is interesting to note that the increase in spindle diameter, nozzle pressure and yarn delivery speed notices a decrease in the value of packing density in the intermediate-zone of yarn.

The 3D surface plot of spindle diameter *vs* yarn delivery speed at 0.5MP a nozzle pressure is shown in

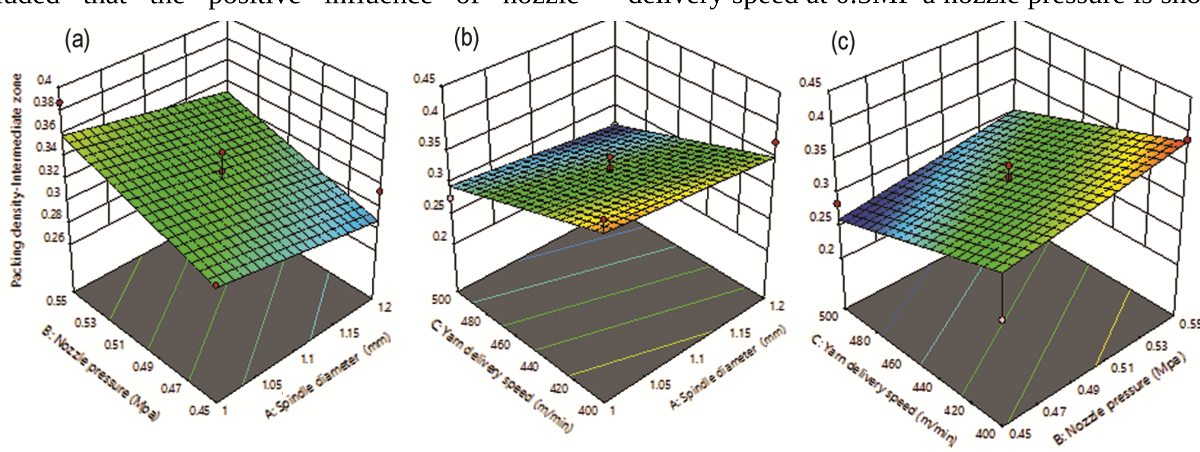


Fig. 6 — Effect of process parameters on packing density in intermediate-zone of yarn (a) yarn delivery speed 450 mm/min, (b) nozzle pressure 0.5 MPa and (c) spindle diameter 1.1 mm

Fig. 6(b). The results of Eq.(3) infer an increase in packing density in the intermediate-zone of yarn with the increase in spindle diameter but a decrease in packing density is confirmed with the increase in yarn delivery speed at respective nozzle pressure. The increase in both spindle diameter and yarn delivery speed notices a high reduction in the value of packing density in the intermediate-zone of yarn at different nozzle pressure but a lesser reduction in packing density is noticed with the increase in nozzle pressure. The increase in spindle diameter, nozzle pressure and yarn delivery speed shows a decrease in packing density in the intermediate-zone of yarn.

Figure 6(c) provides the 3D surface plot of nozzle pressure *vs* yarn delivery speed at spindle diameter of 1.1mm. The packing density in the intermediate-zone of yarn depicts an increase with the increase in nozzle pressure but notices a decrease with the increase in yarn delivery speed at respective spindle diameter, as inferred by Eq.(3). A high decrease in the value of packing density in the intermediate-zone of yarn is observed with the increase in both nozzle pressure as well as yarn delivery speed at respective spindle diameter but a lesser reduction in the packing density in the intermediate-zone of yarn is noticed with the increase in spindle diameter. A decrease in the packing density in the intermediate-zone of yarn is observed with the increase in all three considered variables.

A combination of 1.0 mm spindle diameter, 0.5 MPa nozzle pressure and 400 m/min yarn delivery speed provides maximum value of 0.398 packing density in the intermediate-zone of yarn. But minimum value of 0.267 is obtained with a combination of 1.2 mm spindle diameter, 0.5 MPa nozzle pressure and 500 m/min yarn delivery speed.

### *3.3.3 Packing Density in Surface-zone of Yarn*

Figure 7(a) and Eq. (4) depict an increase in the value of the packing density in the surface-zone of yarn with the increase in spindle diameter and nozzle pressure at respective yarn delivery speed. The increase of both spindle diameter and nozzle pressure follows an increasing and then decreasing trends of the packing density in the surface-zone of yarn at respective yarn delivery speeds but the increase in yarn delivery speed observes a reduction in the value of the packing density in the surface-zone. The value of the packing density in the surface-zone of yarn notices a continuous decrease with the increase in spindle diameter, nozzle pressure and yarn delivery speed.

The 3D surface plot of packing density in the surface-zone of yarn, given in Fig. 7(b), follows an increase with the increase in spindle diameter up to 0.50 MPa nozzle pressure and then a decrease is observed with further increase of nozzle pressure but an increase is noticed with the increase in yarn delivery speed at respective nozzle pressure. The increase in both spindle diameter and yarn delivery speed follows an initial decrease and then increase in packing density in surface- zone of the yarn and a reduction is observed in packing density at respective nozzle pressure. But increase in nozzle pressure notices an initial increase and then decrease in the packing density of yarn. The packing density in the surface-zone of yarn follows a decreasing trend with

