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Properties of air-vortex blended yarn influenced by spinning process parameters

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Box-Behnken three variables three factors design has been used to optimize the machine spindle diameter, nozzle pressure and yarn delivery speed for achieving the required quality of air vortex polyester/cotton blended yarn. The response surface equations for respective yarn properties in terms of coded factors and significant model terms are developed. Yarn tenacity and elongation show an increase with the increase in nozzle pressure and a decrease with an increase in delivery speed and spindle diameter. Yarn thin places, thick places, neps, U% and hairiness index depict an increase with the increase in delivery speed and spindle diameter, while the decrease is observed with an increase in nozzle pressure. A combination of 1.1mm spindle diameter, 0.5 MPa nozzle pressure and 432.38 m/min delivery speed is the optimized value for targeted yarn quality at 0.71 desirability value.

Keywords: Air-vortex blended yarn, Box-Behnken design, Polyester/cotton yarn, Spinning parameters, Yarn properties

1 Introduction

The air-vortex spinning system is one of the most promising new inventions in the market of staple yarn spinning. The air-vortex consists of two-layer structure. The outer layer possesses twisted fibres which provide the helical form, while the inner has 30% untwisted fibres[1]. Soe *et al*.[2] observed a statistical insignificant difference between mass irregularities, U%, CVm% values of Murata vortex spun (MVS) yarn in comparison to corresponding 100% cotton ring and rotor yarns. They have also observed higher breaking elongation, lower coefficient of variation of tenacity and elongation as compared to ring- and rotor-spun yarn, but the ring yarns depicted the highest strength. Basal and Oxenham[3] studied the influence of machine and process parameters on the structure and properties of 100% cotton vortex-spun yarn. Reduction in yarn hairiness was observed at higher air pressure and smaller spindle diameter but the combination of delivery speed and nozzle angle influenced yarn hairiness significantly. The study of Ortlek[4] noticed a decrease in yarn hairiness and reduction in yarn irregularity and tenacity with the increase in spindle diameter. Moučková[5] studied the impact of process parameters on blended vortex yarn. Rajwin *et al.*[6], Ülkü *et al.*[7], Bansal *et al.*[8] , Gulsevincler *et al*[9] and Krifa & Ethridge[10] carried out their studies to see the influence of process parameters on properties of yarns made on ring, open-end and jet–ring, and compact spinning system. The study[11] has been carried out to confirm that the yarn packing density and radial packing density of yarns are influenced by the individual as well as the interaction effect of process parameters in the air–vortex blended yarn. Textile industry shows more interest in the air vortex spinning system because of its unique properties and higher production rates[12].

The reported work, in general, has concluded that the physical and mechanical properties of yarns are only governed by the properties of constituent fibres and process parameters. Rather, structural changes in the yarn influenced by the properties of constituent fibres and process parameters are the basic causes for effective changes in yarn properties. Therefore, it is important to analyse the expected changes in yarn structure that can influence the yarn properties due to process parameters. Then only one can maintain the properties of constituent fibres more effectively to improve the yarn structure and, hence the yarn properties. In any process optimization, the importance of individual variables and their interactions with other variables to optimize product quality are of prime importance. Accordingly, in process optimization, the design of the experimental method is more effective and relevant for industrial trails. Many designs are used to identify the effect of controllable significant factors. The Box-Behnken design is more efficient because of the lesser number of experiments than the full factorial design.

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Box-Behnken design provides information on linear effects and quadratic effects with the two linear interactions which are more effective for process optimisation

In the present study, Box-Behnken three variables three factors design has been used to optimize the spindle diameter, nozzle pressure and yarn delivery speed for achieving the required quality of air vortex polyester/cotton blended yarn for its specific applications.

2 Materials and Methods

Polyester fibre (1.4 denier, 38 mm length) and cotton fibre (4 micronaire) were used to prepare 30 Ne polyester cotton (65/35) blended yarn on air-vortex spinning machine (model MVS 870). In the present work, Box-Behnken three variable designs were used to optimize the nozzle pressure, spindle diameter and yarn delivery speed in order to achieve the required yarn quality. The actual values of variables corresponding to coded levels are shown in Table 1. A three-variable design generated in the above manner is given in Table 2.

Total of 15 samples was prepared with the combination of different parameters as shown in Table 2. The ANOVA technique was applied to see the impact of an individual as well as the combined effect of process variables on yarn properties. Response surface equations were obtained for respective yarn properties.

The yarns were tested for yarn evenness on USTER Tester 5 at speed of 400 m/min. Yarn tensile strength and elongation-at-break were measured at UTR4 at speed of 5000 mm/min. Keisokki Laserspot was used to measure the yarn hairiness at 100 m/min speed for 1 min. All testings were carried out at 65% relative humidity and 27° C temperature after conditioning the yarn for 24h.

3 Results and Discussion

The influence of machine variables with different combinations (Table 2) on the physical and mechanical properties of yarn is shown in Table 3. The response surface equations (regression equations) for different yarn properties are given in Table 4. The analysis of variance (ANOVA) has been used to study the effect of spindle diameter, nozzle pressure and delivery speed. All statistical analysis was carried out at 95% confidence level. The obtained response surface equations can be used to optimize the machine variables in order to achieve a required value for specific yarn property.

The yarn properties are plotted in 3-D graphs against two-variable machine parameters, keeping one of the parameters constant. The obtained trends of different yarn properties influenced by considered process parameters were discussed in subsequent

Table 1 — Actual values of variables corresponding to code levels

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

Table 2 — Box Behnken design for three variables

Sample code	Spindle diameter (A)	Nozzle pressure (B)	Delivery speed (C)
S-1	1.0	0.45	450
S-2	1.2	0.45	450
S-3	1.0	0.55	450
S-4	1.2	0.55	450
S-5	1.0	0.5	400
S-6	1.2	0.5	400
S-7	1.0	0.5	500
S-8	1.2	0.5	500
S-9	1.1	0.45	400
S-10	1.1	0.55	400
S-11	1.1	0.45	500
S-12	1.1	0.55	500
S-13	1.1	0.5	450
S-14	1.1	0.5	450
S-15	1.1	0.5	450

Table 3 — Experimental results of yarn properties

Property	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14	S-15
Uster%	10.62	10.53	10.63	10.52	10.55	10.5	10.63	10.66	10.48	10.63	10.68	10.69	10.52	10.44	10.5
Thin places/km (-50%)	8	7	7.8	6.1	7.7	5.6	6.9	7.7	6.7	5.9	6.7	7.8	6.1	5.6	6.7
Thick places /km (+50%)	41	36	43	30.8	26.4	24.7	59.5	49.1	20.6	24.4	51.4	52	33.9	26.3	27.3
Neps /km(+200%)	32	26	30.6	24.8	38	28.6	34.7	29.2	30.8	36.1	31.9	29.1	26.3	25.3	25.8
H Index	3.94	4.88	3.65	4.39	3.45	4.01	4.11	5.47	4.01	3.66	4.88	4.55	4.12	4.12	4.11
Yarn tenacity cN/tex	19.7	18.88	20.04	19.56	20.05	19.83	19.25	16.64	20.16	19.84	17.37	19.22	19.7	19.72	19.59
Elongation %	8.1	7.81	8.3	8.04	8.38	8.18	7.96	7.3	8.26	8.29	7.49	7.88	8.06	8.15	8.11

