Optimization process of filling the cocoons with process water in a universal vacuum-steaming device

Ziyodulla Kodirov[1*], *Husankhon* Bobojanov[2], *Sharabidin* Dadajonov[3], and *Sabirjon* Yusupov[2]

[1]Andijan Machine-Building Institute, Andijan, Uzbekistan
[2]Namangan Institute of Textile Industry, Namangan, Uzbekistan
[3]Uzbek Research Institute of Natural Fibers, Margilan, Uzbekistan

Abstract. This article presents the results of a study carried out to optimize the process of filling the inner surface of cocoons with process water in a domestically produced universal vacuum-steaming device. Optimization was carried out according to the definition of a second-order polynomial Regression Multifactor Model (RMM) based on the results of the Rotatable Central Composition Experiment (RCCE). For this purpose, experiments were carried out in several versions on a universal vacuum-steaming device at different water temperatures and steaming durations.
Keywords. Cocoons, vacuum, universal, optimal, parameter, raw silk, steaming, experiment, factor, temperature, duration, preparation, unwinding, sericin.

1 Introduction

Natural silk is the most expensive textile raw material of natural origin. The production of natural silk is a labor-intensive and very time-consuming process. The quality of the produced raw silk largely depends on the processes of preparing cocoons for unwinding. In practice, there are three methods of preparing cocoons for unwinding: individual, centralized and vacuum methods of preparation [1,2]. The first two methods have been used before, i.e. when mechanical (KMS-10, KS-10, etc.) and automatic (SKE-4VU, SK-5, KM-90, Gunze, Keinan, etc.) cocoon-winding machines were installed at coco-winding enterprises. However, after the republic gained independence, all coco-winding enterprises were re-equipped with coco-winding equipment made in China, South Korea and Vietnam. On these equipments, the preparation of cocoons for unwinding is carried out using Chinese-made vacuum steaming machines, which have a number of disadvantages, the main one being the duration of steaming. This process has been studied by many researchers and a way to eliminate this drawback has been found [3].

After studying the results of research conducted in this area and the long-term production experience of coco-winding enterprises, an experimental sample of the first domestic small-sized universal vacuum-sealing device was created at the Andijan Machine

* Corresponding author: sherzod.korabayev@gmail.com

building Institute, which passed production testing in several coco-winding enterprises [4,5]. The universal vacuum-sealing device we created is fundamentally different from Chinese-made vacuum-sealing devices, although it looks similar to them. For example, on Chinese machines, cocoons in baskets are released into a steaming chamber filled with process water, then the lid is tightly closed and the vacuum pump is turned on, and a process begins that lasts up to 20 minutes [3]. On the created universal vacuum-steaming device, the cocoons in the basket are released empty into the steaming chamber, the lid is tightly closed and the vacuum pump is turned on, after pumping out the air from the chamber, the tap is opened and process water is supplied to the chamber. The cocoons are quickly filled with water, the process lasts 5-6 minutes. The created device is very simple in design, the need for electrical energy is minimal.

2 Methods

In the production of raw silk, its qualitative and quantitative indicators largely depend on the correct implementation of technological processes at the stage of preparing cocoons for unwinding. At this stage, the following technological processes are performed - sorting cocoons, steaming and finding the ends of cocoon threads. Among these technological processes, the most important is the process of steaming cocoons, which directly affects the quality indicators of the produced raw silk. The technological process of steaming cocoons begins with filling the inner surface of the cocoons with process water using vacuum steaming devices. At the same time, more than 98% of the internal volume of the cocoons is filled with water, which softens sericin, reduces the adhesion force and facilitates the removal of the cocoon thread. After this, the cocoons filled with water are transferred to a stretching machine, where the cocoons are steamed and boiled at a temperature of 96-980C, after which the ends of the cocoon threads are found. Cocoons with found ends are transferred to a coco-winding machine for unwinding them into raw silk of a given linear density.

