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Optimisation of Multi-Response Surface Parameters of the Roving Twist Factor and Spinning Back Zone Draft

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Abstract
In order to obtain the optimal collocation of two important technological parameters in the spinning process, the multi-response surface method was used to optimise the experimental results. Through the orthogonal design of the two factors and four levels of factor encoding, 16 groups of orthogonal experiments were designed; the experimental results were fit using the curve fitting toolbox of Matlab; a regression equation of yarn quality indicators, and in addition to a three-dimensional surface chart, an optimal scheme of the roving twist factor and spinning drafting for a roving twist factor of 110 were established; a spinning back draft of 1.5 was obtained based on experimental results of the response surface analysis and variance regression analysis. Experiments on the optimal scheme were carried out to verify the practicability of the results obtained by this method. The results show that application of the multiple response surface method to the optimisation of process parameters is of practical significance. This method can be applied for the optimisation of other process parameters.

Key words: *twist factor, back zone draft, multi-response surface, orthogonal experiment, 3D surface graph.*

Introduction

The roving twist factor and spinning back zone draft are two process parameters which influence yarn quality in the yarn spinning process. To get better yarn quality, these two factors should be closely combined. However, there is the issue of finding the optimal process between them [1, 2]. With research of the optimal allocation of roving parameters deepening, Zhou [3] applied the orthogonal test to the optimisation of wool roving process parameters, and finally fine purified yarns were spun. Similarly, this method was also utilised by He and Wei [4] to optimise the roving process parameters of a high speed roving machine. Shi [5] optimised these two process parameters by the fuzzy decision making method. In addition, a large number of research achievements have taken place in the application of a neural network in the quality prediction of worsted yarn. Dong [6] used a neural network model to establish a virtual yarn processing system, and then the principal component analysis method to pre-process the input's initial data. Afterwards, through the direct prediction and iterative prediction retrieved characteristic value of the woollen silver and fibre using the neural network model, the quality of yarn was determined. Yin [7] set up a neural network model to improve yarn quality and determine the technological parameters of each process in worsted spinning, so that it is beneficial for spinning mills to control yarn quality according to specific varieties. Furthermore Cheng [8] predicted the physical properties of splicing yarn using a neural network and regression analysis method. The response surface method, a multilayer perceptron neural network and the generalised regression neural network method were applied by Lewandowski [9] to predict the joint geometry size and yarn tenacity of spliced yarn, and their advantages, disadvantages and applicability were analysed.

Many studies on cotton spinning process optimisation also utilised different statistical methods. Karthik and Murugan adopted the Box and Behnken design to study the influence of spinning parameters on the yarn properties in ring spinning [10] and rotor spinning [11]. Cotton/milkweed (60/40) blended yarn of 29.5 tex was produced on a ring spinning system and rotor spinning system. Senthilkumar and Kuthalam designed an experiment with the aid of the response surface method and considered the influence of spinning parameters (delivery speed, spindle size, feed ratio and nozzle pressure) on the tensile properties [12] and hairiness properties [13] of polyester/cotton vortex yarn. Furthermore, Feng et al. [14] systematically investigated the system parameters of fine cotton yarns in a modified spinning system and optimised it by combining fractional factorial and response surface statistical methods. The results showed that the speed ratio and traveller weight had larger influences on yarn evenness and tenacity, while yarn snarling and hairiness were more influenced by the twist multiplier.

In this study, an optimisation model based on empirical regression models is developed to determine the best processing conditions for the roving twist factor and spinning back zone draft with yarn breaking tenacity, yarn elongation at break, yarn unevenness, yarn imperfections and yarn hairiness being the multiple responses. Regression analysis is used to build response surface models for yarn breaking tenacity, yarn elongation at break, yarn unevenness, yarn imperfections and yarn hairiness as a function of the process variables under consideration. The optimisation approach used in this study was successfully employed by Erol and Sagbas in multiple-response optimisation of ring spun yarn for hairiness, tenacity and cost [15], and applied by Arain etc. in multiple-response optimisation of rotor yarn for tenacity, unevenness, hairiness and imperfections [16].