Table 4 — Response surface equations for various yarn properties

Yarn properties	Response surface equation	Correlation coefficient
Yarn tenacity cN/tex	$19.67 - 0.516*A + 0.318*B - 0.925*C + 0.085*A*B - 0.597*A*C + 0.542*B*C - 0.165*A^2 + 0.04*B^2 - 0.562*C^2$	0.9805
Elongation %	$8.020 - 0.176*A + 0.106*B - 0.31*C$	0.8762
Uster%	$10.486 - 0.027*A + 0.02*B + 0.062*C - 0.005*A*B + 0.02*A*C - 0.035*B*C + 0.026*A^2 + 0.061*B^2 + 0.071*C^2$	0.8799
Thin Places/km (-50%)	$6.133 - 0.5*A - 0.1*B + 0.4*C - 0.175*A*B + 0.725*A*C + 0.475*B*C + 0.645*A^2 + 0.445*B^2 + 0.195*C^2$	0.8835
Thick places /km(+50%)	$29.166 - 3.662*A + 14.487*C - 1.8*A*B - 2.175*A*C - 0.8*B*C + 5.679*A^2 + 2.854*B^2 + 5.079*C^2$	0.9785
Neps/km (+200%)	$25.8 - 3.337*A - 0.012*B - 1.075*C + 0.05*A*B + 0.975*A*C - 2.025*B*C + 1.6*A^2 + 20.95*B^2 + 5.225*C^2$	0.9731
Hairiness index	$3.14 + 0.525*A - 0.112*B + 0.512*C$	0.9813

sections. Thereafter, machine parameters are optimized for minimum or maximum values of various yarn properties. Finally, suitable explanations are provided for the obtained trends of respective yarn properties influenced by considered machine variables.

3.1 Yarn Tenacity

The variance analysis of yarn tenacity has been carried out, and the quadratic model is found to be significant. The response surface equation for the yarn tenacity in terms of coded factors and significant model terms is shown in Table 4.

The 3D surface plots of nozzle pressure and delivery speed at three different spindle diameters are shown in Fig. 1 (a). The yarn tenacity depicts an increase with the increase in nozzle pressure but the increase in delivery speed notices a slight increase and then a decrease in yarn tenacity at respective spindle diameters. The yarn tenacity shows a reduction with the increase in both nozzle pressure and delivery speed at different spindle diameters. But the yarn tenacity notices an initial increase and then decrease with the increase in spindle diameter towards lower values of nozzle pressure and delivery speeds. Further, a reduction in yarn tenacity is observed towards higher values of nozzle pressure and delivery speeds. The increase in spindle diameter, nozzle pressure and delivery speed together notice a reduction in yarn tenacity.

The 3D surface plots spindle diameter vs. delivery speed at three different nozzle pressures is shown in Fig. 1 (b). The increase in delivery speed notices a slight increase and then decrease in yarn tenacity, but the increase in spindle diameter shows an increase at respective nozzle pressure. A slight increase in yarn tenacity is observed with the initial increase in both delivery speed and spindle diameter, and later it shows a decrease at different nozzle pressures. But the increase of nozzle pressure depicts the opposite trend of yarn tenacity with the increase in both delivery speed and spindle diameter. A reduction in yarn tenacity is noticed with the simultaneous increase in spindle diameter, nozzle pressure and delivery speed.

Figure 1 (c) provides the 3D surface plots of nozzle pressure vs. spindle diameter at three different delivery speeds. The decrease in nozzle pressure and increase in spindle diameter at 400 m/min delivery speed shows an increase in yarn tenacity. The increase in nozzle pressure shows an increase in yarn tenacity, but a reduction is noticed with the increase in spindle diameter at 450 m/min and 500 m/min delivery. A continuous reduction in the yarn tenacity is noticed with the increase in both nozzle pressure and spindle diameter at respective delivery speeds but the increase in delivery speed depicts an increase and then decrease in yarn tenacity. Further, the increase in all three considered variables shows a reduction in yarn tenacity.

The equation given in Table 4 has been used to optimize machine parameters in order to achieve a maximum value of the yarn tenacity. The maximum value of 20.16 cN/tex for yarn tenacity is achieved with a combination of 1.064 mm spindle diameter, 0.4585 MPa nozzle pressure and 410.74 m/min delivery speed.

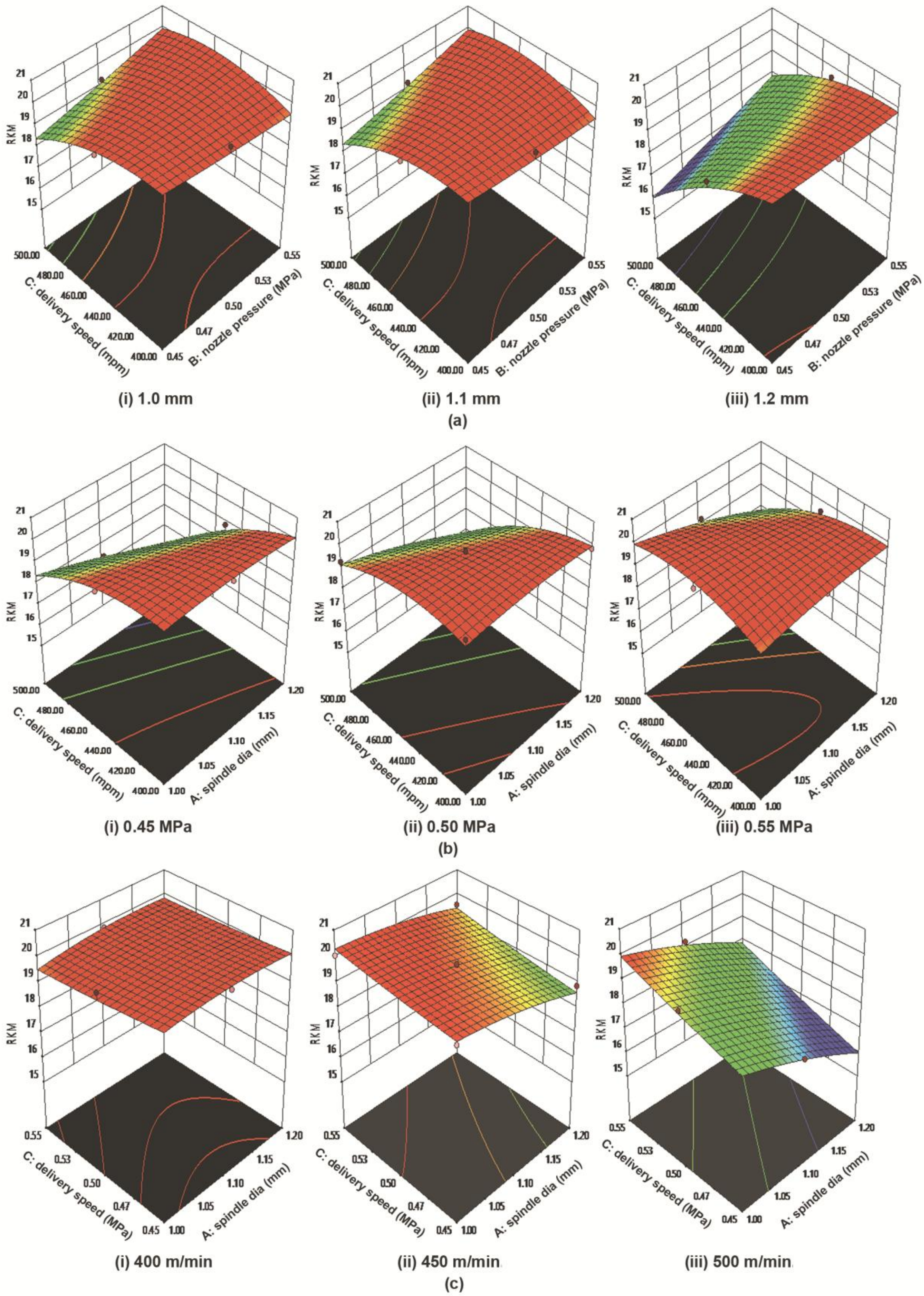

Fig. 1 — Yarn tenacity at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

The results discussed above indicate a reduction in yarn tenacity with the increase in yarn delivery speed and spindle diameter, but an increase in yarn tenacity with the increase in nozzle pressure. However, yarn tenacity shows a reduction with the increase in spindle diameter, nozzle pressure and yarn delivery speed together. The obtained trends can be explained based on the mechanics of yarn formation.

