OPTIMIZATION OF OPERATIONAL PARAMETERS OF FOAM SIZING PROCESS FOR COTTON YARNS BASED ON PLACKETT-BURMAN EXPERIMENT DESIGN

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Abstract:

This study was aimed at investigating the process optimization of foam sizing for cotton yarns. In this work, effects of major foam-sizing process factors including size concentration, blowing ratio, stirring speed, pre-wetting temperature, pre-drying temperature, squeezing pressure and drying temperature were studied on the hairiness (more than 3 mm) and abrasion resistance of foam-sized yarns. The combination of Plackett-Burman, steepest ascent path analysis and Box-Behnken design were adopted to optimize the foam-sizing process of cotton yarns. Results revealed that size concentration, blowing ratio and squeezing pressure were significant factors that affected the hairiness and abrasion resistance. Optimum hairiness and abrasion resistance were obtained when the cotton yarns were sized at size concentration of 19.33%, blowing ratio of 4.27 and squeezing pressure of 0.78kN. The theoretical values and the observed values were in reasonably good agreement and the deviation was less than 1%. Verification and repeated trial results showed that it has good reproducibility and imparts the foam sizing process of cotton yarns.

Keywords:

Foam sizing, cotton yarns, Plackett-Burman design, Box-Behnken design, process optimization

1 Introduction

In recent decades, foam technology such as foam dyeing [1-4] and foam finishing [5-8] rapidly developed in the textile industry. Meanwhile, foam sizing has been studied for 30 years. In 1980, Warren and Robert proved that the properties of warps sized using foam were equivalent or superior to those of similar warps sized conventionally [9, 10]. Namboodri indicated that foam sizing of cotton yarns realized energy savings and increased production speed, and less bridging of warps and reduced warp hairiness were the anticipated benefits [11]. Trauer and Vialon not only discussed the differences between foam sizing and conventional technology, but also studied the influences of size concentration on the quality of warp sizing [12, 13]. Vernekar showed that the energy consumption using foam sizing was almost half that of conventional sizing approach, while the sizing qualities of the two methods had no appreciable difference. [14]. Shah and Gandhi compared the differences of energy consumption between the devices of foam and conventional sizing, and illustrated that the foam-sizing technology needed more fundamental research in the realization of industrialization promotion [15]. Berk pointed out that the technology of foam sizing made the size film on the yarn surface more uniform and the hairiness lower [16]. In 1988, Xiong Yan studied the foaming performances of sizing materials and analyzed the main factors influencing the foamability of size liquor [17]. In 1999, Zhou Xiaohong found that the adhesive, foaming agent and the adhesive concentration played an important role in the foam-sizing technology [18]. In 2014, Weidong Gao [19, 20] in Jiangnan University developed foam sizing into industrial application and studied the sizing effects of foam-sizing and warp pre-wetting combined process.

This paper investigated the impacts of size concentration, blowing ratio, stirring speed, pre-wetting temperature, pre-drying temperature, squeezing pressure, drying temperature on hairiness and abrasion resistance of sized yarns as the response values. Firstly, Plackett-Burman design was used to select significant factors in foam-sizing process. Then, steepest ascent experiment and Box-Behnken design response surface method were adopted to evaluate the optimal range and to determine the optimum levels.

2 Experimental details

2.1 Materials

Oxidized starch and polyacrylic acid (XP-C) were supplied by Fengyang Co. Ltd (China); lauryl sodium sulfate was purchased from Sinopharm Chemical Reagent Co. Ltd. Cotton 19.4 tex single yarns were purchased from Yancheng Yueda cotton spinning Co. LTD.

2.2 Methods

2.2.1 Plackett-Burman design

Plackett-Burman design worked on time-saving and manpower-consumption to analyze the significant parameters with respect to their main effects and not the interaction effects between the various parameter constituents. The required numbers of this experimental design runs were very few, which led to saving of time, chemicals, glassware and manpower. In this paper, Plackett-Burman design was

applied for twelve trails in order to select the significance of seven factors grouped as process factors of foam sizing (size concentration X1, blowing ratio X2, stirring rate X3, pre-wetting temperature X4, pre-drying temperature X5, squeezing pressure X6, drying temperature X7, and X8, X9, X10 and X11 were dummy factors). Each factor was tested at two levels coded as (-1) for lower level and (+1) for higher level, as it is depicted in Table 1. The Design-Expert version 8.0.6 was used for experimental design analysis and data processing.

