Optimization of Chlorine Bleaching Parameters for Indigo Denim Textile Based on the Model of Response Surface Model and Genetic Algorithm

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Abstract. The production of denim clothing has been broadly applied with the sodium hypochlorite washing technique, the parameters of which influence immensely on the effect of washing. It is the unclear declaration of the correlations between parameters of this technique and the final effects that makes it difficult to reduce the cost of washing in an efficient way. In this essay, L25(3⁵) Orthogonal experimental design method has been adopted to process chlorine bleaching experiment, by using parameters of the technique as the input parameters (the time, sodium hypochlorite concentration, temperature), and by using after-washing effects as output response (including K/S value, the bending stiffness, the warp-weft tensile breaking strength). Secondly, building agency theory model for the input-output correlation by utilizing response surface methodology in multivariate second-order to test the accuracy of the model, and to analyze how input parameters correlate to the result of chlorine bleaching. At last, based on the agency model, there will be raised up with the optimization model for production cost of the denim chlorine bleaching technique, which is solved by genetic algorithm method that could satisfy the purpose of reducing costs.

Keywords. Denim washing; orthogonal experiment; response surface methodology model; optimization.

1. Introduction

Denim clothing has been deeply in people’s favorite due to its easy and simple style. Along with the evolution of denim clothing, the self-characterized washing technique, for its production impose, has antique appearance and comfortable texture, which becomes the essential element leading to denim fashion. For all sorts of the techniques, washing technique has been deriving into many different methods so far, and Paul [1] and Kan [2] summarize the common washing method. Among various methods, sodium hypochlorite oxidation method (chlorine bleaching), with its supreme efficiency, has been applied into the further area in industrial production. During the chlorine bleaching, lots of parameters could be of the possibility to influence on the washing effect [3-5]. The washman, in the daily life of denim clothing production, has been dealing with the washing technique according to their own experience and the traditional technique. Their lack of knowledge of the correlation between parameters of the technique and the washing effect make them unable to control the washing result in an accurate manner, which prevent it from the cost declining at the same time.

There is the sophisticated correlation between the parameters of the technique and the washing effect, it is difficult to quantitatively interpret the multi-parameters and washing effect collaboration.
based on the mechanism. Hence, this essay utilizes agency model method to build up the correlation between those two with statistical analysis. Agency model, which is the mathematical model, takes on agency method to process fitting on the scatter data, commonly seen with neural network method and response surface methodology. Neural network method has high accuracy measure in fitting, but with comparatively more needs in sampling sites, which leads to the tendency of over-fitting phenomenon. There is comparatively less sampling sites in the polynomial response surface method, which mainly describes the tendency and neglects the detailed movement. Both of these two methods gain wide application in the textile process, for example, the response surface methodology calculates the PH value of textile product [6], the optimized mix multivariate carboxylic acid non-ironing technique on cotton textile [7], the optimized spherical sprayer electrostatic parameters [8], and the optimized feather fiber ultrasonic chromatic technique [9], etc. Neural network method is adopted in the K/S value on active chromatic textile forecast [10], the wool, cotton, yarn quality forecast, as well as cotton fabric thermal resistance forecast [11-12] and so on.

In order to reduce the experiment times, this essay combines orthogonal experiment and response surface methodology to build up the correlation between parameters of the technique and output effect, which will be checked by the experiment for the same purpose. Based on the efficient condition with the agency model, minimizing the cost as the target, constrained by the technique’s effect, optimization model for the cost will be built up. And the last but not the least, genetic algorithm will solve this model to get the supreme washing scenario which targets at the cost minimization.

2. Experiment
This essay selects washing temperature, washing time, sodium hypochlorite solution concentration as three key factors in the washing technique; four standards including K/S value, bending stiffness, warp breaking strength and weft breaking strength measure the technique’s effect.

2.1. Experiment and Method
In order to completely simulate the washing process how factory does to the denim clothing, the samples are made into 60cm×40cm sewing tubular shape (pants like) to decrease the disseminated samples during the chlorine bleaching process.

Put the tailoring cloth into adjusted 60℃ washing-chromatic machine to start the desizing. During the process, the desizing enzyme concentration is 2g/L, percentage ration is 1: 15; desizing time is 20 min. when finishing the desizing, wash it twice for 5 min with the clean water. For the final step, take out the desizing denim and put it into 75℃ steam drier with 20 min drying, preparing for the later procedure.