Vortex-spun yarn consists of two layers of fibres, viz. yarn core and wrapping layer. The core of the yarn is formed by the leading ends of the fibres of the drafted fibre ribbon, and fibres are arranged parallel to the yarn axis without twist. The wrapping layer of fibres consists of trailing ends of fibres separated from the drafted fibre ribbon by the swirling airflow and are twisted around the core of the yarn. Therefore, the tenacity of vortex yarn is governed by the ratio of wrapper and core fibres and the wrapping length of the sheath fibre. Higher yarn delivery speed provides a slightly higher ratio of wrapper fibres to core fibres. The airflow caused by the front drafting roller running at a high surface speed separates more trailing ends of fibres from the drafted fibre ribbon. Further, the number of wrapper loops per unit length decreases with the increase in yarn delivery speed. The wrapper to core ratio plays a more important role than the tightness of the twist for deciding the tenacity of the yarn. The increase of yarn delivery speed also reduces the time spend by free trailing end of fibres in the spindle chamber. This provides insufficient wrapping intensity of fibre over the yarn core. Both the reasons are responsible for lowering the packing density of yarn, hence lowering the tenacity of the yarn at a higher delivery speed.

The increase of nozzle pressure affects the fibre bundle radially, thus providing more open trailing end of fibres. The higher radial velocity increases the whirling effect around the spindle, thereby making more wrapper fibres available in the yarn. But, too high nozzle pressure produces more wild and waste fibres, because fibres are easily taken out from the drafted fibre bundle by the high-speed airflow. The tangential velocity acts perpendicular to the fibre axis and generates the cross flow on the wrapper fibres. The increase in tangential velocity enhances the twisting of the trailing end of the fibres, but the decrease in tangential velocity reduces the twisting effect. The increase of nozzle pressure is responsible for the increase of both axil and tangential velocity. As a result, the fibre bundle receives more twists and therefore, increases the packing density of yarn; the yarn becomes stronger but stiffer. The increase in yarn stiffness is due to an increase in packing density in the core zone of the yarn.

The spindle with higher diameter results in lower yarn tenacity, because the higher diameter spindle provides more freedom to the fibre bundle to move inside the spindle. Freedom of fibres movement inside the spindle is responsible for twist loss and loosening of wrapper fibres. This is mainly due to lower friction among fibres within the yarn, thereby reducing the packing density of yarn as well as yarn tenacity with a larger spindle diameter. But smaller spindle diameter wraps the yarn core more tightly, which makes fibre slippage more difficult.

3.2 Yarn Elongation-at-break

The variance analysis of the elongation at break shows that the 2FI model is significant. The response surface equation for elongation at break in terms of coded factors and significant model terms is represented in the equation given in Table 4.

The 3D surface plots of nozzle pressure *vs*. delivery speed at three different spindle diameters are shown in Fig. 2 (a). The increase in nozzle pressure notices an increase in yarn elongation %, but it observes a decrease with the increase in delivery speed at respective spindle diameters. The increase in both nozzle pressure and delivery speed shows a reduction in the yarn elongation % at different spindle diameters and it reduces continuously with the increase in spindle diameter. The increase in all three machine parameters decreases the yarn elongation %.

Figure 2 (b) illustrates the 3D surface plots of spindle diameter *vs.* delivery speed at three different nozzle pressure. An increase in yarn elongation % is noticed with the increase in spindle diameter, but a decrease is observed with the increase of delivery speed. The increase in both spindle diameter and delivery speed depicts a decrease in yarn elongation % at different nozzle pressures, but yarn elongation % shows an increase with the increase in nozzle pressure. The increase in spindle diameter, nozzle pressure and delivery speed together notice a reduction in the value of yarn elongation %.

Figure 2 (c) provides the 3D surface plots of spindle diameter *vs*. feeder speed at three different delivery speeds. The elongation % notices a decrease with the increase in spindle diameter but an increase with the increase in nozzle pressure at respective delivery speeds. The elongation % shows a reduction with the increase in both spindle diameter as well as