Materials and methods

Rational allocation of the roving twist factor and spinning back zone draft has a significant impact on yarn quality, but the selected drafting system, cots and aprons, cradle system, environmental temperature and humidity etc., also have a great impact on test data. Thus, on the condition of fixing the above factors' value, the roving twist factor and spinning back zone draft were selected for testing, and the influence of these two factors on yarn quality was studied. Cotton yarns of 21 tex were spun on a ring spinning machine, cotton fibre properties of which

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are shown in ***Table 1***. Denoting the roving twist factor and spinning back zone draft as A and B, 4 levels were selected for each factor, shown in ***Table 2***, and then a 2 factor and 4 level orthogonal test was carried out, the test plan for which is shown in ***Table 3***. The test conditions are coded in the test scheme, as shown in ***Table 4***.

Yarn quality indicators were selected, such as yarn breaking tenacity, elongation at break, unevenness CV, thinness (-50%), thickness (+50%), nep (+200%) and hairiness index, and its CV was comprehensively considered.

Taking 20.21 g/5 m carded sliver, roving spinning test sets for four roving twist factors, respectively, were carried out on a DSRO-11 type digital roving frame (Jiacheng Electromechanical Equipment co. LTD, Tianjin, China) roving process parameters of which are shown in ***Table 5***. In each group of roving twist coefficient tests, 6 rovings were taken to test the average value, respectively. The roving density was controlled at 500 tex.

6 rovings were spun into yarns on a spinning frame type DSSp01 (Jiacheng Electromechanical Equipment co. LTD, Tianjin, China) at the same time, process parameters of which are shown in ***Table 6***. Each group of roving was spun into two yarns, and the average value of 12 spun yarns was measured, on Electronic Single Yarn Strength Machine type YG(B)021DJ produced by Wenzhou Darong Textile Instruments co. LTD (China), Evenness Tester type YG136 produced by Shaanxi Changling Textile Electromechanical Technology co. LTD (China).

Results and analysis

Results of the yarn quality test data for each scheme are shown in ***Table 7***.

Each index analysis

In accordance with the test data, we obtain a regression equation of yarn breaking tenacity, elongation at break, unevenness CV, thinness, thickness, neps, hairiness index and hairiness index CV. In the following equations, y is the value of each index, x_1 the roving twist factor (A), and x_2 is the spinning back zone draft (B) of the yarn.

Breaking tenacity: $y = -64.92 + 1.57x_1 – 11.39x_2 + 3.89 \times 10^{-2}x_1x_2 – 7.54 \times 10^{-3}x_1^2 + 1.69x_2^2$

Table 1. *Cotton fibre properties.*

Items	Average length, mm	Fineness, dtex	Breaking tenacity, $cN·tex^{-1}$	Elongation at break, %	Moisture regain, %
Cotton fibre	31.4	1.6	3.1	9.2	6.7

Table 2. *Factors and levels.*

Serial number	Roving twist factor A	Spinning back zone draft B
1	105	2.5
2	110	2.2
3	115	1.8
4	120	1.5

Table 3. *Experiment scheme.*

Test number	Roving twist factor A	Spinning back zone draft B	Test number	Roving twist factor A	Spinning back zone draft B
1	105	2.5	9	115	2.5
2	105	2.2	10	115	2.2
3	105	1.8	11	115	1.8
4	105	1.5	12	115	1.5
5	110	2.5	13	120	2.5
6	110	2.2	14	120	2.2
7	110	1.8	15	120	1.8
8	110	1.5	16	120	1.5

Table 4. *Experiment condition code.*

Test number	Roving twist factor A	Spinning back zone draft B	Test number	Roving twist factor A	Spinning back zone draft B
1	-1.5	1.5	9	0.5	1.5
2	-1.5	0.5	10	0.5	0.5
3	-1.5	-0.5	11	0.5	-0.5
4	-1.5	-1.5	12	0.5	-1.5
5	-0.5	1.5	13	1.5	1.5
6	-0.5	0.5	14	1.5	0.5
7	-0.5	-0.5	15	1.5	-0.5
8	-0.5	-1.5	16	1.5	-1.5

Table 5. *Main processing parameters of roving frame.*

Spindle speed/rpm			500	
Output speed/($m·min^{-1}$)		9.02		
Roving density/($g·10m^{-1}$)	4.92	4.89	5.10	5.07
Twist factor	105	110	115	120
Draft	main zone		5.64	
	back zone		1.20	
Gauge/mm	front roller and middle roller		24.5	
	middle roller and front roller		35	