The after-desizing denim, according to the various experiment cases, is allocated with the various processing time when we put the denim into the sodium hydroxide solution with the various temperature and the various concentrated sodium hypochlorite. Pay attention here for all of the experiments, the solution’s sodium hydroxide concentration should be controlled within 2g/L and the washing bath ratio be 1:15. During the washing process, temperature is controlled between 20℃-60℃, sodium hypochlorite concentration is controlled between 10g/L-50g/L, and washing time is controlled between 10min-50min. After the predefined washing procedure, wash the clothing with clean water twice.

Finally, put all the managed clothing into the dehydrator for 4 minutes at 200 r/min for dehydrating, and then into the 75℃ steam drier with 20 min drying, preparing for later.

2.2. Experiment Design and Result
This research adopts the orthogonal experiment method for the experiment design, which creates the evenly-distributed and high-performance spatial filling sampling sites within the design space. Hence, current issue is the designing problem involved with three factors five levels, it could be to generate a L25(3^5) orthogonal array, as shown in table 1. In order to enlarge the popularity of the sampling, 2 more sampling sites are added to the 25 sampling sites, listing at the end of the table, the samples covered
will be more comprehensive in this way. In Table 1, the testing statistics of 27 sodium hypochlorite washing experiments are used in the training of the procedure, at the same time, other 5 experimental points are randomly selected for the accuracy of the response surface model, as seen in Table 1. TEM, CCL, K/S, BS means Temperature, color, concentration of sodium hypochlorite, bending rigidity. The smaller the K/S, the better the fading effect. The smaller the BS, the smaller the bending rigidity and the better the elasticity.

Table 1. Experiment case and the results.

| NO | TEM (°C) | CCL (g/L) | Time (min) | K/S | BS (mN·cN) | Breaking strength (N) |
|----|----------|-----------|------------|-----|------------|----------------------|
|    |          |           |            |     |            | Warp  | Weft  |
| 1  | 20       | 10        | 10         | 23.6| 64         | 1238.8 | 380.8 |
| 2  | 20       | 20        | 20         | 23.3| 61         | 1199.9 | 353.8 |
| 3  | 20       | 30        | 30         | 23.0| 56         | 1184   | 353.6 |
| 4  | 20       | 40        | 40         | 22.5| 55         | 1159.3 | 347.3 |
| 5  | 20       | 50        | 50         | 20.1| 53         | 1145.3 | 341.8 |
| 6  | 30       | 10        | 20         | 25.2| 54         | 1271.9 | 393.0 |
| 7  | 30       | 20        | 30         | 22.8| 54         | 1266.2 | 412.7 |
| 8  | 30       | 30        | 40         | 22.7| 53         | 1109.4 | 326.8 |
| 9  | 30       | 40        | 50         | 16.3| 52         | 939.5  | 284.8 |
| 10 | 30       | 50        | 10         | 24.8| 52         | 1184   | 352.2 |
| 11 | 40       | 10        | 30         | 22.4| 56         | 1222.7 | 357.9 |
| 12 | 40       | 20        | 40         | 20.3| 55         | 1071.9 | 301.3 |
| 13 | 40       | 30        | 50         | 16.3| 54         | 1002.9 | 292.6 |
| 14 | 40       | 40        | 10         | 21.3| 55         | 1096.4 | 325.3 |
| 15 | 40       | 50        | 20         | 18.4| 46         | 974.4  | 291.4 |
| 16 | 50       | 10        | 40         | 21.7| 46         | 1065.7 | 297.3 |
| 17 | 50       | 20        | 50         | 19.0| 51         | 1039.8 | 295   |
| 18 | 50       | 30        | 10         | 21.2| 50         | 1263.8 | 393   |
| 19 | 50       | 40        | 20         | 15.8| 49         | 1123.7 | 340   |
| 20 | 50       | 50        | 30         | 10.7| 52         | 1086.5 | 323.6 |
| 21 | 60       | 10        | 50         | 20.0| 56         | 1112.7 | 333.5 |
| 22 | 60       | 20        | 10         | 20.3| 56         | 1160.5 | 347.8 |
| 23 | 60       | 30        | 20         | 13.5| 54         | 1047.5 | 295.3 |
| 24 | 60       | 40        | 30         | 9.2 | 53         | 895.47 | 276.3 |
| 25 | 60       | 50        | 40         | 4.8 | 47         | 798.37 | 272.8 |
| 26 | 20       | 10        | 50         | 23  | 54         | 1173.5 | 350.5 |
| 27 | 60       | 50        | 10         | 20  | 55         | 1113   | 353.7 |
| Tasting data | | | | | | |
| 1  | 25       | 40        | 10         | 24.7| 54         | 1195.4 | 367   |
| 2  | 35       | 50        | 30         | 17.2| 51         | 1053.3 | 339.6 |
| 3  | 40       | 10        | 50         | 24.1| 52         | 1099   | 342.9 |
| 4  | 50       | 20        | 20         | 19.7| 55         | 1115   | 334   |
| 5  | 65       | 30        | 40         | 9.5 | 53         | 955.8  | 274   |
3. Result and Discussion