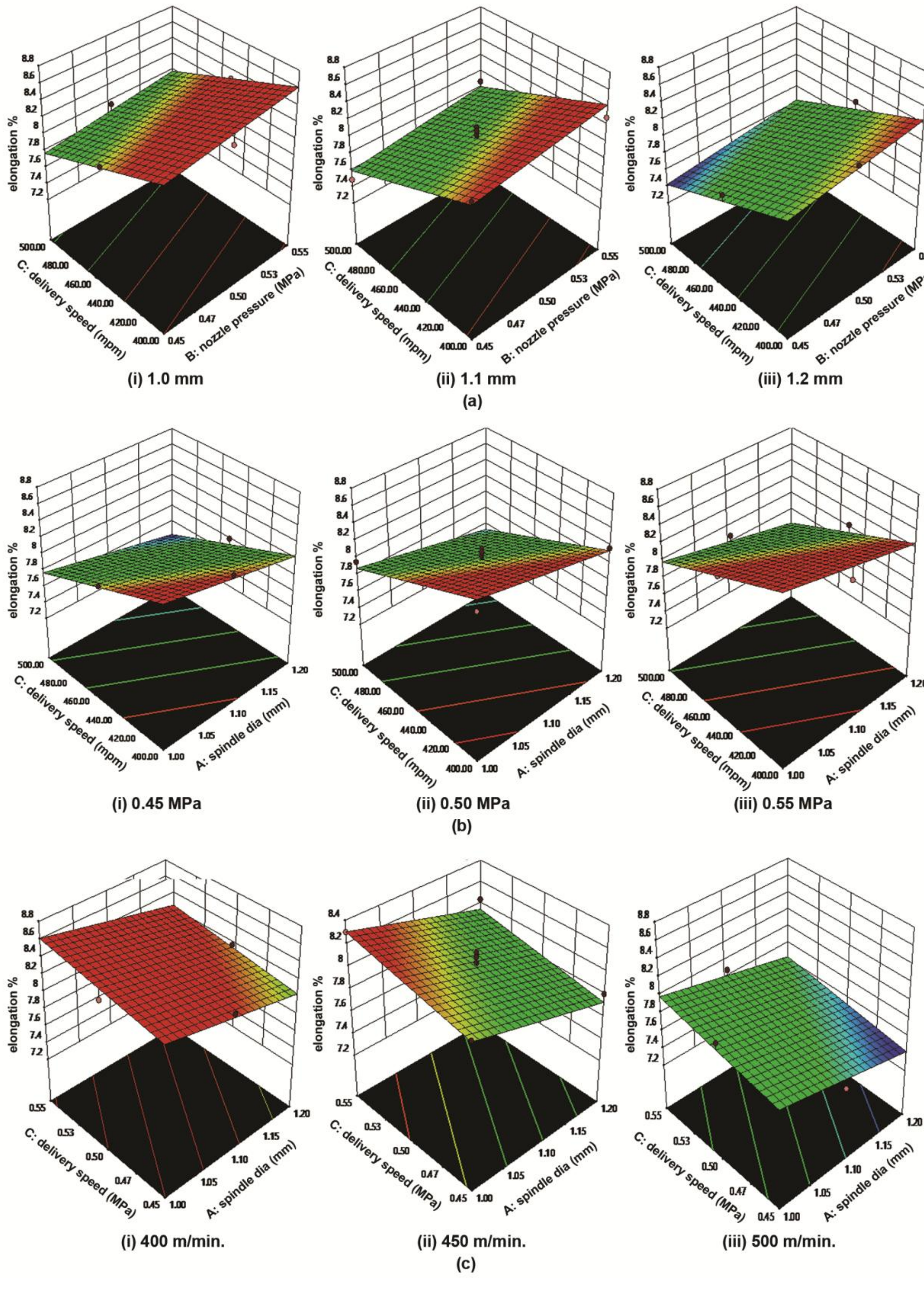

Fig. 2 — Yarn elongation % at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

nozzle pressure at different delivery speeds, but it shows a continuous decrease with the increase in delivery speed. A reduction in yarn elongation % is observed with the increase in all three machine variables.

The equation given in Table 4 is used to optimize machine parameters to achieve a maximum value of the yarn elongation%. The maximum value of 7.43% yarn elongation % is achieved at a combination of 1.2 mm spindle diameter, 0.45 MPa nozzle pressure and 499.9 m/min delivery speed.

An increase in yarn elongation % is also noticed with the increase in nozzle pressure, but the increase in spindle diameter and yarn delivery speed causes a reduction in yarn elongation %. The increase in nozzle pressure both in the direction of yarn twist and in the opposite direction of yarn twist results in higher yarn elongation due to the higher wrapper fibres. But a higher increase in yarn elongation is noticed when nozzle pressure is applied in the opposite direction of yarn twist. The negative pressure formed by the nozzle pressure in the opposite direction of yarn twist which changes the fibre orientation of yarn core and wrapping length of the sheath fibres is found to be responsible for the increase in elongation % with the increase of nozzle pressure.

Wrapping fibres are twisted around the core fibre through air swirl. The generation of the swirl on the fibre bundle inside the nozzle is also influenced by spindle diameter. A higher diameter spindle provides more freedom to the fibre bundle to move inside the spindle. Freedom of fibres movement inside the spindle is responsible for twist loss and loosening of wrapper fibres. These factors influence the core and wrapping layer of the yarn, helix angle of wrapping fibre, tightness of wrapping fibre and thus yarn elongation.

As discussed above, higher yarn delivery speed provides a slightly higher ratio of wrapper fibres to core fibres. Further, the number of wrapper loops per unit length decreases with the increase in yarn delivery speed. The increase of yarn delivery speed also reduces the time spent by the free trailing end of fibres in the spindle chamber. This provides insufficient wrapping intensity of fibre over the yarn core. Both the reasons are responsible for lowering the packing density of yarn, thus lowering the elongation % of the yarn at a higher delivery speed.

3.3 Thin Places

The variance analysis of thin places has been carried out and the quadratic model is found to be insignificant. The response surface equation for the thin places in terms of coded factors and significant model terms is shown in Table 4.

The 3D surface plots of nozzle pressure and delivery speed at three spindle diameters are shown in Fig. 3 (a). A decrease and then increase in yarn thin places is observed with the increase in nozzle pressure at respective spindle diameters. The increase in delivery speed at 1.0 mm spindle diameter notices an initial decrease and then increase in thin places, but at 1.1 mm and 1.2 mm spindle diameters a continuous increase is observed. The increase in both nozzle pressure and delivery speed notices an initial decrease and then increase in yarn thin places at different spindle diameters, but a continuous increase in spindle diameter also shows the similar trend of thin places. The trend is more prominent towards higher nozzle pressure and delivery speeds. The increase in spindle diameter, nozzle pressure and delivery speed together shows an initial decrease and then increase in yarn thin places.

The 3D surface plots of spindle diameter *vs.* delivery speed at three different nozzle pressures are shown in Fig. 3 (b). The yarn thin places depict a decreasing and increasing trend with the increase of spindle diameter, but an increase is noticed with the increase in delivery speed at respective nozzle pressures. The yarn thin place shows an initial decrease and then increase with the increase in both delivery speed and spindle diameter at different nozzle pressures. The thin places also follow a similar pattern with the continuous increase in nozzle pressure. The simultaneous increase in spindle diameter, nozzle pressure and delivery speeds together follow a decrease and then increase of yarn thin places.

Figure 3 (c) shows the 3D surface plots of nozzle pressure vs. spindle diameter at three different delivery speeds. A decrease and then increase in the yarn thin places is noticed with the increase in nozzle pressure and spindle diameter at respective delivery speeds. The observed trend is more prominent towards higher values of spindle diameter and nozzle pressure. But the increase in delivery speed towards lower values of spindle diameter and nozzle pressure notices a reduction, but towards higher values, it provides an increase of thin places. Initial decrease and then increase of yarn thin places are noticed with the increase in all three considered machine variables.

The equation given in Table 4 is used to optimize machine parameters to achieve a minimum value of the yarn thin places. The minimum value of 5.45 thin