Table 6. *Main processing parameters of spinning frame.*

Yarn density/tex	21.0			
Speed	Spindle speed/($r·min^{-1}$)		8000	
	Output speed/($m·min^{-1}$)		9.65	
Gauge/mm	Front roller and middle roller		18	
	Middle roller and front roller		30	
Twist factor	380			
Twist/(numbers·10 cm^{-1})	83.0			
Back zone draft	2.5	2.2	1.8	1.5

Table 7. *Spinning yarn quality test data.*

Test number	Roving twist factor (x_1)	Spinning back zone draft (x_2)	Breaking strength, cN·tex^{-1}	Elongation at break, %	Unevenness CV, %	Thin-50%, number·km^{-1}	Thick+50%, number·km^{-1}	Neps+200%, number·km^{-1}	Hairiness index, %	Hairiness index CV, %
1	-1.5	1.5	8.8	4.33	22.52	41.0	93.0	190.0	7.20	34.00
2	-1.5	0.5	8.7	4.47	22.57	39.0	110.0	271.5	6.50	38.84
3	-1.5	-0.5	8.9	4.46	19.55	19.5	72.5	155.0	6.75	45.55
4	-1.5	-1.5	8.9	4.24	18.22	13.0	55.5	160.0	6.40	43.09
5	-0.5	1.5	9.0	4.56	23.04	45.0	94.0	219.5	7.30	31.10
6	-0.5	0.5	8.3	4.59	20.54	29.0	77.5	155.0	7.45	29.39
7	-0.5	-0.5	8.8	4.53	18.69	13.5	69.0	140.0	7.00	43.49
8	-0.5	-1.5	9.7	4.52	17.63	10.5	52.5	145.0	5.60	42.18
9	0.5	1.5	8.9	4.85	22.58	55.0	93.0	252.5	6.10	35.54
10	0.5	0.5	8.6	4.64	20.98	39.0	80.5	245.0	6.05	27.40
11	0.5	-0.5	7.6	4.27	19.79	22.5	74.5	238.5	4.95	58.03
12	0.5	-1.5	9.0	4.41	20.49	26.0	55.0	250.5	6.00	36.84
13	1.5	1.5	8.2	4.85	23.45	57.0	121.0	218.5	5.80	53.95
14	1.5	0.5	8.1	4.64	21.22	40.0	86.0	255.5	6.30	43.23
15	1.5	-0.5	7.9	3.75	19.68	28.5	80.5	239.0	6.25	66.86
16	1.5	-1.5	8.2	3.54	18.46	19.0	87.0	163.0	6.15	75.32

Table 7.a. *Variance analysis of breaking tenacity.*

Variance source	S	f	V	F	Significance
A	0.01715	3	5.7167×10^{-3}	3.99	*
B	0.01035	3	3.45×10^{-3}	2.41	non-significant
e	0.0129	9	1.4333×10^{-3}		
sum	0.0404	15			

Table 7.b. *Variance analysis of elongation at break.*

Variance source	S	f	V	F	Significance
A	0.3379	3	0.1126	1.23	non-significant
B	0.6631	3	0.2210	2.41	non-significant
e	0.8264	9	0.0918		
sum	1.8274	15			

$F_{0.01}(3,9) = 6.99$, $F_{0.05}(3,9) = 3.86$, $F_{0.1}(2,2) = 2.81$.

Table 8.a. *Variance analysis of yarn unevenness CV.*

Variance source	S	f	V	F	Significance
A	2.17	3	0.72	1.07	insignificant
B	43.17	3	14.39	21.29	**
e	6.08	9	0.66		
sum	51.42				

Table 8.b. *Variance analysis of yarn thin places.*

Variance source	S	f	V	F	Significance
A	392.55	3	130.85	9.24	**
B	2671.17	3	890.39	62.91	**
e	127.39	9	14.15		
sum	3191.11				

Table 8.c. *Variance analysis of yarn thick places.*

Variance source	S	f	V	F	Significance
A	998.42	3	332.81	2.71	insignificant
B	3263.42	3	1087.81	8.86	**
e	1105.02	9	122.78		
sum	5366.86				

Table 8.d. *Variance analysis of yarn neps.*

Variance source	S	f	V	F	Significance
A	14606.30	3	4868.77	4.03	*
B	6895.55	3	2298.52	1.90	non-significant
e	10885.52	9	1209.50		
sum	32387.36				

Elongation at break: $y = -37.48 + 0.92x_1 - 9.78x_2 + 9.27 \times 10^{-2}x_1x_2 - 4.98 \times 10^{-3}x_1^2 - 3.21 \times 10^{-2}x_2^2$