3.1. Second-Order Response Surface Regression Model

Multivariate non-linear regression equation closely interprets the correlation between the input parameters of washing technique and technique’s effect. For each individual response output, the K/S value, bending stiffness and warp-weft breaking strength with their corresponding input variables including washing temperature, washing time, sodium hypochlorite solution concentration, we could build the formula (1) the second-order response surface equation:

\[ f(x) = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{ij} x_i x_j \]

In the formula, \( \beta_i \) is coefficient, \( x_i \) is the i-th input variable. By substituting the data in table 1, we can evaluate the coefficient of the approaching multivariable by minimal square method, we obtain the response surface model \( f_{KS}(x) \), \( f_{BS}(x) \), \( f_Y(x) \), and \( f'_Y(x) \) representing the faceted K/S value, the bending stiffness and the warp-weft breaking strength. The response surface model is as the following:

\[ f_{KS}(x) = 20.1842 + 0.2184 x_{c} + 0.2094 x_{t} + 0.0215 x_{d} - 0.0016 x_{t}^2 + 0.0019 x_{c}^2 + 0.0026 x_{d}^2 - 0.0074 x_{c} x_{d} - 0.0033 x_{c} x_{t} - 0.0066 x_{t} x_{d} \]

\[ f_{BS}(x) = -81.3694 - 0.9344 x_{c} - 0.0709 x_{t} + 0.5119 x_{d} + 0.0088 x_{t}^2 - 0.0048 x_{c}^2 + 0.0044 x_{d}^2 + 0.0018 x_{c} x_{d} + 0.0029 x_{c} x_{t} + 0.002 x_{t} x_{d} \]

\[ f_Y(x) = 1220.7 + 3.1971 x_{c} - 1.6489 x_{t} + 3.3038 x_{d} - 0.0916 x_{t}^2 - 0.0252 x_{c}^2 - 0.0252 x_{d}^2 - 0.127 x_{c} x_{d} - 0.1193 x_{c} x_{t} - 0.0541 x_{t} x_{d} \]

\[ f'_Y(x) = 430.1748 - 0.6261 x_{c} - 2.2274 x_{t} + 0.0260 x_{d} + 0.0105 x_{t}^2 + 0.0298 x_{c}^2 - 0.00064342 x_{c} x_{d} - 0.0125 x_{c} x_{t} - 0.0325 x_{t} x_{d} - 0.003 x_{c} x_{d} \]

According to the response surface model obtained, we picture the three-dimensional graph between the input variables and washing effect characterized variables, as it is shown in figure 1. In the figure, X-axis shows the chlorine bleaching temperature, the Y-axis shows the sodium hypochlorite concentration, Z-axis shows the chlorine bleaching time. Different colors indicate the response value of the corresponding characterized variable. This Graph shows how three input variables influence on the collaboration of the characterized variables under chlorine bleaching technique.

3.2. Precision Verification

In order to verify the accuracy of the obtained response surface model, we forecast the 5-groups experiments at the back section in table 1. By comparing the performance parameters from the practiced experiment and the performance parameters from the response surface model, we can judge on the accuracy as well as the availability of the response surface model. As it is shown in table 2, by comparing the K/S, bending stiffness, warp-weft breaking strength data of the indigo chromatic cotton
denim under chlorine bleaching with the forecasting values from the response surface model, we are able to obtain the deviation, the deviation rate, and the root-mean-square deviation.

![Sample points](image1)

![Sample points](image2)

![Sample points](image3)

![Sample points](image4)

**Figure 1.** K/S value, flexural rigidity and longitudinal and latitudinal fracture strength under response surface.

In table 2, through comparing and analyzing the actual value and the forecasting value under response surface model, we obtain the absolute deviation of the K/S value, the bending stiffness value, warp-weft breaking strength value for the chlorine bleaching indigo chromatic cotton denim are 0.68, 2.00, 28.65, 11.66, respectively; the average absolute deviation rate are 3.63%, 3.76%, 2.7%, 3.5%, respectively; the root-mean-square deviation are 0.72, 2.1, 33.25, 12.35, respectively, all the deviations are within the boundary. After the verification of the accuracy under response surface model for indigo chromatic cotton denim under chlorine bleaching technique, we can proof that it is available to apply chlorine bleaching technique on to the indigo cotton denim.