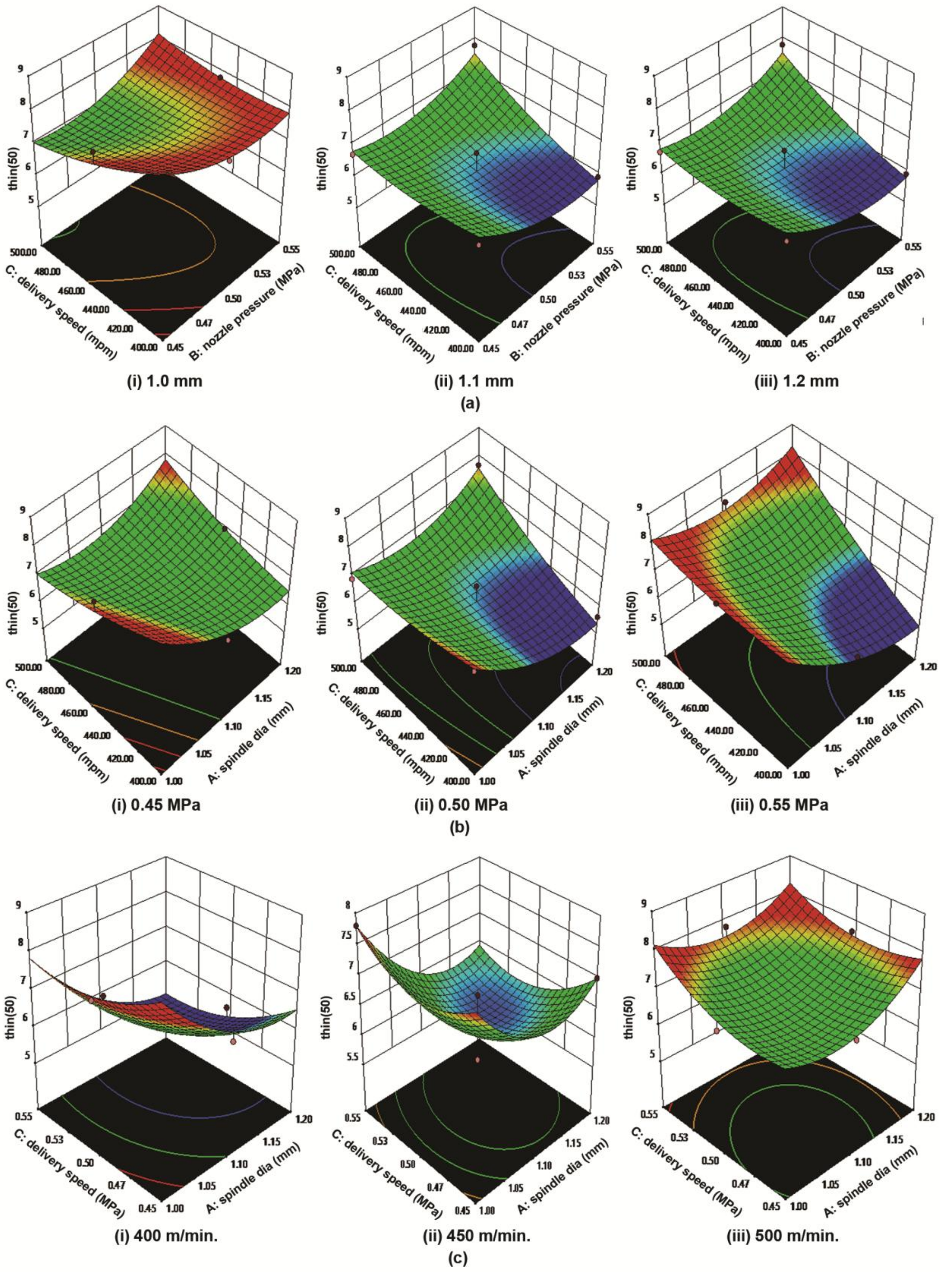

Fig. 3 — Yarn thin places (-50%) at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

places is achieved with a combination of 1.16 mm spindle diameter, 0.54 MPa nozzle pressure and 414.72 m/min delivery speed.

3.4 Thick Places

As per the variance analysis of the yarn thick places, the quadratic model is found to be significant. The response surface equation for yarn thick places in terms of coded factors and significant model terms is shown in the equation given in Table 4.

The 3D surface plots of nozzle pressure *vs*. delivery speed at three different spindle diameters are shown in Fig. 4 (a). The results show an increase in yarn thick places with the increase in nozzle pressure and delivery speed at respective spindle diameters. But the continuous increase of spindle diameter follows an initial decrease and then increase. The increase in spindle diameter, nozzle pressure and delivery speed together infer an increase in thick places.

Figure 4 (b) illustrates the 3D surface plots of spindle diameter vs. delivery speed at three different nozzle pressures. An increase in yarn thick places is noticed with the increase in spindle diameter and delivery speed at respective nozzle pressure. The increase in both spindle diameter and delivery speed follow an initial decrease and then an increase of yarn thick places at different nozzle pressures. Continuous increase in nozzle pressure (0.45-0.55MPa) follows a similar pattern in yarn thick places. The increase in spindle diameter, nozzle pressure and delivery speeds together enhance the value of yarn thick places.

Figure 4 (c) illustrates the 3D surface plots of spindle diameter *vs.* nozzle pressure at three different delivery speeds. The thick places follow an initial decrease and then increase with the increase in spindle diameter, but observe an increase with the increase in nozzle pressure at respective delivery speeds. The increase in both spindle diameter, as well as nozzle pressure at different delivery speeds, follow a decreasing and increasing trend of thick places, but in thick places, a continuous increase is observed with the increase in delivery speed. The increase in all three machine variables provides an increase in thick places.

The equation given in Table 4 is used to optimize machine parameters to achieve a minimum value of the yarn thick places. The minimum value of 20.52 thick places is achieved with a combination of 1.13 mm spindle diameter, 0.473 MPa nozzle pressure and 401.03 m/min delivery speed.

3.5 Neps

The variance analysis of yarn neps shows a significant quadratic model. The response surface equation for yarn neps in terms of coded factors and significant model terms is represented in Table 4.

The 3D surface plots of yarn neps given in Fig. 5 (a) depict an increasing trend of neps with the increase of nozzle pressure, but the increase in delivery speed has shown a decrease and then increase in neps at respective spindle diameters. The increase in both nozzle pressure and delivery speed observed an initial decrease and then an increase in the yarn neps at respective spindle diameter. But the continuous increase of spindle diameter follows a decrease in yarn neps. A decreasing trend of yarn neps is observed with the simultaneous increase of spindle diameter, nozzle pressure and delivery speed.

Figure 5 (b) shows a decrease and then increase in the value of neps with the increase of delivery speed and spindle diameter at different nozzle pressures. Continuous increase in nozzle pressure (0.45-0.55MPa) follows a similar pattern in neps places, The value of the yarn neps shows a decrease with the simultaneous increase in spindle diameter, nozzle pressure and delivery speed.

Figure 5 (c) illustrates the 3D surface plots of nozzle pressure and spindle diameter at three different delivery speeds. At 400 m/min and 450 m/min delivery speeds, the yarn neps follow a decreasing and increasing trend with the increase in spindle diameter but an increasing trend with the increase in nozzle pressure is noticed at respective delivery speeds. The increase in both nozzle pressure and spindle diameter shows an initial decrease and then an increase in neps at respective delivery speeds, but the continuous increase in delivery speed (400-500m/min) represents the same trend in neps. A decreasing trend of neps is noticed with the increase in all three considered machine variables.

Further, the process parameters are optimised for the minimum value of neps using the equation given in Table 4. The combination of 1.165 mm spindle diameter, 0.475 MPa nozzle pressure and 406.08 m/min delivery speed has provided 24.48 neps.

It is observed that the increase of spindle diameter, nozzle pressure and yarn delivery speed together has shown an increase in thick places, decrease in neps, and decrease and increase in thin places. Thin, Thick and neps have increased when the spindle air pressure is applied on the surface of the yarn. When the spindle air pressure is applied in the same