Unevenness CV: $y = 412.50 - 8.52x_1 + 84.64x_2 - 0.98x_1x_2 + 4.60 \times 10^{-2}x_1^2 + 5.83x_2^2$

Thin-50%: $y = -6.38 \times 10^5 + 11215.87x_1 + 10962.51x_2 - 546.06x_1x_2 - 44.8x_1^2 + 11524.33x_2^2$

Thick+50%: $y = 72276.33 - 1394.43x_1 + 7870.39x_2 - 20.15x_1x_2 + 6.26x_1^2 - 1248.28x_2^2$

Nep+200%: $y = 1677.15 - 244.34x_1 + 15436.91x_2 - 124.67x_1x_2 + 2.03x_1^2 - 430.44x_2^2$

Hairiness index: $y = 15.10 - 0.32x_1 + 11.76x_2 - 7.88 \times 10^{-2}x_1x_2 + 1.87 \times 10^{-3}x_1^2 - 0.58x_2^2$

Hairiness index CV: $y = 2783.00 - 51.32x_1 + 85.39x_2 - 0.93x_1x_2 + 0.24x_1^2 + 0.84x_2^2$

The above regression equation is illustrated by Matlab software in ***Figure 1-3***.

In ***Figure 1.a***, the influence of x_1 on the breaking tenacity first increased and then decreased, and x_2 on the breaking tenacity first decreased and then increased. When x_1 is 108 and x_2 1.5, the maximum value of breaking tenacity increases to 9.805. In ***Figure 1.b***, the effect of x_1 and x_2 on the elongation at break first increased and then decreased. When x_1 is 116 and x_2 2.5, the maximum value of elongation at break is attained – 4.916.

Variance analysis of the test data was recorded in ***Table 7.a*** and ***Table 7.b***, respectively. (***Note:*** in the following analysis of ***Table 7***, ***Table 8***, and ***Table 9***, S is the sum of deviations in the square, f the freedom, V the mean square, and

F is the significant test index, where "*" means significant and "**" means very significant).

Table 7.a presents the primary and secondary order of factors: A > B; Optimal scheme: A_2B_4. ***Table 7.b*** shows the primary and secondary order of factors: B > A; Optimal scheme: A_2B_1.

It can be seen from ***Table 7*** that only the influence of the factor A (roving twist coefficient) on yarn breaking tenacity and elongation is significant, and that of factor B on the tensile properties of the yarn is not obvious.

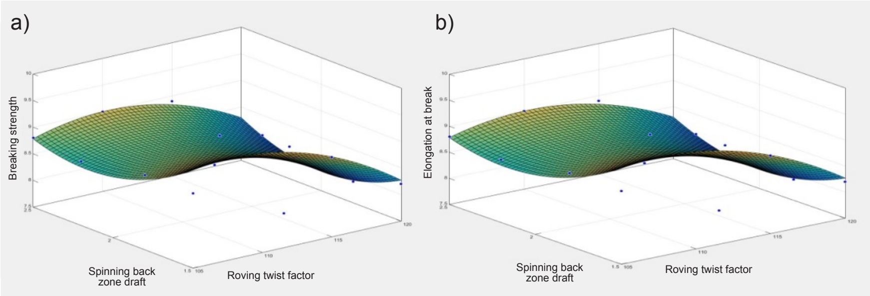

Figure 1. *Three-dimentional curve of yarn tensile property: a) breaking tenacity regression equation, b) elongation at break regression equation.*

