STUDY OF EFFECT OF SPINNING PROCESS VARIABLES ON THE PACKING DENSITY OF RING, ROTOR AND AIR-JET YARNS USING THE TAGUCHI METHOD

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Abstract

The effect of lap hank, card draft, draft/doublings and drafts at speed frame, ring frame, rotor and air-jet on packing density parameters were analysed using the Taguchi method. The trends of change in packing density with process variables are opposite to those of the yarn diameter and helix angle of the ring, rotor and air-jet yarns studied. The packing density is found to be the highest in air-jet yarn and the lowest in rotor yarn. An increase in draft in the air-jet and a decrease in the rotor spinner increases the packing density of the respective yarns.

Key words:

Anova, air-jet yarn, card draft, draft/doublings, packing density, yarn diameter, regression model, ring yarn, rotor yarn, Taguchi method, viscose yarn

1. Introduction

The study of packing fibres in a yarn cross-section was started by Schwarz (1934). Hamilton (1959) suggested a direct method of measuring yarn diameters and bulk densities under conditions of thread flattening. He showed how the denier and the major & minor diameters vary with twist. Later on, Hearle *et al.* [1] gave some formulae to calculate specific volume of yarn based on yarn twist, twist angle and yarn linear density. The formula given by Hearle *et al.* is only valid in the case of an idealised ring yarn structure, and is not applicable for other structures of yarns manufactured on different spinning technologies, such as rotor, air-jet techniques etc. In this regard, Ishtiaque [2] derived a formula to calculate the packing density of the yarn. This formula is applicable for the yarns manufactured on different technologies. This formula is based on the actual values of yarn diameter, helix twist and number of fibres in the yarn cross-section, as obtained by the study of fibre migration behaviour.

In this paper, the effect of change in the preparatory process variables on helix angle, helix twist, yarn diameter and packing density of ring, rotor and air-jet yarns was studied. The Taguchi method and the Anova technique are used to analyse the effect of process variables. The regression models were also fitted to quantify the effect of speed frame, ring frame, rotor and air-jet draft on the parameters mentioned above.

2. Materials and methods

2.1. Preparation of yarn samples

Viscose rayon staple fibre (44 mm, 1.67 dtex) was processed on an L R blow room line & a Texmaco Howa card, and given two passages on an L R DO/6 draw frame (breaker and finisher). The samples were prepared according to the L8 mixed orthogonal array as shown in Table 1. The design variable array shows that the two levels of lap hank, four levels of card draft and two sets of draft/doublings at the breaker and finisher drawframe were selected. The factor levels at various stages were chosen on the basis of certain practical considerations. The prepared finisher sliver samples of eight different linear densities were processed into two different types of rovings, and 24^s Ne rotor and air-jet yarns. The direction of the sliver fed to the air-jet machine was reversed for feeding the majority of hooks as trailing. The established trend in spinning preparatory for air-jet spinning is to use three passages of drawframe before yarn preparation, so as to feed the majority of hooks in the trailing direction. In the present research work, only two drawframe passages were used to produce equivalent ring and rotor yarns. For roving-type I, the draft at speed frame was kept constant in all the samples; while for roving-type II, the draft at speed frame was changed in such a way so as to produce the same roving hank for all the eight samples. These rovings were processed into two types of ring yarns, types I and II, in such a way so as to produce 24^s Ne yarn. The effect of uncontrollable variables, such as spindle to spindle variation and doff position, was duly taken into consideration.

Table 1. Sample preparation plan

	Design Variable Array									Experimental Result Matrix			
Run	Lap hank (Ne)	Card draft	Draft/ doublings at drawframe (breaker and finisher)	S/ F draft Type I	S/ F draft Type II	R/ F draft Type I	R/ F draft Type II	Rotor draft	Air-jet draft	Noise variable array			
										A 1	2	2	1
										B 1	2	1	2
										C 1	1	2	2
1	0.00122	88	6/6	8.4	11.4	26.7	19.7	225.4	225.4	R11	R12	R13	R41
2	0.00144	88	8/8	8.4	9.7	22.7	19.7	191.0	191.0	R21	R22	R23	R42
3	0.00122	101	6/6	8.4	10.0	23.3	19.7	196.4	196.4	R31	R32	R33	R43
4	0.00144	101	8/8	8.4	8.4	19.7	19.7	166.4	166.4	R41	R42	R43	R44
5	0.00122	114	8/8	8.4	8.8	20.6	19.7	174.0	174.0	R51	R52	R53	R53
6	0.00144	114	6/6	8.4	7.5	17.5	19.7	147.4	147.4	R61	R62	R63	R63
7	0.00122	127	8/8	8.4	7.9	18.5	19.7	156.2	156.2	R71	R72	R73	R73
8	0.00144	127	6/6	8.4	6.7	15.7	19.7	132.3	132.3	R81	R82	R83	R83
where: S/F = speed frame, R/F = ring frame, and in Noise variable array A = doff position (1= top, 2= bottom), B = spindle position (1= spindle no. 1 and 2 ,and 2= spindle no. 3 and 4), and C = material conditioning in testing laboratory; 1 = unconditioned; 2 = conditioned													

2.2. Measurement of packing density in the yarns

The parameters needed to calculate packing density, such ashelix angle, helix twist, yarn diameters, were measured by using the classical tracer fibre technique [3]. Tracer fibres of red and green colour, each 0.03% by weight, were mixed with parent grey viscose fibres while laying the stack. The configuration of tracer fibre was studied at 100× under a projection microscope. Benzyl alcohol was used to optically dissolve the grey fibres in the yarn. Four different replications for fibre orientation parameters were measured at the yarn stage, in order to take the effect of uncontrollable factors (noise) into account. The packing density in the yarns was further calculated from the values of these parameters using Ishtiaque's formula as given below. The schematic view of a tracer fibre seen under the projection microscope for the study of yarn structure is given in Figure 1, where $D = 2R$ = yarn diameter (in mm); $d = 2r$ = helix diameter (in mm); θ = helix angle (in degrees) = $\tan^{-1}(\pi\, d\, Z / 25.4)$; Z = number of turns of twist in the fibre helix per mm; n = actual number of fibres in the yarn cross-section, obtained by multiplying the theoretical number of fibres in 24^s Ne yarn by the cosine of the helix angle (θ); The theoretical number of fibres in the yarn cross section = 148, calculated by {5315 / (yarn count (Ne) x fibre denier)}.F' the cross-sectional area of the viscose fibre used (mm^2) = 1.0964×10^{-4}.