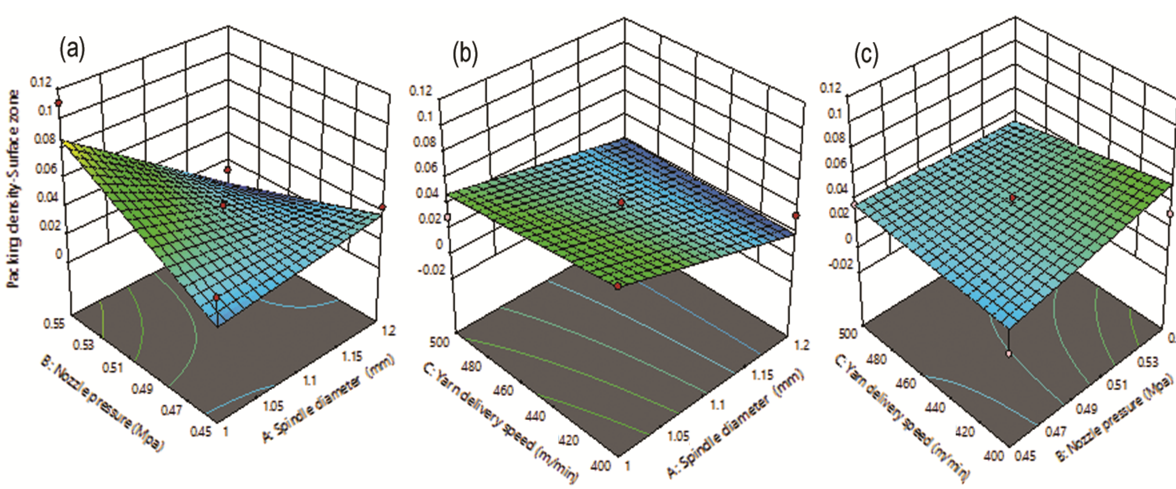


Fig. 7 — Effect of process parameters on packing density in surface-zone of yarn (a) yarn delivery speed 450 mm/min, (b) nozzle pressure 0.5 MPa and (c) spindle diameter 1.1 mm

the simultaneous increase of spindle diameter, nozzle pressure and yarn delivery speed.

The 3D surface plot of nozzle pressure and yarn delivery speed at spindle diameter of 1.1mm is given in Fig.7(c). The Eq. (4) depicts an increase in packing density of the surface-zone of yarn was noticed with the increase in yarn delivery speed at respective spindle diameter. But the value of packing density in the surface-zone of yarn shows an increase with the increase of nozzle pressure up to 1.1 mm spindle diameter, but a reduction is followed with the increase in nozzle pressure at 1.2 spindle diameter. The increase in both nozzle pressure and yarn delivery speed reveals an initial increase and then decrease in packing density in the surface-zone of yarn at respective spindle diameter but a decrease in the packing density of yarn is noticed with the increase in spindle diameter. A decreasing trend of packing density in the surface-zone of yarn is noticed with the increase in all three considered variables.

The surface-zone of yarn results in a maximum 0.111 packing density at a combination of 1.0 mm spindle diameter, 0.45 MPa nozzle pressure and 450 m/min yarn delivery speed. But a combination of 1.1 mm spindle diameter, 0.55MPa nozzle pressure and 400 m/min yarn delivery speed provides minimum 0.009 packing density.

### 3.4 Mechanism of yarn formation

It has been observed from above discussion that a significant impact of individual as well as interaction effect of considered process parameters is noticed on packing density in different zones of yarn. The reasoning given below can explain the mechanics of structure of vortex yarn influenced by process parameters.

The packing of fibres in the vortex yarn depends on the ratio of wrapper and core fibres as well as wrapping length of the sheath fibres. Higher yarn delivery speed results in a slightly higher ratio of wrapper to core fibres. The air flow caused by higher surface speed of the front drafting rollers separates more fibre ends from the drafted ribbon of fibres. Further, the residence time of fibres in twisting chamber also reduces with the increase of yarn delivery speed which attributes poor wrapping of sheath fibres. But increase of nozzle pressure increases both tangential and axial velocity and is responsible for increment of whirl force of nozzle air flow. Therefore, core fibre bundles are tightly held together by wrapper fibres due to more twist. There is likely to be less freedom for the expansion of fibre bundle when it enters spindle of lower diameter. This is responsible for higher friction between the fibres and provides higher twist, tighter wrapping and denser yarn.

## 4 Conclusion

The results confirm the non-uniformity of radial packing density of vortex yarns across the yarn cross sections. The packing density vortex yarn is not found to be maximum near the yarn axis. In general, the maximum packing density is observed in between 1/4$^{th}$ and 1/3$^{rd}$ of yarn radius from yarn axis. The packing density of ring-spun yarn is found to be higher than vortex yarns with distinctly higher packing in the core zone of the yarn. Packing density of yarn depicts an increase with increase in nozzle pressure and a decrease is observed with increase of yarn delivery speed and spindle diameter. But with the increase in spindle diameter, nozzle pressure and yarn delivery speed simultaneously, a reduction in yarn packing density is noticed. Therefore, it can be concluded that the process parameters and fibre consolidation mechanism used in different spinning systems have played a significant role to modulate the structure of yarn. It is depicted that packing density of core, intermediate and surface zones of the yarn observes an increase with the increase of nozzle pressure but a reduction is noticed with the increase of spindle diameter and yarn delivery speed. A reduction in packing density of all three zones is also noticed with the simultaneous increase of spindle diameter, nozzle pressure and yarn delivery speed. Therefore, it can be summarized that proposed work will lead a new direction to engineer the cross-sectional structure of vortex yarn to achieve the required functional properties of fabrics for specific end use by using right combination of process parameters.

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