2.2.2 Steepest ascent experiment

The steepest ascent experiment was performed to approach the center points of each factor for further optimization study. The path of steepest ascent (descent) was the direction in which the response increased the most. The step-size was determined based on process knowledge and practical considerations. This method was used by modelling and analyzing the relationships between several independent variables and response variable(s). Effective response surface equations can be built when the response variables infinitely approach the optimum values.

Table 1 Factors and levels used in Plackett-Burman design

Codes	Factors	Levels	
		-1	+1
X1	Size concentration (%)	10	20
X2	Blowing ratio	5	10
X3	Stirring rate (r/min)	350	750
X4	Pre-wetting temperature (°C)	85	95
X5	Pre-drying temperature (°C)	60	80
X6	Squeezing Pressure (kN)	0.5	1.5
X7	Drying temperature (°C)	100	120
X8; X9; X10; X11	Dummy factors	-	-

Table 2 Design table (code) and response values of Plackett-Burman experiment

Run	X1	X2	X3	X4	X5	X6	X7	R1	R2
1	1	-1	-1	-1	1	1	-1	2.69	261.2
2	1	1	-1	1	1	-1	1	3.17	222.1
3	-1	1	1	1	-1	-1	-1	8.06	102.3
4	1	-1	1	1	1	-1	-1	1.65	297.6
5	-1	-1	-1	1	-1	1	1	7.36	116.8
6	-1	1	1	-1	1	1	1	9.14	93.6
7	1	-1	1	1	-1	1	1	2.78	256.2
8	-1	-1	1	-1	1	-1	1	6.36	147.4
9	1	1	-1	-1	-1	-1	1	3.28	219.3
10	-1	1	-1	1	1	1	-1	9.35	89.7
11	1	1	1	-1	-1	1	-1	3.92	192.5
12	-1	-1	-1	-1	-1	-1	-1	6.34	142.3

2.2.3 Box-Behnken Design

A statistical Box-Behnken design was used as a means of adequately optimizing significant factors. To systematically evaluate the main and interaction variables that affected foam sizing process of cotton yarns, Box-Behnken statistical design was selected for the optimization study and the Design Expert 8.0.6 software was used for experimental design analysis and data processing.

2.2.4 Statistic analysis

To verify the reliability of the results, the experiments were carried out in triplicate and averages and standard deviations were obtained.

3 Results and Discussion

3.1 Plackett-Burman analysis

Design table (code) and response values of Plackett-Burman experiment was presented in Table 2. Effects of factors on hairiness index (R1) and abrasion resistance (R2) are depicted in Table 3.

Factors evidencing P-values of less than 0.05 were considered to have significant effects on the response values and defined as a remarkable factor, and were therefore selected for further optimization studies. Stirring rate X3, pre-wetting temperature X4, pre-drying temperature X5 and drying temperature X7 had p-value more than 0.05 and were excluded from the following optimization due to significantly smaller contributions to the hairiness of sized yarns. The factors displaying significant positive effects on hairiness were size concentration ($p=0.0001$), blowing ratio ($p=0.0002$) and squeezing pressure ($p=0.0008$), and the corresponding confidence level respectively were 85.97, 9.62 and 4.13. Similarly, for the analysis of abrasion resistance, the significant factors to R2 were size concentration ($p=0.0001$), blowing ratio ($p=0.0011$) and squeezing pressure ($p=0.0281$), and the corresponding confidence level were 82.17, 12.87 and 3.97, respectively; the other factors had no significant effects on R2.