Finally, the formula used for calculating the packing density from the above defined parameters is as follows:

Packing density of yarn = $\mu = 2\pi nFZ^2/(\sqrt{1+(\pi DZ)^2}-1)$

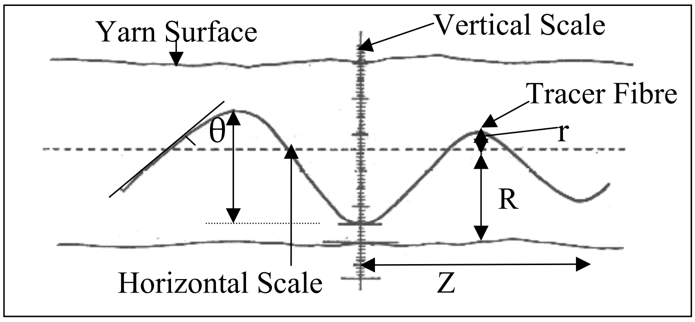

Figure 1. Schematic view of a tracer fibre seen under projection microscope

A total of 100 tracer fibres per sample (25 tracer fibres per replication and a total of 4 replications per sample) were studied to calculate the packing density parameters in ring, rotor and air-jet yarns.

2.3. Analysis of the response

Analysis of the response depends upon whether a smaller or larger response value is desired. The helix angle and yarn diameter were classified under the response type of 'smaller is better', because the smaller are the values of these parameters, the higher the packing density of the yarn will be. The helix twist was classified under the response type of 'larger is better', because higher values of these parameters are required to obtain a higher packing density for the yarn. The packing density itself was classified under the response type of 'larger is better' because a higher packing density value contributes positively toward yarn tenacity. The formulae used for the calculation of the S/N ratio for the above response types are given below.

1. for 'smaller is better' $S/N = -10.\log_{10}.(1/n\sum_{i=1}^{n} y_i^2)$;

   where: y_i = the *i*th value of the result, and n = the number of replications;

2. for 'larger is better' $S/N = -10.\log_{10}.(1/n\sum_{i=1}^{n} 1/y_i^2)$;

The actual values of S/N ratio maximum were also evaluated directly from the curves of the S/N ratio with a change in the process variable by using the equation:

$$\overline{S/N}\max = \overline{S/N} + (S/NA\max - \overline{S/N}) + (S/NB\max - \overline{S/N}) + (S/NC\max - \overline{S/N})$$

where: $\overline{S/N}\max$ = the maximum actual value from the graph,

$\overline{S/N}$ = the overall average value of the S/N ratio,

$S/NA\max$ = the maximum value of the S/N ratio in the plot of the lap hank,

$S/NB\max$ = the maximum value of the S/N ratio in the plot of the card draft,

$S/NC\max$ = the maximum value of the S/N ratio in the plot of draft/doublings.

The calculated value is statistically compared with the actual value of S/N ratio at a 95% confidence level for a significant difference between the two values. As previous researchers did [4], the rule followed was that if there was a significant difference in the two values, the experiment had to be repeated by maintaining the process variables at the optimum level observed from the graphs. Note that S/N ratios of the various parameters should be maximised to obtain the optimum set of process variables; that is, for reading the plot, the highest values of S/N ratio are looked up in order to determine the optimum value of the process variables in all the cases.

3. Results and Discussion

Tables 2 to 5 show the S/N ratios and mean values of parameters required for calculating the packing density in ring, rotor and air-jet yarns in eight different samples prepared. The overall percentage changes by process variables and the actual values of S/N ratios with 95% confidence limits (S/N L and S/N H) of the various migration parameters studied are also given in the respective tables. The average values of S/N ratios and mean values are given in the last row of respective tables. Since the highest calculated values of S/N ratio lie within the 95% confidence limits for actual response by the graphical method in all the cases, there was no need to do a confirmatory test. The coefficient of correlation 'R' (almost 1 in all cases) between the values of S/N ratios and the means of various parameters shows that the variation in means follow the variation in the S/N ratio.

Table 2. S/N ratios ('smaller is better') and mean values of helix angle in various yarn

	Ring yarn-type I		Ring yarn-type II		Rotor yarn		Air-jet yarn	
Run	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean
1	-23.13	14.3	-22.62	13.5	-23.90	15.7	-22.24	12.9
2	-22.39	13.1	-22.50	13.3	-24.47	16.7	-22.12	12.7
3	-22.17	12.8	-22.69	13.6	-24.54	16.9	-21.25	11.5
4	-21.56	12.0	-21.56	12.0	-24.46	16.7	-23.11	14.2
5	-22.16	12.8	-22.72	13.7	-24.45	16.7	-22.45	13.2
6	-21.80	12.3	-23.01	14.1	-24.14	16.1	-22.21	12.9
7	-22.31	13.0	-22.56	13.4	-24.64	17.1	-21.67	12.1
8	-22.75	13.7	-22.03	12.6	-24.68	17.1	-22.16	12.7
% C	6.8	19.7	5.1	18.1	3.2	8.9	8.0	23.3
R	-1.000		-1.000		-0.999		-0.999	
S/N Actual	-21.5		-21.8		-24.1		-21.2	
S/N L	-22.4		-23.2		-24.8		-23.4	
S/NH	-20.7		-20.5		-23.3		-19.1	
AVG		13.0		13.3		16.6		12.8

Table 3. S/N ratios ('larger is better') and mean values of number of turns of twist in fibre helix in yarns

	Ring yarn-type I		Ring yarn-type II		Rotor yarn		Air-jet yarn	
Run	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean
1	23.68	15.30	23.27	14.66	25.62	19.15	25.01	17.82
2	23.24	14.56	23.27	14.60	25.84	19.69	23.37	14.86
3	23.05	14.21	23.53	15.04	25.70	19.31	23.24	14.60
4	23.18	14.45	23.18	14.45	25.44	18.73	24.52	17.04
5	23.75	15.42	23.64	15.23	25.71	19.32	24.27	16.40
6	23.55	15.10	23.68	15.40	25.57	19.11	23.76	15.54
7	23.56	15.17	23.29	14.62	25.66	19.30	24.00	15.87
8	23.54	15.11	22.92	14.00	25.65	19.31	23.91	16.26
% C	2.7	7.6	3.3	9.9	1.6	5.2	7.6	22.1
R	0.998		0.997		0.982		0.988	
S/N Actual	23.7		23.7		25.8		24.3	
S/N L	23.1		23.2		25.3		21.3	
S/NH	24.4		24.3		26.3		27.4	
AVG		14.9		14.7		19.2		16.0

Table 4. S/N ratios ('smaller is better') and mean values(1/100 mm) of yarn diameter