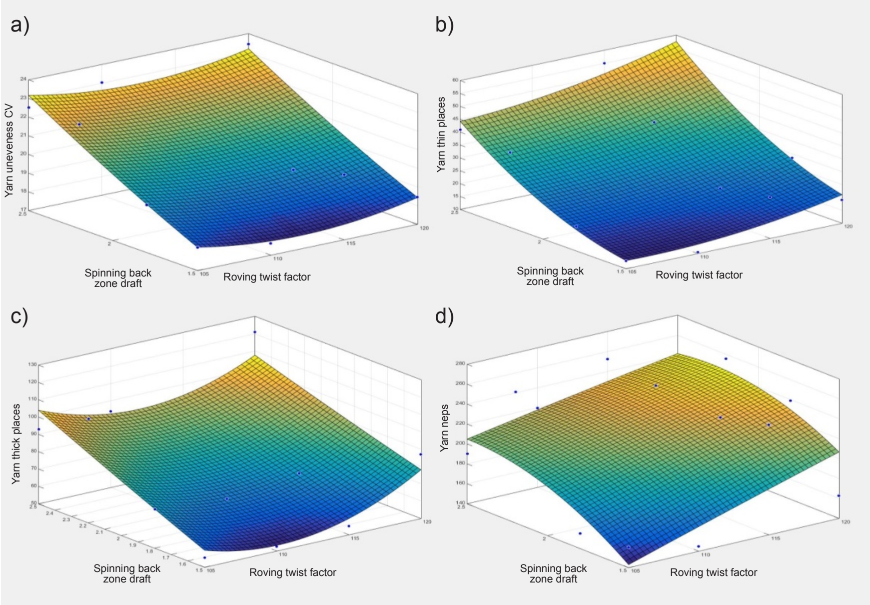

Figure 2. *Three-dimentional curve of yarn unevenness: a) yarn unevenness CV regression equation, b) yarn thin places regression equation, c) yarn thick places regression equation, d) yarn neps regression equation.*

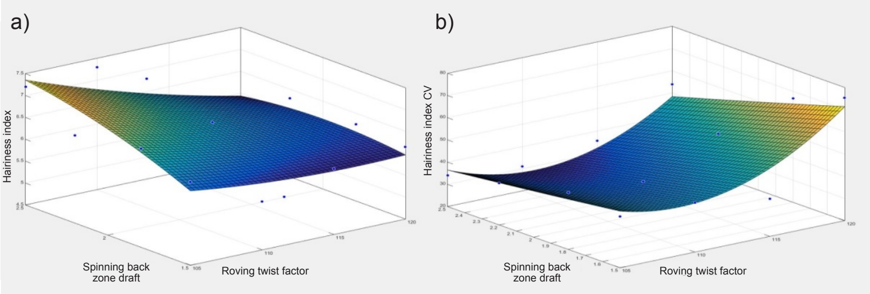

Figure 3. *Three-dimentional curve of yarn hairiness: a) hairiness index regression equation, b) hairiness index CV regression equation.*

In ***Figure 2.a***, the influence of x_1 (roving twist factor) on the unevenness is relatively flat, while that of x_2 (spinning back zone draft) on the unevenness is significant, proportional to the value of unevenness. When x_1 is 112 and x_2 1.5, the minimum value of unevenness CV is 17.339. In ***Figure 2.b***, both x_1 and x_2 have a significant impact on the numbers of thin sections and present a positive ratio. When x_1 is 107 x_2 1.5, the number of thin places reaches a minimum of 8.175. In ***Figure 2.c***, the influence of x_1 and x_2 on thick places is not as significant as on thin places. The influence of x_1 on thick sections first decreases and then increases. When x_1 is 110 and x_2 1.5, the minimum value of the thick places number is 49.07. In ***Figure 2.d***, the effects of x_1 and x_2 on the neps are both relatively gentle and present them in a positive ratio state. When x_1 is 105 and x_2 1.5, the minimum value of the neps number reaches 133.42.

Variance analysis of the test data is recorded in ***Table 8.a-8.d***, respectively.

Table 8.a presents the primary and secondary order of factors: B > A; Optimal scheme: A_2B_4.

Table 8.b shows the primary and secondary order of factors: B > A; Optimal scheme: A_2B_4. ***Table 8.c*** presents the primary and secondary order of factors: B > A; Optimal scheme: A_2B_4. ***Table 8.d*** shows the primary and secondary order of factors: A > B; Optimal scheme: A_2B_4.

From ***Table 8*** above, the maximum value of F occurs due to the effect of factor B on the yarn thin places. The number of thin places is a quality indicator that affects the quality of the yarn and is important for subsequent weaving. Secondly, the influence of factor B on yarn unevenness CV and thick sections is in turn, and next is the effect of factor A on thin sections. The impact of the rest is not significant.

In ***Figure 3.a***, the influence of x_1 and x_2 on the hairiness index is relatively flat. When x_1 is 120 and x_2 1.5, the value of the hairiness index reaches a minimum of 4.825. In ***Figure 3.b***, the influence of x_1 and x_2 on the hairiness index CV value is significantly more than for the hairiness index. The influence of x_1 on the hairiness index CV value first decreases and then increases, while x_2 shows a digressive state. When x_1 is 112 and x_2 2.2, the minimum value of the hairiness index CV is 25.004.