3.2 Steepest ascent analysis

The steepest ascent path was analyzed to find the appropriate direction of changing factors, increasing the levels of each factor response values. Design table of the steepest ascent experiment with hairiness and abrasion resistance are displayed in Table 4. According to the effect of the three factors – the direction of size concentration, blowing ratio and squeezing pressure – a set of experimental runs were designed. As shown in Table 4, the smallest value of hairiness appeared in the fourth step and the largest value was also located in step 4. Comprehensively, the optimum value areas of process parameters were 10-20% of size concentration, 4-8 of blowing ratio and 0.50-1.00kN squeezing pressure.

3.3 Box-Behnken Analysis

A sequence of Box-Behnken experiments were performed that would yield the most information about the factors and their interactions in as less experiments as possible (17 runs). A 3factor and 3 level factorial Box-Behnken experimental design technique was carried out around the optimum to locate true optimum levels of size concentration, blowing ratio and squeezing pressure. Factors and levels of BBD experiment were shown in Table 5 and Design table and results of BBD experiment were shown in Table 6.

An interactive second order polynomial model was utilized to evaluate both response factors. The polynomial equations generated by design expert is described as equation (1) and (2):

$$Y1 = 218.30 + 76.91X1 + 20.19X2 + 8.12X6 + 5.85X1X2 + 0.025X1X6 + 2.78X2X6 + 0.30(X1)^2 + 8.33(X6)^2 \quad (1)$$

$$Y2 = 3.28 - 2.36X1 + 0.22X2 + 0.51X6 - 0.24X1X2 - 0.15X1X6 + 0.34X2X6 + 0.33(X2)^2 - 0.0052(X6)^2 + 0.31(X1)^2X6 - 0.29X1(X2)^2 \quad (2)$$

The two equations represented the quantitative effect of factors (X1, X2, and X6) and their interactions on the response values. The values of X1, X2 and X6 were substituted in the equation to obtain the theoretical values of Y1, Y2. The model equations were tested for significance and their variance was analyzed. The p-value of both equations was less than 0.05, which indicated a significant effect of independent factors on the response values. Hence, it assured that the current model provided a satisfactory fit to the data.

Table 3 Effects of factors on hairiness and abrasion resistance

Factors	Hairiness			Abrasion resistance		
	P-value	Confidence (%)	Standard Error	P-value	Confidence (%)	Standard Error
X1	0.0001	85.97	0.059	0.0001	82.17	0.029
X2	0.0002	9.62	0.059	0.0011	12.87	0.029
X3	0.7109	0.07	0.059	0.3476	1.04	0.029
X4	0.4144	0.05	0.059	0.4734	0.43	0.029
X5	0.4279	0.04	0.059	0.0840	0.54	0.029
X6	0.0008	4.13	0.059	0.0281	3.97	0.029
X7	0.9149	0.06	0.059	0.4479	0.02	0.029

Table 4 Design table of steepest ascent experiment with hairiness and abrasion resistance

Number of steps	Size concentration (%)	Blowing ratio	Squeezing Pressure (kN)	Hairiness (pieces/m)	Abrasion resistance(times)
1	5	2	0.25	9.27	68.6
2	10	4	0.50	4.84	145.8
3	15	6	0.75	3.42	184.9
4	20	8	1.00	2.89	224.3
5	25	10	1.25	4.03	202.6

Table 5. Factors and levels of BBD experiment

Codes	Factors	Code level		
		-1.00	0.00	1.00
X1	Size concentration (%)	10	15	20
X2	Blowing ratio	4	6	8
X6	Squeezing pressure (kN)	0.50	0.75	1.00

Table 6. Design table and results of BBD experiment

Run	X1	X2	X6	Y1 Hairiness (pieces/m)	Y2 Abrasion resistance(times)
1	0.00	1.00	1.00	7.89	118.7
2	1.00	-1.00	0.00	4.67	168.3
3	0.00	0.00	0.00	3.28	218.3
4	0.00	-1.00	1.00	2.11	265.2
5	0.00	0.00	0.00	6.02	141.5
6	-1.00	0.00	-1.00	2.98	183.4
7	-1.00	1.00	0.00	3.28	218.3
8	-1.00	0.00	1.00	3.27	218.3
9	0.00	0.00	0.00	3.28	218.3
10	1.00	1.00	0.00	6.97	129.6
11	0.00	0.00	0.00	3.22	236.8
12	1.00	0.00	-1.00	3.28	218.3
13	0.00	0.00	0.00	1.60	290.9
14	-1.00	-1.00	0.00	1.94	279.1
15	1.00	0.00	1.00	6.35	139.9
16	0.00	1.00	-1.00	3.56	210.6
17	0.00	-1.00	-1.00	1.54	309.8