	Ring yarn-type I		Ring yarn-type II		Rotor yarn		Air-jet yarn	
Run	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean
1	-26.1	20.2	-26.6	21.5	-27.3	23.2	-25.8	19.4
2	-25.8	19.6	-26.5	21.0	-27.5	23.7	-25.6	19.1
3	-26.3	20.6	-26.5	21.2	-27.4	23.5	-25.8	19.4
4	-25.82	19.53	-25.8	19.4	-27.2	23.0	-26.1	20.2
5	-25.81	19.51	-26.2	20.3	-27.4	23.5	-26.0	19.9
6	-26.0	20.0	-26.3	20.7	-26.8	21.8	-26.2	20.4
7	-26.3	20.8	-26.3	20.6	-26.9	22.2	-26.1	20.1
8	-26.3	20.7	-26.4	20.8	-27.3	23.2	-26.1	20.0
% C	1.74	5.40	3.29	10.50	2.56	8.49	2.18	6.67
r	-1.000		-1.000		-1.000		-1.000	
S/N Actual	-25.74		-25.91		-27.06		-25.65	
S/N L	-26.03		-26.50		-28.24		-26.21	
S/NH	-25.44		-25.32		-25.88		-25.08	
AVG		20.12		20.68		23.01		19.82

Table 5. S/N ratios ('larger is better') and mean values of packing density of yarns

	Ring yarn-type I		Ring yarn-type II		Rotor yarn		Air-jet yarn	
Run	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean	S/N ratio	Mean
1	-5.96	0.506	-6.97	0.454	-8.07	0.396	-5.11	0.557
2	-5.36	0.541	-6.56	0.470	-8.44	0.380	-4.97	0.566
3	-6.20	0.491	-6.74	0.466	-8.30	0.385	-5.17	0.557
4	-5.29	0.545	-5.20	0.551	-7.98	0.400	-5.88	0.513
5	-5.27	0.547	-5.99	0.503	-8.36	0.384	-5.60	0.530
6	-5.72	0.520	-6.26	0.486	-7.13	0.443	-6.10	0.504
7	-6.35	0.485	-6.25	0.492	-7.39	0.428	-5.74	0.521
8	-6.34	0.483	-6.38	0.482	-8.30	0.396	-5.77	0.525
% C	17.1	12.7	25.5	21.4	15.5	16.7	18.4	12.4
R	0.999		0.996		0.987		0.996	
S/N Actual	-5.12		-5.48		-7.67		-4.90	
S/N L	-5.69		-6.65		-9.99		-5.90	
S/NH	-4.55		-4.31		-5.33		-3.91	
AVG		0.515		0.488		0.401		0.534

3.1. Effect of process variables on the helix angle

The response type used for the helix angle, 'smaller is better', implies that the increase in values of the S/N ratio decreases the helix angle in the yarn.

3.1.1. Ring Yarn-Type I

Table 2 shows that the average helix angle in ring yarn-type I is more than that of the air-jet yarn, but less than the rotor yarn. This is because the ring-yarn fibres are well-oriented, due to better drafting and fibre control in the ring frame, which in turn gives better parallelisation of fibres inside the yarn body similar to the helical model. In air-jet yarn, the wrappers have an end which lies almost straight in the core. Furthermore, the fibres in the core are almost straight, which gives rise to a lower helix angle. In rotor yarn, the higher mechanical twist required for yarn manufacturing and the random arrangement of fibres (hooks, loops and buckling) and the yarn twist mechanism necessitates more twist, due to the greater torque required to twist the consolidated fibre band in a rotor groove, which gives a higher value of helix angle [5].

Table 6. Effect of process variables on change in S/N ratios of helix angle, helix twist, yarn diameter and packing density in ring yarn, as analysed by Taguchi method and Anova technique

		Ring yarn-type I				Ring yarn-type II			
		Hel Ang	H T	Dia.	PD	Hel Ang	H T	Dia.	PD
Lap Hank	% Effect	0.0	0.6	0.5	4.6	0.0	0.7	0.7	6.2
	Taguchi rank	3	2	3	3	2	2	3	3
	%V Ex	10.7	7.8	8.7	9.2	17.4	12.3	13.7	14.9
	F value	2.16	0.8	3.3	3.66	1.2	1.6	1.7	1.87
Card draft	% Effect	0.1	2.3	1.6	14.7	0.1	2.4	1.5	12.6
	Taguchi rank	1	1	1	1	1	1	1	1
	%V Ex	63.2	71.7	55.2	54.8	44.5	71.9	35.3	34.8
	F value	4.26	2.4	6.9	7.26	1.02	3.0	1.4	1.46
Draft/ doublings	% Effect	0.0	0.1	0.9	8.4	0.0	0.0	1.1	9.4
	Taguchi Rank	2	3	2	2	3	3	2	2
	%Vari. Ex	16.2	0.2	30.7	31.0	8.9	0.0	34.58	34.5
	F value	3.3	0.0	11.5	12.3	0.6	0.0	4.23	4.4
	R^2	90	80	95	95	71	84	84	84
where: An of = actual no. of fibres, Hel ang = helix angle, H.T. = helix twist, Dia = yarn diameter Pd = packing density ,% V Ex =% variation explained									

Table 6 shows the effect of change in the spinning process variables on the helix angle in ring yarn-type I. The change in card draft and corresponding changes in ring frame draft, followed by draft/doublings and lap hank, influence most of the changes in helix angle. A high value of R^2 shows that the helix angle is considerably influenced by the changes in preparatory process variables. Table 8 shows that there is a considerable effect of the change in ring frame draft on the helix angle.