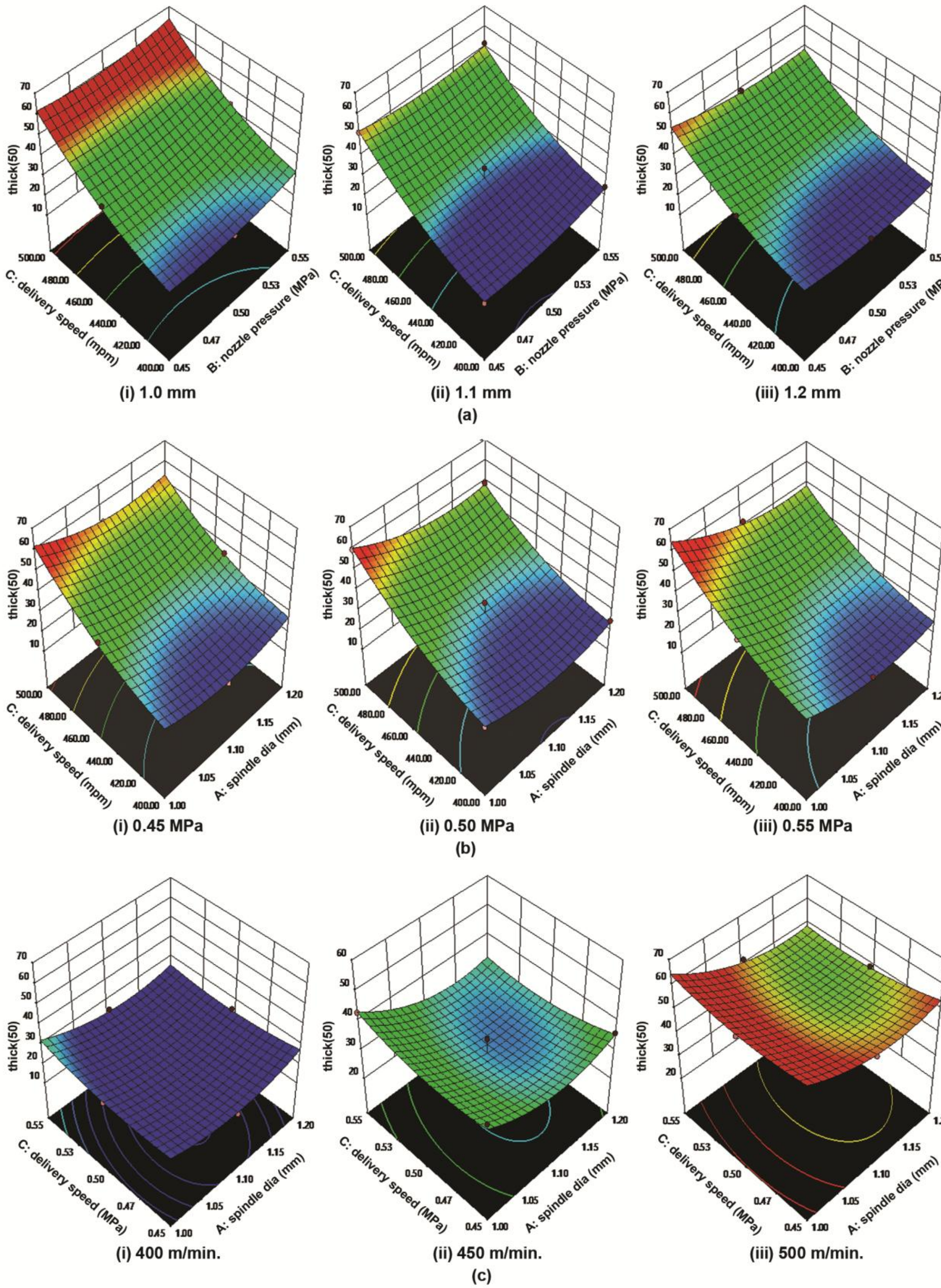

Fig. 4 — Yarn thick place (+50%) at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

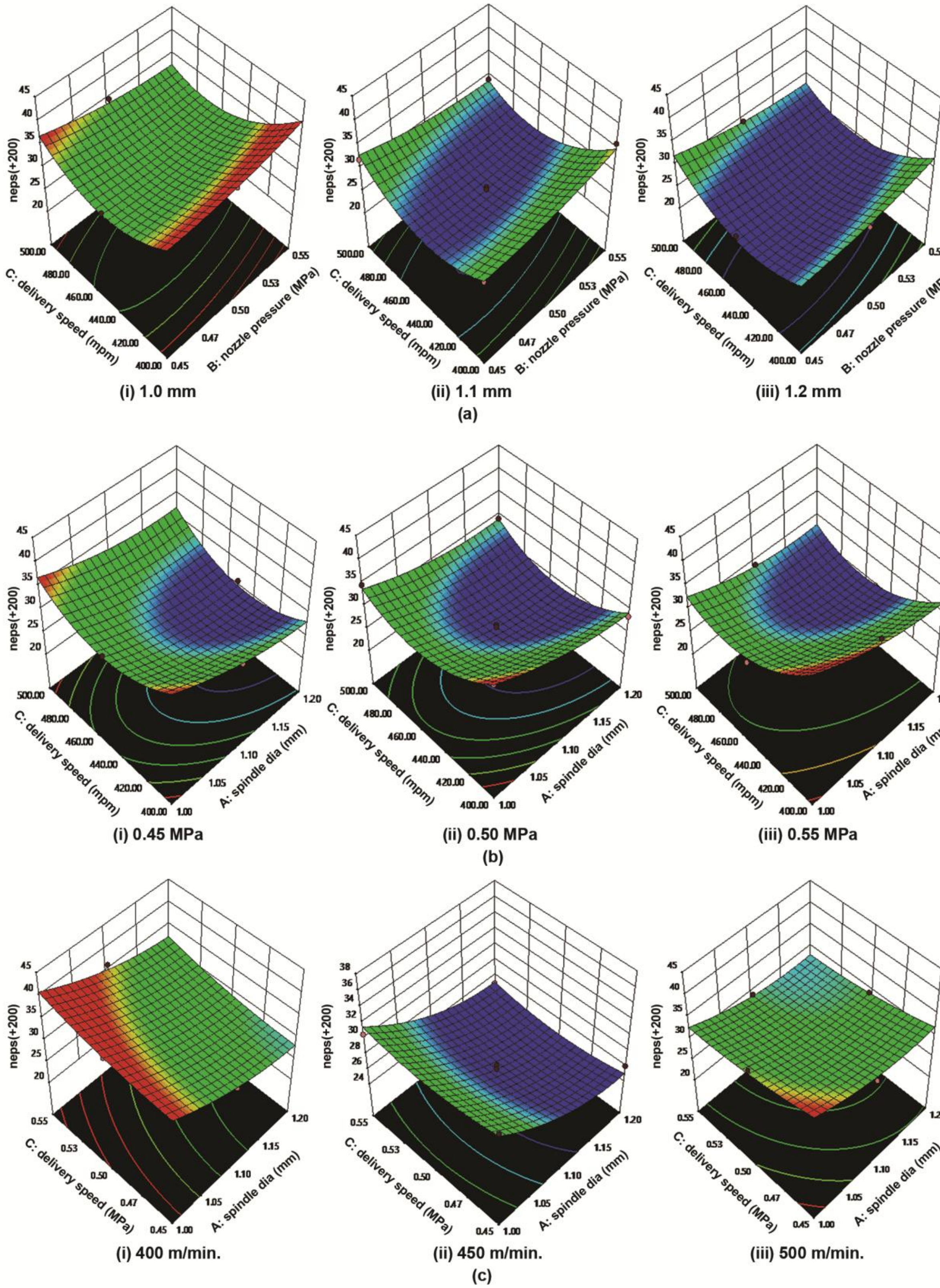

Fig. 5 — Yarn neps (+200%) at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

direction (z-direction) of basic yarn twist, it further supports the twisting action of the wrapper fibres at the yarn formation zone. Due to additional air pressure, the uneven vortex yarn has more wild fibres and causes higher imperfections. In the case of spindle air pressure with the opposite direction of basic yarn twist, it disturbs the wrapper fibres as the fibres enter the tip of the spindle and cause higher imperfections.

3.6 Yarn Unevenness

The variance analysis of yarn unevenness shows the insignificant quadratic model. The response surface equation for yarn evenness in terms of coded factors and significant model terms is represented in Table 4.

Figure 6 (a) shows the 3D surface plot of delivery speed and nozzle pressure at three different spindle diameters. The increase in delivery speed and nozzle pressure at respective spindle diameter depicts an increase of yarn U%. The increase in both delivery speed and nozzle pressure represents a decrease and then increase of yarn U% at different spindle diameters, but a continuous increase in spindle diameter follows a similar trend of U%. The simultaneous increase in all three variables depicts a decrease and then increases of U%. But all the changes in the values of U% are found to be very marginal.