4. **Optimization**

4.1. **Building Optimization Model**

In the actual washing process, washman will compare the washing effect every time based on the predefined washing parameters, they would like to get the best result as they can according to their own experience. However, very less likely that they could be able to obtain the better result and the less cost at the same time.

In the actual chlorine bleaching, there are mainly three parameters which influence on the property. We define these parameters as the input parameters, they are bleaching temperature $x_t$, bleaching time $x_d$, and sodium hypochlorite concentration $x_c$. In the real production, the experienced washman would composite the selected corresponding value from each parameter, thus to obtain the washing result they want. Here, we would define the restriction of these three input parameters, and the restriction rule is as the following:
minc \leq x_c \leq max_c \tag{7} \\
\text{min}_d \leq x_d \leq max_d \tag{8}

Table 2. Error analysis of response surface model.

| NO | Actual value | Forecast value | Deviation | Deviation rate (%) | Root mean square deviation |
|----|--------------|----------------|-----------|--------------------|---------------------------|
| K/S |              |                |           |                    |                           |
| 1  | 24.7         | 25.8           | 1.1       | 4.45               |                           |
| 2  | 17.2         | 17.9           | 0.7       | 4.07               |                           |
| 3  | 24.1         | 23.4           | -0.7      | -2.90              |                           |
| 4  | 19.7         | 20.2           | 0.5       | 2.54               |                           |
| 5  | 9.5          | 9.9            | 0.4       | 4.21               |                           |
| Bending stiffness |          |                |           |                    |                           |
| 1  | 54           | 57             | 3         | 5.56               |                           |
| 2  | 51           | 49             | -2        | -3.92              |                           |
| 3  | 52           | 51             | -1        | -1.92              | 2.09                      |
| 4  | 55           | 53             | -2        | -3.64              |                           |
| 5  | 53           | 55             | 2         | 3.77               |                           |
| Breaking strength (warp) |          |                |           |                    |                           |
| 1  | 1195.4       | 1198.9         | 3.5       | 0.29               |                           |
| 2  | 1053.3       | 1073.9         | 20.6      | 1.96               | 33.23                     |
| 3  | 1099         | 1129           | 30        | 2.73               |                           |
| 4  | 1115         | 1170           | 55        | 4.93               |                           |
| 5  | 955.8        | 921.7          | -34.1     | -3.57              |                           |
| Breaking strength (weft) |          |                |           |                    |                           |
| 1  | 367          | 357.5          | -9.5      | -2.59              |                           |
| 2  | 339.6        | 322.4          | -17.2     | -5.06              | 12.35                     |
| 3  | 342.9        | 328.3          | -14.6     | -4.26              |                           |
| 4  | 334          | 345.6          | 11.6      | 3.47               |                           |
| 5  | 274          | 279.4          | 5.4       | 1.97               |                           |

Under such restriction condition, we define the cost as output to formulate the function, the function is as the following:

$$f_{\text{cost}}(x_i, x_c, x_d) = \frac{x_i - \text{min}_i}{\text{max}_i - \text{min}_i} \cdot \beta_i + \frac{x_c - \text{min}_c}{\text{max}_c - \text{min}_c} \cdot \beta_c + \frac{x_d - \text{min}_d}{\text{max}_d - \text{min}_d} \cdot \beta_d$$ \tag{9}

In the function, $\beta_i$, $\beta_c$, and $\beta_d$ are the parameters of chlorine bleaching temperature, sodium hypochlorite concentration, and chlorine bleaching time which affect the cost, we can make certain adjustment according to the real situation. In the optimization procedure, under the ideal condition, which means each parameter is within the limited range, we obtain the minimal cost which is defined as the minimal value of $f_{\text{cost}}$. However, not only the input parameters are self-limited, but also is constraint to the after-washing performance demand. For example, in the actual production, we need K/S value is
smaller to a specific value, or the bending stiffness is fluctuated within a specific range and so on, the optimization model for the denim chlorine bleaching technique will be formulated as the following shown in equation (10):

Minimal value:

\[
\begin{align*}
\min_{x_t, x_c, x_d} & \quad f_{\text{cost}}(x_t, x_c, x_d) = \frac{x_t - \min_t}{\max_t - \min_t} \cdot \beta_t + \\
& \quad \frac{x_c - \min_c}{\max_c - \min_c} \cdot \beta_c + \frac{x_d - \min_d}{\max_d - \min_d} \cdot \beta_d
\end{align*}
\]