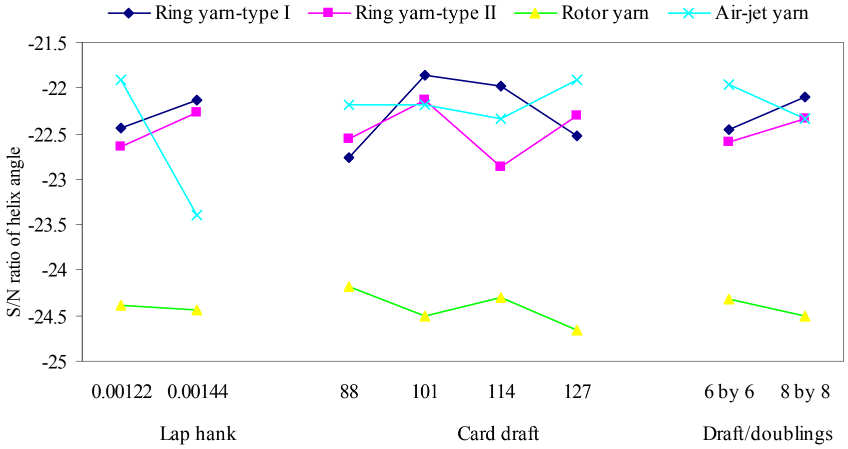

Figure 2. S/N ratio plot of helix angle with change in process variables

Figure 2 shows the S/N ratio plots of helix angle with change in process variables. The increase in lap hank and the corresponding decrease in ring frame draft decreases the helix angle. This is because a finer lap hank and a correspondingly lower ring-frame draft reduces the width of the drafting band in the drafting zone of the ring frame, which further reduces the convergence angle of fibres in the spinning triangle (comparatively shorter) during the yarn formation zone, and is thus responsible for the reduction in helix angle. Also, feeding finer lap hank into the card improves the opening and carding action of fibres. These fibres shows better tendencies to straighten and parallelise in the subsequent process of drafting, and thus reduce the helix angle in the resultant yarn even at lower ring-frame drafts [5]. The effect of card draft and the corresponding change in the ring-frame draft counterbalance each other in deciding the helix angle. As the card draft increases from 88 to 101, the helix angle in yarn decreases because of increased fibre straightening in the subsequent drafting zone. Further, an increase in card draft from 101 to 127 and a corresponding decrease in ring-frame draft increases the helix angle. This is because the sliver and roving produced at higher card draft have a higher proportion of curved fibre ends and lower values of K_{rpm} [6]. These factors show that the decrease in fibre extent increases the helix angle and vice versa. An increase in draft/doublings at draw frame reduces the helix angle. This is because the increase in draft/doublings increases the compactness of sliver due to the increase in width of the fibre band in the drafting zone of the draw frame, which increases the tension in the edge fibres of the delta zone. These edge fibres try to migrate inside the sliver body to ease its tension, and thus produce a compact sliver. This compact sliver produces compact roving, which produces a smaller width of the drafting band in the ring-frame drafting zone. Finally, it reduces the helix angle in the yarn. This relationship between the width of drafting ribbon and helix angle is in agreement with the findings of Ishtiaque *et al.* [7,8].

3.1.2. Ring Yarn-Type II

Table 2 shows that the average helix angle in ring yarn-type II is slightly more than that of ring yarn-type I.

Table 4 shows the effect of spinning process variables on helix angle in ring yarn-type II. The change in card draft is the major influencing factor, followed by lap hank. The draft/doublings have negligible effect. A high value of R^2 shows that the helix angle is greatly influenced by changes in preparatory process variables. Table 8 shows that the effect of change in speed frame draft on the helix angle is only marginal.

Figure 2 shows the S/N ratio plot of helix angle with the change in process variables. As in ring yarn-type I, the increase in lap hank and draft/doublings decreases the helix angle in yarn. This is due to the reasons already explained. The change in card draft changes the helix angle in a random way with no particular trend.

3.1.3. Rotor Yarn

Table 2 shows that the average helix angle in rotor yarn is the highest amongst the three yarns.

Table 7. Effect of process variables on change in S/N ratios of helix angle, helix twist, and packing density in rotor and air-jet yarn, as analysed by Taguchi method and Anova technique

		Rotor Yarn				Air-jet yarn			
		Hel Ang	H. T	Dia.	PD	Hel Ang	H.T.	Dia.	PD
Lap Hank	% Effect	0.0	0.2	0.2	0.8	0.1	1.0	0.5	4.9
	Taguchi rank	3	2	2	3	1	2	2	2
	%V Ex	1.2	4.9	1.4	0.6	23.95	4.8	9.7	13.0
	F value	0.08	0.15	0.0	0.01	0.88	0.10	0.8	1.29
Card draft	% Effect	0.1	0.6	1.1	6.4	0.0	1.3	1.5	14.5
	Taguchi rank	1	1	1	1	2	1	1	1
	%V Ex	57.9	28.5	25.7	21.3	8.62	4.3	64.5	66.8
	F value	1.4	0.29	0.2	0.18	0.11	0.03	1.7	2.21
Draft/ doublings	% Effect	0.0	0.10	0.2	1.1	0.0	0.24	0.0	0.2
	Taguchi rank	2	3	3	2	3	3	3	3
	%V Ex	13.3	1.45	1.4	1.0	13.3	0.25	0.0	.02
	F value	1.0	0.04	0.0	0.0	0.49	0.01	0.0	0
	R^2	72	35	28	23	46	9	74	80

where: An of = actual no. of fibres, Hel ang = helix angle, H. T = helix twist, Dia. = yarn diameter, Pd = packing density ,% V Ex =% variation explained

Table 7 shows the effect of change in the spinning process variables on helix angle in rotor yarn. The card draft is the major influencing factor, followed by draft/doublings and lap hank. A high value of R^2 shows that the helix angle is greatly influenced by changes in the preparatory process variables. Table 8 shows that the effect of change in rotor draft on the helix angle is negligible.

Figure 2 shows the S/N ratio plot of helix angle with a change in the process variables in rotor yarn. Increases in lap hank, card draft and draft/doublings increase the helix angle in rotor yarn. This is because of a decrease in fibre parallelisation and straightening in the sliver and yarn [6].

3.1.4. Air-jet Yarn

Table 2 shows that the average helix angle in air-jet yarn is the lowest amongst the three yarns.

Table 7 shows the effect of the change in spinning process variables on helix angle in air-jet yarn. The change in lap hank is the major influencing factor, followed by the change in draft/doublings and the change in card draft. The value of R^2 shows that the helix angle is greatly influenced by changes in the preparatory process variables. Table 8 shows that the effect of change in air-jet draft on the helix angle is negligible.

Figure 2 shows the S/N ratio plot of helix angle with the change in process variables. The increase in draft/doublings & lap hank and the corresponding decrease in air-jet draft increase the helix angle in the yarn. This is because of a reduction in the width of the fibre band with the finer lap hank, corresponding lower air-jet draft and higher draft/doublings (due to greater compactness) in the drafting zone of the air-jet machine. This decreases the generation of wrapper fibres and increases the core diameter, which is responsible for the increase in helix angle. An increase in card draft marginally changes the helix angle. The helix angle slightly increases from 88 to 114 card draft, and there is a corresponding decrease in the air-jet draft due to a decrease in the ribbon width, as explained in the case of finer lap hank and the corresponding decrease in the air-jet draft. Furthermore, from 114 to 127 card draft, the helix angle decreases in the yarn. This is because at 114 card draft and a relatively higher air-jet draft, the ribbon width is more than 127 card draft. So, at higher width more fibres are detached from the twisting core at the front roller nip; they describe a longer curvature and a big balloon, to meet again in the twisting core by making a higher angle with a twisting axis. Thus, the delay in the re-entry of detached fibres, which shifts the convergence point away from the front roller nip, is responsible for the higher helix angle in yarn at 114 card draft.