Additionally, a series of the three-dimensional (3D) frameworks for the optimization of parameters of foam sizing process for cotton yarns were further depicted to study the interaction and quadratic effects of the three factors on the response values. The 3D response surface illustrations for hairiness and abrasion resistant are presented in Figure 1 and 2, respectively.

In Figure 1(a), (b) and (c), size concentration, blowing ratio and squeezing pressure had significant correlations. When size concentration (X1) was increased from 10 to 20%, the hairiness (Y1) also increased to a large extent. Figure 1 (b) expressed that a less value of Y1 could be obtained when X2 ranged from 4-8. While X6 level was increased from 0.50 to 1.00, Y1 had a trend of first increasing and then decreasing.

In Figure 2(a), (b) and (c), the correlations among size concentration, blowing ratio and squeezing pressure were significant. The abrasion resistance (Y2) had an increasing trend as size concentration (X1) increased from 10 to 20%. A lower value of Y2 could be obtained with an X2 ranging from

4-8, when X1 and X6 were fixed. Y2 tended to increase first and then decrease, when X6 level ranged from 0.50 to 1.00.

In summary, higher size concentration was favorable to increase the abrasion resistance and decrease hairiness. Whereas, both abrasion resistance and hairiness decreased as the blowing ratio increased. The squeezing pressure should be controlled in a certain scope. Too high or too low squeezing pressure was not conducive in increasing the yarn properties.

In order to optimize and analyze the experimental results, the optimization objectives were defined as: the hairiness was less than 2 pieces/m and the abrasion resistance was greater than 290 times. To verify the validity of the optimization results, predicted and experimental response values led by optimal parameters after optimization with response surface method were shown in Table 7. The theoretical (predicted) values and the observed values were in reasonably good agreement and the deviation was less than 1%, indicating that the optimization results proved the validity of the model.

(a) Effects of Size concentration and blowing ratio on hairiness

(a) Effects of size concentration and blowing ratio on abrasion resistance

(b) Effects of size concentration and squeezing pressure on hairiness

(b) Effects of size concentration and squeezing pressure on abrasion resistance

(c) Effects of squeezing pressure and blowing ratio on hairiness

(c) Effects of squeezing pressure and blowing ratio on abrasion resistance

Figure 1 The 3D response surface illustrations for hairiness

Figure 2 The 3D response surface illustrations for abrasion resistant

Table 7. Predicted and experimental response values led by optimal parameters after optimization with response surface method

Size concentration (%)	Blowing ratio	Squeezing pressure (kN)	Hairiness (pieces/m)		Abrasion resistance(times)	
			Predicted	Experimental	Predicted	Experimental
19.33	4.27	0.78	1.72	1.81	297.9	311.3

4. Conclusions

This paper, using Plackett-Burman (PB) design, investigated the impact of operational parameters of the foam sizing process, including the size concentration, blowing ratio, stirring speed, pre-wetting temperature, pre-drying temperature, squeezing pressure and drying temperature, on the outcome of foam sizing. Yarn hairiness and abrasion resistance were employed as the response values to identify significant factors influencing the foam sizing quality. Then, the steepest ascent experiment with hairiness and abrasion resistance was used to evaluate the optimal range of significant factors. Box-Behnken design response surface method was employed to optimize the factors that were found to be significant. Size concentration, blowing ratio and squeezing pressure were significant factors that affected the foam sizing quality of cotton yarns. The response values reached the maximum level when the values were set at size concentration of 19.33%, blowing ratio of 4.27, and squeezing pressure of 0.78kN. The three statistic approaches were useful to optimize the foam sizing for cotton yarns, greatly reduce the harmful hairiness and enhance the abrasion resistance, and provided a scientific basis for further investigation in the sizing industry.

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