Limitation condition:

\[
\begin{align*}
& f_{K/S}(x_t, x_c, x_d) = T_1 \\
& f_{BS}(x_t, x_c, x_d) \leq T_2 \\
& f_y(x_t, x_c, x_d) \geq T_3 \\
& \min_t \leq x_t \leq \max_t \\
& \min_c \leq x_c \leq \max_c \\
& \min_d \leq x_d \leq \max_d
\end{align*}
\]

\[
\begin{align*}
f_{K/S}(x_t, x_c, x_d) &= T_1 \\
f_{BS}(x_t, x_c, x_d) &\leq T_2 \\
f_y(x_t, x_c, x_d) &\geq T_3
\end{align*}
\]

(10)

\[
f_{K/S}(x_t, x_c, x_d) = 15 \\
f_{BS}(x_t, x_c, x_d) \leq 52 \\
f_y(x_t, x_c, x_d) \geq 1000 \\
f_y'(x_t, x_c, x_d) \geq 320
\]

(11)

\[
\begin{align*}
& 20 \leq x_t \leq 60 \\
& 10 \leq x_c \leq 50 \\
& 10 \leq x_d \leq 50
\end{align*}
\]

Among this, \(x_t\), \(x_c\), and \(x_d\) represent the washing temperature, sodium hypochlorite concentration and washing time respectively. \(f_{K/S}\), \(f_{BS}\), \(f_y\), \(f_y'\) represent the correlations between K/S value, bending

4.2. Case Study

Assuming that there is a denim factory who would like to satisfy the needs of the customers while decrease the cost of chlorine bleaching at the same time. Assuming that in this factory, contribution rate of the chlorine bleaching time for the cost is 25%, the contribution rate of the temperature for the cost is 35%, and the contribution rate of the sodium hypochlorite for the cost is 40%. Upon these product, what the customers ask for is that K/S value is between 12-15, bending stiffness is smaller than 52mg·cm, warp breaking strength is greater than 1000N, and the weft breaking strength is greater than 320N.

Minimal value:

\[
\begin{align*}
f_{\text{cost}}(x_t, x_c, x_d) &= \frac{x_t - 20}{40} \cdot 0.35 + \\
& \quad \frac{x_c - 10}{40} \cdot 0.25 + \frac{x_d - 10}{40} \cdot 0.4
\end{align*}
\]

Limitation condition:

\[
\begin{align*}
f_{K/S}(x_t, x_c, x_d) &= 15 \\
f_{BS}(x_t, x_c, x_d) &\leq 52 \\
f_y(x_t, x_c, x_d) &\geq 1000 \\
f_y'(x_t, x_c, x_d) &\geq 320
\end{align*}
\]

(11)

\[
\begin{align*}
& 20 \leq x_t \leq 60 \\
& 10 \leq x_c \leq 50 \\
& 10 \leq x_d \leq 50
\end{align*}
\]

Among this, \(x_t\), \(x_c\), \(x_d\) represent the washing temperature, sodium hypochlorite concentration and washing time respectively. \(f_{K/S}\), \(f_{BS}\), \(f_y\), \(f_y'\) represent the correlations between K/S value, bending
stiffness, warp breaking strength, weft breaking strength with the temperature, washing time, sodium hypochlorite, respectively, which is based on response surface methodology. Their agency model is represented by equations (2)-(5).

Equation (11) belongs to the multivariate non-linear optimization model, and this essay proceeds the solution by genetic algorithm, and proceeds the coding in the software MATLAB2014a. After calculation and comparison, the optimization parameters composite is (49.4, 24.5, 28.3); in CPU: Inteli7-6560U@1.6GHz, RAM: 8G computer device; computing time: 0.98 second, all of these satisfy the corresponding requirement of the industrial production.

5. Conclusion

This essay raises the issue of utilizing the response surface methodology which combines with the genetic algorithm to obtain with the optimization scenario of the chlorine bleaching technique for the indigo chromatic cotton denim. From the experiments and the optimization result, we reach for the following conclusions:

Building up the correlation between chlorine bleaching technique and the washing effect is based on the response surface methodology, we verify the average absolute deviation value of the K/S value, bending stiffness, warp-weft breaking strength under the agency model are 0.68, 2.00, 28.65, 11.66, respectively; average absolute deviation rate are 3.63%, 3.76%, 2.7%, 3.5% respectively; average root mean square of deviation are 0.72, 2.1, 33.25, 12.35 respectively. All these deviations are within the accepted boundary, which proof that the response surface methodology is available and sufficient to forecast the chlorine bleaching effect.

Based on the built up agency model, we obtain the optimization model for the cost of the production in chlorine bleaching technique with denim fabric. This model is targeted at minimizing the cost, and optimizing the washing effect. This essay solves the issue by utilizing genetic algorithm, the efficiency of which satisfy the corresponding industrial production needs.

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