The value of the actual number of fibres is calculated by multiplying the theoretical number of fibres in the yarn cross section by the cosine of the helix angle. It thus reflects the same trends as the helix angle in the different yarns.

<u>3.2. Effect of process variables on helix twist</u>

The response type used for the helix twist is ‘larger is better’. This implies that an increase in the value of the S/N ratio increases the mean value of the response.

3.2.1. Ring Yarn-Type I

Table 3 shows that the average values of helix twist in the ring yarn-type I are lower than those of the rotor and air-jet yarns. This is because the ring yarn fibres are well-oriented due to better drafting and the fibre control in the ring frame, which gives a better parallelisation of the fibres inside the yarn body, similar to the helical model. Thus a lower mechanical twist is required to produce ring yarn equivalent to rotor and air-jet yarn.

Table 6 shows the effect of spinning process variables on the helix twist in ring yarn-type I. The change in card draft and the corresponding changes in the ring-frame draft influences most of the change in helix twist, followed by that of lap hank. The effect of draft/doublings on helix twist is the least. A high value for R^2 shows that helix twist is considerably influenced by changes in the preparatory process variables. Table 8 shows that the effect of change in the ring-frame draft on helix twist is considerable.

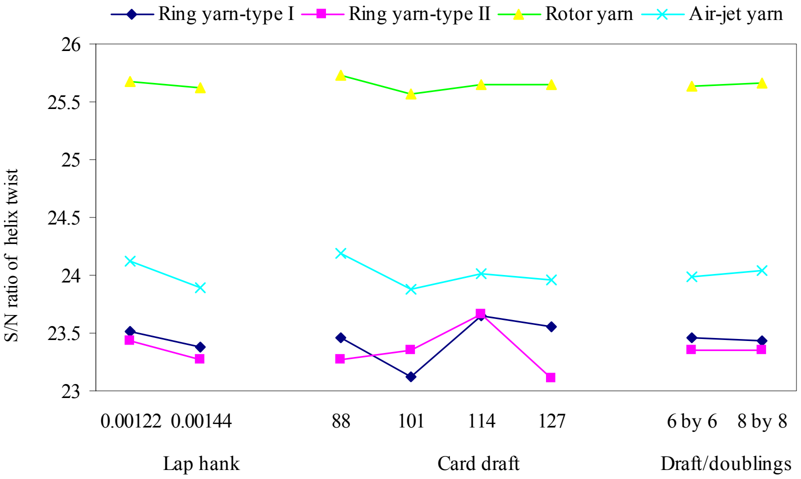

Figure 3. S/N ratio plot of helix twist with the change in process variables

Figure 3 shows the S/N ratio plots of helix twist with the change in process variables. The increase in lap hank and the corresponding decrease in ring frame draft marginally decrease the helix twist in the yarn. The effect of change in card draft and the corresponding changes in ring-frame draft on helix twist do not show any clear trend. The increase in draft/doublings does not alter the helix twist. This is due to the increase in mean migration intensity (MMI) increases helix twist and vice-versa [6,9].

3.2.2. Ring Yarn-Type II

Table 3 shows that the average helix twist in ring yarn-type II is slightly lower than that in ring yarn-type I.

Table 4 shows the effect of the spinning process variables on helix twist in ring yarn-type II. The change in card draft and the corresponding speed frame draft are seen to be the major influencing factors, followed by lap hank and the corresponding speed frame draft. The change in draft/doublings has no effect on helix twist. A high value of R^2 shows that helix twist is considerably influenced by changes in the process variables. Table 8 shows that the effect of change in the speed frame draft on the helix twist is considerable.

Figure 3 shows the S/N ratio plot of helix twist with the change in process variables. The increase in lap hank and the corresponding decrease in the speed frame draft decreases the helix twist in the yarn. The change in helix twist with the change in card draft and the corresponding change in speed frame draft passes through the maximum. Furthermore, as in ring yarn-type I, the increase in mean migration intensity increases helix twist, and vice-versa [6,9].

3.2.3. Rotor Yarn

Table 3 shows that the average helix twist in rotor yarn is the highest amongst the three yarns. This is because in rotor yarn, the high mechanical twist and the presence of high twist in the yarn core give rise to the highest value of helix twist. This is due to similar reasons to those explained in the case of higher helix angle in rotor yarn.

Table 7 shows the effect of change in the spinning process variables on helix twist in rotor yarn. The change in card draft is seen to be the major influencing factor. The effect of draft/doublings and lap hank is only marginal. A moderate value of R^2 shows that helix twist is influenced by changes in preparatory process variables. Table 8 shows that the effect of change in rotor draft on the helix twist is negligible.

Figure 3 shows the S/N ratio plot of helix twist with the change in process variables. The overall changes in helix twist are only marginal, with change in the process variables. The increases in lap hank, card draft and draft/doublings do not affect the helix twist much.

3.2.4. Air-jet Yarn

Table 3 shows that the average helix twist in air-jet yarn is lower than that in the rotor yarn but greater than that in the ring yarn, due to the high twist frequency of wrapper fibres. However, one end of the wrapper always lies straight in the yarn core (which is at lower helix twist). Also, the core fibres are almost straight, with negligible twist. These counterbalancing factors give rise to helix twist values higher than those of ring yarn, but lower than those of rotor yarn. In the air-jet yarn, the higher value of twist frequency leads to a higher value of average helix twist.

Table 7 shows the effect of change in the preparatory process variables on helix twist in air-jet yarn. The very low value of R^2 in the table shows that the helix twist is not influenced by changes in process variables. Table 8 shows that the small changes in helix twist in air-jet yarn can be attributed to air-jet draft.

Figure 3 shows the S/N ratio plot of helix twist with the change in process variables. The overall changes in helix twist in air-jet yarn with change in process variables are only marginal. As in ring yarn-type I, helix twist varies directly with the MMI in air-jet yarn [6].

3.3. Effect of process variables on yarn diameter

The type of response used for analysing yarn diameter is ‘smaller is better’. This implies that increases in the S/N ratio of yarn diameter decrease the actual value of the yarn diameter.