Figure 6 (b) provides the 3D surface plots of delivery speed *vs*. spindle diameter at three different nozzle pressures. The value of U% follows an initial decrease and then increase with the increase of delivery speed and spindle diameter at respective nozzle pressure. The increase in both delivery speed and spindle diameter at respective nozzle pressure observes an initial decrease and then increase of U%, but the continuous increase of nozzle pressure (0.45-0.55 MPa) also shows a similar trend in Uster %. The increase in spindle diameter, nozzle pressure and delivery speed depicts an initial decrease and then an increase of U%.

Figure 6 (c) shows a decrease and then increase in the value of yarn U% with the increase in nozzle pressure at respective delivery speeds. But at 400 m/min delivery speed, U% notices a reduction and at 450 m/min and 500 m/min delivery speeds, U% has followed an increase with the increase in spindle diameter. The increase in both spindle diameter and nozzle pressure provides an initial decrease and then increase of U% at different delivery speeds but U% follows a similar trend with the continuous increase in delivery speed. The increase in spindle diameter, nozzle pressure and delivery speed infers an initial decrease and then an increase in the value of U%.

The equation given in Table 4 has provided a 10.454 minimum value of U% at 10.45 mm spindle diameter, 0.485 Mpa nozzle pressure and 419.49 m/min delivery speed.

The increase in spindle diameter, nozzle pressure and delivery speed has depicted an initial decrease and then an increase of U%. Higher spindle diameter results in a significant increase in yarn unevenness because fibres have more freedom to orient themselves with a large spindle diameter. An increase in nozzle pressure increases radial velocity, which enhances the spreading effect on the fibre bundle, thereby generating more wrapper fibres in the yarn. But the tangential velocity which is perpendicular to the fibre axis and generates the cross-flow part acts on the wrappers fibres. Increasing the tangential velocity benefits the twisting of open trail end fibres and, while decreasing it, results in weakening the twisting effect of open trail end fibres. At too high nozzle pressure, the separated fibres are sucked out from the fibre bundle by the high speed air flow, thereby producing more wild and waste fibres which deteriorate the yarn uniformity. The increase in nozzle pressure in opposite direction of basic yarn twist reduces the axial air velocity, thereby increases yarn unevenness.

3.7 Yarn Hairiness index

The variance analysis of the yarn hairiness (H) index is shown in Fig. 7 (a), and the 2FI model is found significant. The response surface equation for yarn hairiness in terms of coded factors and significant model terms are represented in the equation given in Table 4.

The 3D surface plots of yarn hairiness, given in Figure 7 (a), depicts an increasing trend with the increase in delivery speed but its value observes a reduction with the increase in nozzle pressure at respective spindle diameters. The increase in both nozzle pressure and delivery speed notices an increase in yarn hairiness at respective spindle diameters, but the yarn hairiness follows a similar trend with the increase in spindle diameter. The yarn hairiness observes an increasing trend with the simultaneous increase of all three considered variables.

It is observed from Fig.7 (b) that the value of yarn hairiness shows an increase with the increase in delivery speed and spindle diameter at respective