Variance analysis of the test data is recorded in ***Table 9.a*** and ***Table 9.b***, respectively.

Table 9.a. Variance analysis of hairiness index.

Variance source	S	f	V	F	Significance
A	2.9988	3	0.9996	3.33	(*)
B	0.8913	3	0.2971	0.99	insignificant
e	2.7025	9	0.3003		
sum	6.5925				

Table 9.b. Variance analysis of hairiness index CV.

Variance source	S	f	V	F	Significance
A	1361.6144	3	453.8715	9.82	**
B	933.8834	3	311.2945	6.74	*
e	416.1075	9	46.2342		
sum	2711.6053				

Table 10. Optimum scheme of yarn quality.

Yarn characteristics	Roving twist factor (x_1)	Significance	Spinning back zone draft (x_2)	Significance
Breaking tenacity, cN·tex^{-1}	110	*	1.5	insignificant
Elongation at break, %	110	insignificant	2.5	insignificant
Unevenness CV, %	110	insignificant	1.5	**
Thin, number·km^{-1}	110	**	1.5	**
Thick, number·km^{-1}	110	insignificant	1.5	**
Nep, number·km^{-1}	110	*	1.5	insignificant
Hairiness index, %	115	(*)	1.5	insignificant
Hairiness index CV, %	110	**	2.2	*

Table 9.a presents the primary and secondary order of factors: A > B; Optimal scheme: A_3B_4. ***Table 9.b*** shows the primary and secondary order of factors: A > B; Optimal scheme: A_2B_2.

It can be seen from ***Table 9*** that the influence of factor A on the CV value of the hairiness index is very significant, and that on the hairiness index is even more significant. The effect of factor B on the CV value of the hairiness index is significant, while that on the hairiness index is not significant.

Considering the yarn's breaking tenacity, elongation at break, hairiness index and unevenness CV, the optimal index and significance of coordination between the roving twist coefficient and spinning back area draft are shown in ***Table 10***.

From the statistical results in ***Table 10***, combined with the significance analysis of the optimal scheme, excluding the impact of insignificant quality indices such as the elongation at break, unevenness CV and thick sections, and considering very significant quality indices such as thin sections, hairiness index, breaking tenacity and nep sections, the roving twist factor and spinning back draft should be selected as 110 and 1.5.

Verification test

The optimised scheme was used to spin the yarn and verify the yarn quality index. The test results are shown in ***Table 11***.

According to the data from ***Table 11***, the yarn quality based optimal scheme is at a high level compared with other test schemes. The hairiness index CV is higher, due to the spinning variety and conditions.

Conclusions

It is very crucial that the roving twist factor and spinning back zone draft are reasonably allocated in the spinning process. This paper adopted the multi-parameter optimisation method of response surface, through calculating two linear regression equations, using the polynomial function of Matlab software, to establish an optimisation model of response surface regression. Through drawing a three dimensional curve and analysing the variances of each yarn index, we got the best configuration scheme of the roving twist factor and spinning back area draft, which is 110 and 1.5, respectively. Based on the results above, when the spinning back zone draft ratio is small, the configuration of the roving twist factor should be moderate, which can improve yarn tightness and enhance the drafting force, thereby improving the yarn breaking tenacity and elongation. When the draft in the spinning back area is too small, it will affect the drafting force, and opposite results will be attained. For the hairiness index, thick places, neps and the unevenness CV, a smaller spinning back zone draft should be appropriate for a larger roving twist factor, thereby reducing the yarn end-breaking rate and improving yarn unevenness. But when the drafting ratio and roving twist factor are large, it is easy to make the yarn twist move to the finer section, so that the yarn twists near the middle nip are increased and the yarn twists near the rear nip are reduced. Because it can cause twist redistribution, we should try to avoid a larger spinning back zone draft. The multi-response surface method is used to optimise the process parameters accurately and intuitively, and it can also be used for the optimisation of other process parameters.

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Table 11. Performance data of optimum scheme.

Yarn characteristics	Breaking tenacity, cN·tex^{-1}	Breaking tenacity CV, %	Elongation at break, %	Elongation at break CV, %	Unevenness CV, %	Thin-50% number·km^{-1}	Thick+50%, number·km^{-1}	Nep+200%, number·km^{-1}	Hairiness index, %	Hairiness index CV, %
Data	9.2	9.8	4.9	9.8	20.0	23.0	54.5	191.0	5.60	31.7

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