3.3.1. Ring Yarn-Type I

Table 4 shows that the average diameter of ring yarn-type I is higher than the diameter of air-jet yarn, but lower than that of rotor yarn. This is because in rotor yarn, the loosely bound wrappers on the surface increase the diameter when compared with the equivalent ring and air-jet yarns. Also, in rotor yarn, fibres are deposited in the rotor groove in the form of triangular fibre band. However, in twisting at final yarn formation, the corner of the triangular band collapses and these fibres are loosely wrapped over the yarn surface. Fibres lying inside the triangular band are firmly twisted and form a solid yarn core. These could be the reasons for the higher rotor yarn diameter. In air-jet yarn, parallel core fibres are bound by tight wrapper fibres, which results in the smallest diameter. Further, according to Punj *et al.* [10] and Ishtiaque & Khare [11], yarn spun from air-jet system consists of bundle of parallel fibres wound by some tight wrapper fibres. The system consists of two nozzles which are responsible for producing false twist. While the core fibres untwist, the wrapper fibres become twisted in the opposite direction and impart transverse forces to the parallel core, which gives rise to a compact yarn structure with the smallest diameter.

Table 6 shows the effect of change in process variables on the change in yarn diameter of ring yarn-type I. The effect of card draft, corresponding ring frame draft and draft/doublings at draw frame influences most of the changes in yarn diameter. The effect of change in card draft is almost significant at 90% confidence level, and the effect of change in draft/doublings is significant at 90% confidence level. The effect of lap hank on the change in yarn diameter is only marginal. A very high value of R^2 shows that the process variables influence the yarn diameter considerably. Table 8 shows that the effect of change in ring frame draft influences the yarn diameter.

Figure 4 shows the S/N ratio plot of yarn diameter with change in process variables. Finer lap hank and corresponding lower ring frame draft reduces the diameter of yarn. This is because of a reduction in the width of fibre band in the drafting zone at lower ring frame draft, which produces a compact yarn with smaller yarn diameter. The increase in card draft (from 88 to 114 card draft) and the corresponding decrease in ring frame draft tends to marginally decrease the diameter of yarn, due to the reasons described above. Further, the increase in card draft (from 114 to 127) and the corresponding decrease in ring frame draft increases the diameter. This is because of the considerable reduction in ribbon width at the front roller. So, the tension arising in the edge fibres in the spinning triangle is reduced, due to a reduction in the path length of the fibres, which in turn reduces the fibre migration in the yarn body, and thus reduces the compactness of the yarn [6]. The yarn thus produced has a greater diameter. Increasing draft/doublings decreases the yarn diameter due to the increase in the compactness of the fibre band, as already explained. The dependence of yarn compactness on the ribbon width and subsequent fibre migration parameters is in accordance with the findings of Ishtiaque *et al.* [8].

3.3.2. Ring Yarn-Type II

Table 4 shows that the average diameter of ring yarn-type II is slightly higher than that of ring yarn-type I. This can be attributed to slightly lower values of mean fibre position (MFP) in ring yarn-type II as compared to that in ring yarn-type I [6].

Table 6 shows the effect of change in process variables on the change in yarn diameter of ring yarn-type II. The effect of card draft, corresponding speed frame draft and draft/doublings at the draw frame explains most of the variations in yarn diameter. The effect of the change in lap hank on yarn diameter is the least. A high value of R^2 shows that the process variables influence the yarn diameter considerably. Table 8 shows that the effect of change in the speed frame draft influences the change in yarn diameter.

Table 8. Regression model for S/N ratios of helix angle, helix twist, and packing density in ring, rotor and air-jet yarn

Ring yarn-type I	Regression Model	% V Ex by R/F draft	R^2	F value
Helix angle	46.9 - 16386 Lh - 0.219 cdrft - 0.00424 d/d - 1.15 Ring draft	65.39	93.7	11.13
Helix Twist	3.5 + 4357 Lh + 0.0685 cdrft + 0.00404 d/d + 0.320 Ring draft	19.4	65.2	0.55
Yarn diameter	- 14.1 - 2461 Lh - 0.0457 cdrft + 0.00574 d/d - 0.197 Ring draft	8.6	72.8	2.01
Packing density	20.0 - 5392 Lh - 0.0966 cdrft + 0.0110 d/d - 0.426 Ring draft	32.09	72.1	1.94
Ring yarn-type II		% V Ex by S/F draft		
Helix angle	- 42.3 + 5927 Lh + 0.053 cdrft + 0.0130 d/d + 0.64 S/F draft	4.34	32.4	0.36
Helix Twist	57.7 - 8936 Lh - 0.104 cdrft - 0.00807 d/d - 1.24 S/F draft	51.69	64.5	1.38
Yarn diameter	- 11.9 - 3242 Lh - 0.0464 cdrft + 0.00652 d/d - 0.617 S/F draft	11.7	67.7	1.6
Packing density	23.2 - 6591 Lh - 0.0955 cdrft + 0.0130 d/d - 1.26 S/F draft	2.11	68.4	1.62
Rotor Yarn		% V Ex by Rotor draft		
Helix angle	- 26.7 + 732 Lh + 0.0029 cdrft - 0.00573 d/d + 0.0076 Rotor Draft	0.72	47.7	0.69
Helix Twist	21.7 + 856 Lh + 0.0122 cdrft + 0.00197 d/d + 0.0082 Rotor Draft	4.29	13.6	.12
Yarn diameter	- 21.3 - 1484 Lh - 0.0140 cdrft - 0.00364 d/d - 0.0133 Rotor Draft	2.3	27.1	0.3
Packing density	4.7 - 3218 Lh - 0.032 cdrft - 0.0066 d/d - 0.0270 Rotor Draft	2.69	20.5	0.19
Air-jet Yarn		% V Ex by Air-jet draft		
Helix angle	- 13.0 - 3727 Lh - 0.014 cdrft - 0.0146 d/d - 0.0113 A/J draft	0.38	39.6	0.49
Helix Twist	- 17.1 + 9502 Lh + 0.128 cdrft + 0.0122 d/d + 0.081 A/J draft	16.65	23	022
Yarn diameter	- 33.0 + 1617 Lh + 0.0176 cdrft + 0.00194 d/d + 0.0165 A/J draft	5.7	66.6	1.5
Packing density	- 22.1 + 3754 Lh + 0.0437 cdrft + 0.00445 d/d + 0.0383 A/J draft	7.68	72.6	1.99
where: Lh = lap hank, cdrft= card draft, d/d = total draw frame drafts i.e. 36 or 64, R/F = ring frame, S/F = speed frame A/J = air-jet				

Figure 4 shows the S/N ratio plot of yarn diameter with the change in process variables. As in ring yarn-type I, the finer lap hank and higher draft/doublings reduce the yarn diameter. The increase in card draft (from 88 to 101) and the corresponding decrease in speed frame draft reduces the yarn diameter. This could be because of the reduction of draft at the speed frame, which reduces the ribbon width and makes the yarn more compact. Further, although the increase in card draft and the corresponding reduction in speed frame draft reduces the width of the fibre band, it also reduces the fibre migration in roving, due to the decrease in tension in the edge fibres [6]. This makes the roving and corresponding yarn less compact, as they have a bigger diameter.