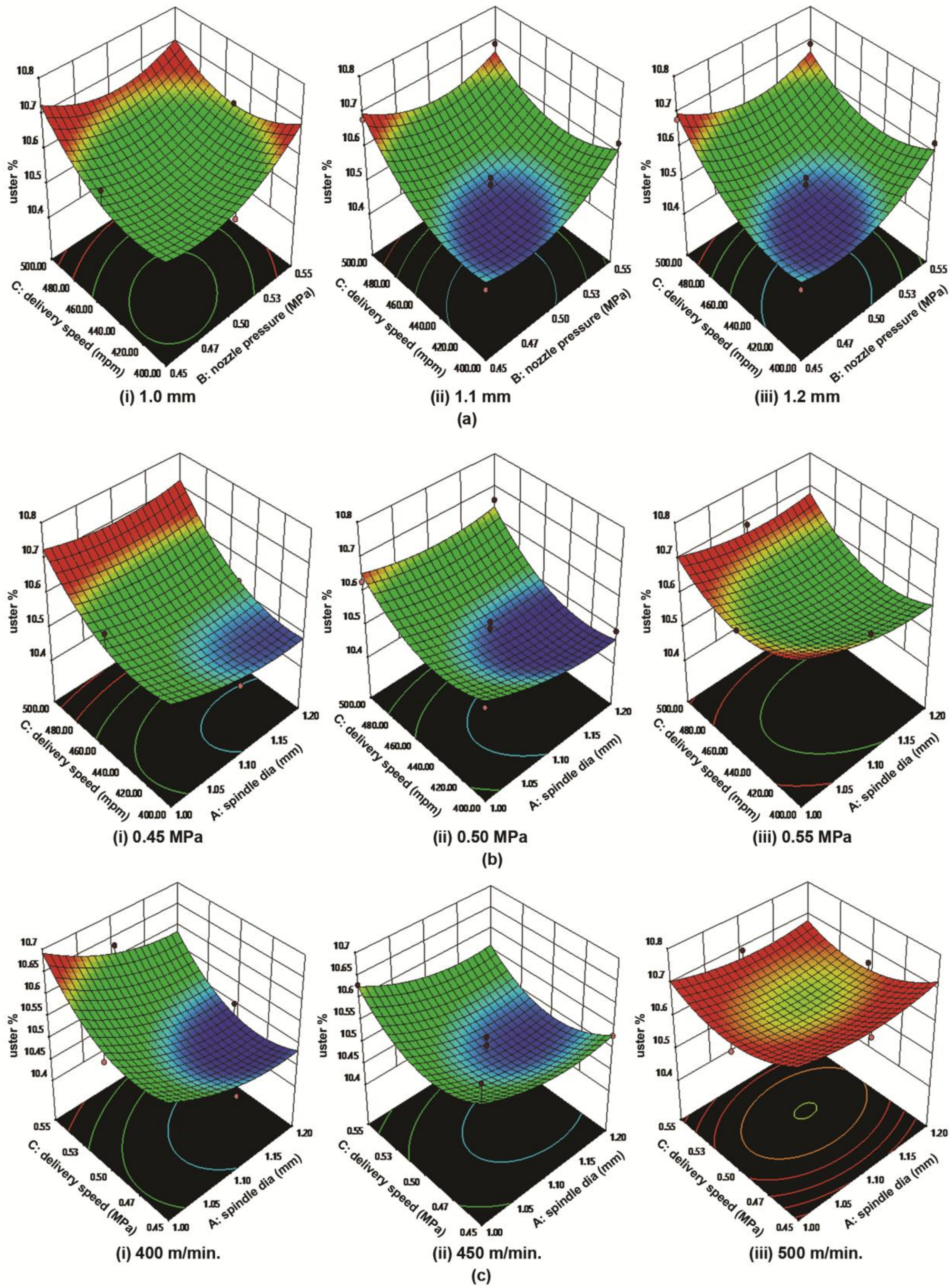

Fig. 6 — Yarn uster % at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

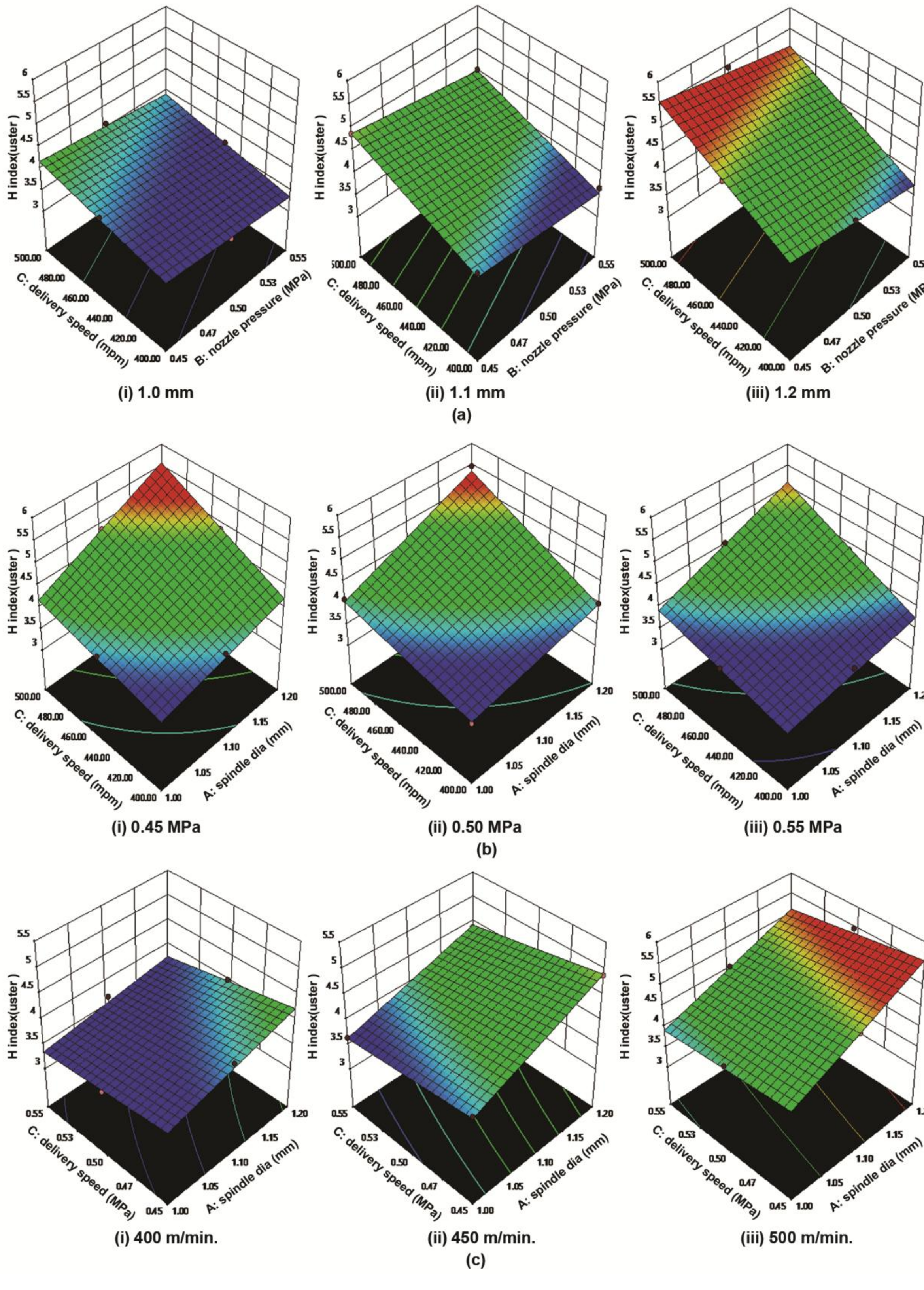

Fig. 7 — Yarn Hairiness index at constant (a) spindle diameter, (b) nozzle pressure and (c) delivery speed

nozzle pressure. The increase in both delivery speed and spindle diameter at different nozzle pressures provides an increasing trend of yarn hairiness, but with a reduction in hairiness value while nozzle pressure is increased. The value of the yarn hairiness shows an increase with the increase in spindle diameter, nozzle pressure and delivery speed.

Figure 7 (c) illustrates the 3D surface plots nozzle pressure and spindle diameter at three different delivery speeds. The value of the yarn hairiness notices a decreasing trend with the increase in nozzle pressure, but it increases with the increase of spindle diameter at respective delivery speeds. The increase in both nozzle pressure and spindle diameter increases the yarn hairiness at respective delivery speeds, but the increase in delivery speed notices an increase in the value of yarn hairiness. An increasing trend in the value of the yarn hairiness is noticed with the increase in all three considered machine variables.

Further, the process parameters of the card are optimised for the minimum value of the yarn hairiness using the equation given in Table 4. The combination of 1.03 mm spindle diameter, 0.55 MPa nozzle pressure and 400.48 m/min delivery speed has provided a 3.41 value of the yarn hairiness.

The results of yarn hairiness have revealed a reduction with the increase in nozzle pressure but an increase with the increase in spindle diameter and yarn delivery speed. The increase of twist with the increase in nozzle pressure integrates fibres more tightly into the yarn structure. Accordingly, higher nozzle pressure depicts low hairiness values. Spindle diameter also determines the tightness of the wrappings. A small spindle diameter allows less freedom for the fibre bundle to expand as it enters the spindle. This produces higher friction between fibres and leads to higher twists, tighter wrappings, and in turn, less yarn hairiness. The results indicate that a small spindle diameter results in low hairiness. At lower delivery speed, the fibres get more residence time inside the spindle for twisting into yarn. Therefore, wrapping fibres are tightly twisted on the yarn core at the lowest delivery speed as compared to that at higher delivery speed. Also, fibres in the yarn core are more compressed due to the lowest spindle diameter.

3.8 Optimization of Machine Parameters

The spindle diameter, nozzle pressure and yarn delivery speed parameters of yarn have been optimized by using Box-Behnken design for achieving the required yarn characteristics. While setting the required goals for yarn properties, yarn tenacity and elongation% are maximised while other properties, like U%, thin places, thick places, neps, and hairiness index are minimised to achieve the overall required quality of the yarn. The optimised spindle diameter, nozzle pressure and yarn delivery speed and achieved yarn properties are shown in Table 5.

Table 5 — Optimized machine parameters of yarn properties [Optimized parameters: Spindle diameter 1.10mm, nozzle pressure 0.50MPa, and delivery speed 432.38m/min]

Yarn properties	Values
Thin places (-50%)	5.98
Thick places (+50%)	24.63
Neps (+200%)	26.75
H index	4.0552
Yarn tenacity	19.92 cN/tex
Elongation	8.13 %
Uster	10.47 %
Desirability	0.71

4 Conclusion

The response surface equations for respective yarn properties in terms of coded factors and significant model terms have been developed. A very strong correlation is observed between respective yarn property and spindle diameter, nozzle pressure and yarn delivery speed. The obtained response surface equations are being used for the industrial purpose to optimize the machine variables for achieving a required value for specific yarn property. Yarn tenacity and elongation% show an increase with the increase in nozzle pressure but notice a decrease with an increase in delivery speed and spindle diameter. Yarn thin places, thick places, neps, U% and hairiness index depict an increase with the increase in delivery speed and spindle diameter, while the decrease is observed with an increase in nozzle pressure. The machine parameter is optimized for targeted yarn quality. A combination of 1.1mm spindle diameter, 0.5 MPa nozzle pressure and 432.38 m/min delivery speed achieves the targeted yarn quality at a 0.71 desirability value. Hence, it is justified to conclude that structural changes in the yarn, influenced by process parameters are the major causes for effective changes in yarn properties.

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