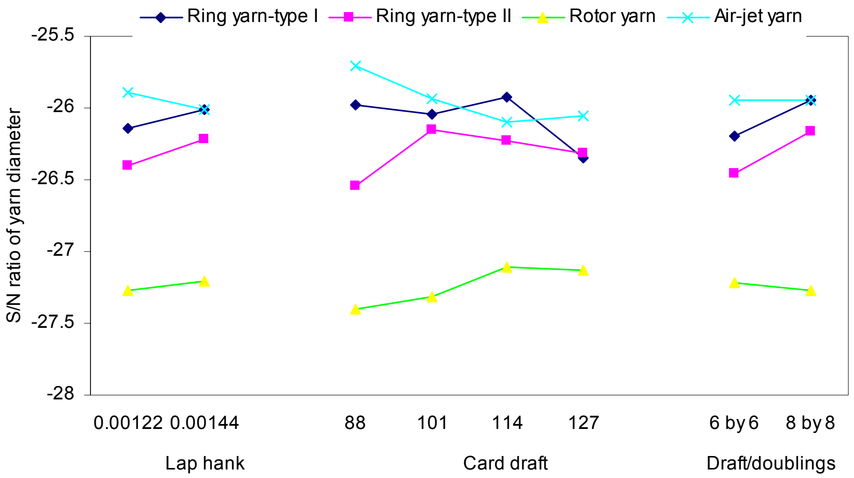

Figure 4. S/N ratio plot of yarn diameter with change in process variables

3.3.3. Rotor Yarn

Table 4 shows that the average diameter of rotor yarn is the highest, due to the reasons mentioned earlier in section 3.3.1. This can also be due to the MFP values being the lowest, as well as the root mean square deviation (RMSD) in rotor yarn [6].

Table 7 shows the effect of change in process variables on the change in yarn diameter of the rotor yarn. A lower R^2 value shows that the process variables do not affect the yarn diameter much. However, most of the change in diameter is due to a change in card draft alone. The changes in lap hank and draft/doublings have no effect on yarn diameter. Table 8 shows that the effect of change in rotor draft is only marginal.

Figure 4 shows the S/N ratio plot of yarn diameter with the change in process variables. The increase in card draft and the corresponding decrease in rotor draft decrease the yarn diameter. This is because of the increase in fibre tension [6]. This helps the fibre to be deposited uniformly in the rotor groove, and thus increases the compactness of fibre band in the rotor groove, producing the yarn with smaller diameter. Overall, the yarn diameter depends on the compactness of the fibre band in the rotor groove, which in turn is mainly dependent on the centrifugal force, and thus on the rotor speed. These factors are almost the same because the rotor speed is the same. This could be the reason for the non-dependence of rotor yarn diameter on the process variables selected.

3.3.4. Air-jet Yarn

Table 4 shows that the average diameter of air-jet yarn is the lowest. This can also be due to the highest values of MMI and RMSD in air-jet yarn [6].

Table 7 shows the effect of change in process variables on the change in yarn diameter of air-jet yarn. A high R^2 value shows that the process variables influence the yarn diameter. However, most of the change in diameter is due to a change in card draft and the corresponding changes in the air-jet draft alone. The effect of the change in lap hank is only marginal, and draft/doublings have no effect on yarn diameter. Table 8 shows that the change in air-jet draft influences the yarn diameter.

Figure 4 shows the S/N ratio plot of yarn diameter with change in process variables. Finer lap hank, the increase in card draft and the corresponding decrease in air-jet draft increases the yarn diameter. This is because of the decrease in the width of the fibre band, which reduces the wrapper twist frequency and the generation of wrappers fibres [7]. This iun turn reduces the binding force generated by wrappers on the core of parallel fibres, thus producing yarn with lower compactness and larger diameter. The draft/doublings have no influence on yarn diameter.

3.4. Effect of process variables on packing density

The type of response used for analysing packing density was ‘larger is better’. This implies that increases in S/N ratio of packing density increase the actual value of the yarn’s packing density.

3.4.1. Ring Yarn-Type I

Table 5 shows that the average packing density of ring yarn-type I is higher than that of the rotor yarn but lower than that of the air-jet yarn. This is because the ring yarn has a greater yarn diameter than the equivalent air-jet yarn, but smaller than that of the rotor yarn. Also, in ring yarn, fibres change from a thin ribbon to a roughly circular shape, with fibres gripped at the nip of the front roller. The outermost fibres are under greater strain, and unless there is excessive yarn tension, the core is subjected to compression. In one case, the stress is relieved by shortening the path length of the fibre in yarn, and in the other case by lengthening it. The net result is that fibres depart from a purely helical configuration, to give an interlocking structure which has higher packing density in comparison to rotor yarn [2].

Table 6 shows the effect of change in process variables on the change in packing density of ring yarn-type I. The effect of card draft, the corresponding ring frame draft and draft/doublings at draw frame explains most of the changes in packing density. The effect of change in card draft is almost significant at 90% confidence level, and the effect of change in draft/doublings is significant at 90% confidence level. The effect of change in lap hank on yarn packing density is the least. A very high value of R^2 in the table shows that the change in process variables highly influences the packing density. Table 8 shows that the effect of change in ring frame draft influenced the change in packing density considerably.

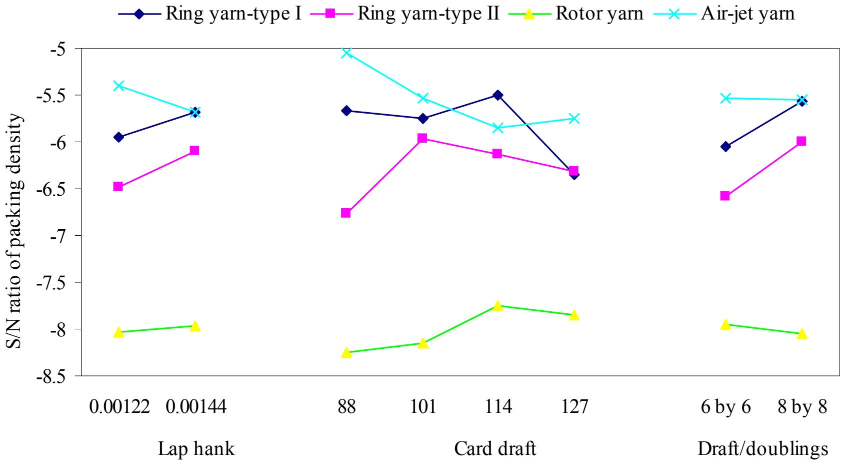

Figure 5. S/N ratio plot of packing density with change in process variables

Figure 5 shows the S/N ratio plot of the packing density of ring yarn with the change in process variables. Finer lap hank and the corresponding lower ring-frame draft increases the packing density of yarn, because of the smaller diameter. Furthermore, the lower helix angle with finer lap hank further increases the packing density of the yarn. The increase in card draft (from 88 to 114 card draft) and the corresponding decrease in ring frame draft tends to increase the packing density of yarn, mainly because of the reduction in yarn diameter. Further increase in card draft (from 114 to 127) and the corresponding decrease in ring frame draft decreases the packing density. This is due to the increase in yarn diameter and the increase in helix angle. The increase in draft/doublings increases the packing density, due to the increase in compactness of the fibre band. The decrease in helix angle at higher draft/doublings is also responsible for the increase in the packing density of yarn. The dependence of packing density on yarn diameter is in agreement with the findings of some previous researchers [8,12]. Similarly, in this research work, the trends of S/N ratio plot of ring yarn packing density are very similar to those of yarn diameter. This shows that in ring yarn, packing density and diameter are inversely related.

3.4.2. Ring Yarn-Type II

Table 5 shows that the average packing density of ring yarn-type II is slightly lower than that of ring yarn-type I. This can be attributed to the slightly bigger yarn diameter of ring yarn-type II.

Table 6 shows the effect of change in process variables on the packing density of ring yarn-type II. The effect of card draft and draft/doublings on the draw frame explains most of the change in yarn packing density. The effect of the change in lap hank on packing density is the least. A high value of R^2 indicates that the process variables influence the packing density considerably. Table 8 shows that the effect of change in speed frame draft on packing density is marginal.

Figure 5 shows the S/N ratio plot of yarn packing density with the change in process variables. As in ring yarn-type I, the finer lap hank and higher draft/doublings increase the packing density of yarn. This is mainly due to the decrease in helix angle and in the yarn diameter. The increase in card draft (from 88 to 101) and the corresponding decrease in speed frame draft increases the packing density mainly by reducing the yarn diameter. Further, the increase in card draft and the corresponding reduction in speed frame draft makes the roving and corresponding yarn less compact, due to the increase in yarn diameter [6].

3.4.3. Rotor Yarn

Table 5 shows that the packing density of rotor yarn is the lowest amongst the three yarns. The rotor yarn possesses a single helical structure, and the fibres are distributed from inner core to the outer core without fibre migration. The fibres are twisted more uniformly, as a result of which the inner core receives more compression. The inner zone is subjected to a variety of tensions in spinning, and the migrated structure will be somewhat similar to that of ring-spun yarn. Thus, the packing density of the inner zone is higher in rotor yarn as compared to that of the inner core of the ring yarn. However, the intermediate and outer zone contain hairs and loosely-bound wrapper fibres, and have less packing density than ring yarn in these zones. Overall, the packing density of rotor yarn is less than the ring yarn. Also, the higher rotor yarn diameter is responsible for the low packing density [5-11].

Table 6 shows the effect of change in the process variables on the change in the yarn packing density of rotor yarn. A low value of R^2 shows that the process variables do not affect the yarn packing density much. This is because of the compactness of the fibre band in the rotor groove, which is mainly dependent on centrifugal force, and thus on rotor speed. These factors are almost identical because the rotor speed is the same in all cases. This could be the reason for the non-dependence of rotor yarn packing density on the process variables chosen. However, most of the change influenced by the process variables can be attributed to card draft. The effect of change in lap hank and draft/doublings has no effect on packing density. Table 8 shows that the effect of change in rotor draft is only marginal.

Figure 5 shows the S/N ratio plot of packing density with the change in process variables. The increase in card draft and the decrease in rotor draft increase the packing density mainly due to the increase in the helix twist and the decrease in the yarn diameter, as explained in previous sections. As in ring yarn, the trends of the S/N ratio plot of the packing density of rotor yarn are similar to those of yarn diameter.

3.4.4. Air-jet Yarn

Table 5 shows that the average packing density of air-jet yarn is the highest due to its having the smallest diameter.

Table 7 shows the effect of change in process variables on the change in packing density of air-jet yarn. A high value of R^2 shows that the process variables influence the packing density considerably. The change in card draft and the corresponding change in air-jet draft influence most of the change in packing density. The effect of the change in lap hank follows the effect of card draft. The change in draft/doublings has no effect on packing density. Table 8 shows that the change in air-jet draft also influences packing density.

Figure 5 shows the S/N ratio plot of packing density with the change in process variables. Finer lap hank, the increase in card draft and the corresponding decrease in air-jet draft decrease the yarn packing density by increasing the yarn diameter and helix angle, and the reduction in helix twist. The draft/doublings have no influence on yarn diameter. Overall, the trends of change in the S/N ratio of packing density in air-jet yarn are similar to those of yarn diameter and helix angle. This implies that a decrease in yarn diameter or a decrease in helix angle will increase the packing density of the yarn

Tables 6 to 7 show that the changes in helix angle, helix twist, yarn diameter and packing density as analysed by the Anova technique and ranked by the Taguchi method are in agreement with each other. Furthermore, the change in above parameters is influenced by the change in card draft.

4. Conclusions

1. Helix angle is highest in rotor and the lowest in air-jet yarn. A decrease in the ring-frame draft increases the helix angle in the yarn. Increases in lap hank, card draft and draft/doublings increase the helix angle in rotor yarn.
2. Increases in lap hank, card draft and draft/doublings do not affect the helix twist in rotor and air-jet yarn much.

3. Increases in lap hank and draft/doublings decrease the diameter of ring yarn. Increases in ring frame & air-jet draft and decreases in speed frame and rotor draft decrease yarn diameter.
4. The yarn diameter is the highest and the packing density the lowest in rotor yarn. The yarn diameter is the lowest and the packing density the highest in air-jet yarn. Packing density is inversely related to the diameters of ring, rotor and air-jet yarns.
5. The packing density of ring yarn tends to increase with the decrease in helix angle, and the packing density of air-jet yarn tends to increase with the increase in helix twist.
6. The change in card draft influences most of the change in helix angle, helix twist, and yarn diameter and packing density.

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