The quality of steaming is influenced by the temperature of the process water and the duration of filling the cocoons with water. Therefore, optimization of the process of steaming cocoons on a vacuum steaming device is a very pressing problem. Based on this, we carried out a number of experimental studies in order to optimize the steaming process on a universal vacuum steaming device. Optimization was carried out according to the definition of a second-order polynomial regression multifactor model (RMM) based on the results of the rotatable central composition experiment (RCCE) [6]. The following input parameters were chosen: water temperature, ^{0}C (X_1) and steaming duration, min. (X_2). The selected output parameters are: the length of the continuously unwinding cocoon thread, m (Y_1) and the yield of raw silk, % (Y_2).

3. Results and Discussions

The coefficients of the rotatable central compositional experiment and their variance are determined using the following formulas:

$$b_0 = g_1 \sum_{u=1}^{N} \overline{Y_u} - g_2 \sum_{i=1}^{M} * \sum_{u=1}^{N} x_{iu}^2 \overline{Y_u} \tag{1}$$

$$b_i = g_3 \sum_{u=1}^{N} x_{iu} \overline{Y_u} \tag{2}$$

$$b_{ij} = g_4 \sum_{u=1}^{N} x_{iu} x_{ju} \overline{Y_u} \tag{3}$$

$$b_{ii} = g_5 \sum_{u=1}^{N} x_{iu}^2 \overline{Y_u} - g_6 \sum_{i=1}^{M} * \sum_{u=1}^{N} x_{iu}^2 \overline{Y_u} - g_7 \sum_{u=1}^{N} \overline{Y_u} \tag{4}$$

$$S^2\{b_0\} = g_1 S^2\{\overline{Y}\} \qquad S^2\{b_i\} = g_3 S^2\{\overline{Y}\} \tag{5}$$

$$S^2\{b_{ij}\} = g_4 S^2\{\overline{Y}\} \qquad S^2\{b_{ij}\} = g_7 S^2\{\overline{Y}\} \tag{6}$$

Based on the results of the experiment, we find a second-order regression multifactor mathematical model. As a result of this experiment, we obtain the following regression model:

$$Y_R = b_0 + \sum_{i=1}^{M} b_i x_i + \sum_{i=j=1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{M} b_{ij} x_i^2 \tag{7}$$

Since two factors are involved in the experiment, formula (7) takes on the following form:

$$Y_R = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 \tag{8}$$

where Y_R are the calculated values of the output parameter,
b_0...b_1... – regression coefficients,
x_1, x_2 – coded values of factors.
With the help of preliminary experimental studies, the intervals of variation of factors were determined, which are presented in Table 1.

Table 1. Factor variation intervals

Factors	Levels of variation					I_i
	-1,414	-1	0	1	1,414	
X_1	38,00	42,00	48,00	54,00	58,00	10,00
X_2	3,00	4,00	7,00	10,00	11,00	4,00

To obtain a regression model that defines the station space, a rotatable central compositional experiment was carried out using the following working matrix, which is given in Table 2.

Using this matrix, we determine the length of the continuously unwinding cocoon thread and enter them into the 7th column of Table 2. Each experiment is performed in 3 repetitions. To find the regression coefficients using the above formulas, we first find the following values:

$\sum x_{1u} Y_u$ =262,3; $\sum x_{2u} Y_u$ =409;

$\sum x_{1u}^2 Y_u$ =5406; $\sum x_{1u} x_{2u} Y_u$ = -46;

$\sum x_{2u}^2 Y_u$ = 5718; $\sum Y_u$ =9943;

$\sum_{u=1}^{N_M} (Y_{uM} - \overline{Y_M})^2$ = 2990,8 $\overline{Y_M}$ =876,2

$\sum_{u=1}^{N} (Y_u - \overline{Y_{Ru}})^2$ =153115

Then we determine the regression coefficients:

b_0 =0,2*9943-0,1*11 124=876,2;

b_1 =0,125*262,3=32,79;

b_2 =0,125*409=51,13;

b_{12} =0,25*(-46)= -11,50;

b_{11} =0,125*5406+0,0187*11 124-0,1*9943=-110,53;

b_{22} =0,125*5718+0,0187*11 124-0,1*9943=-71,53;

The variance of the output parameter is determined by the following formula:

$S^2 = \{Y\} = S_M^2\{Y\} = \frac{2990,8}{5-1}$ =747,7

Using formula (5), the variances of the regression coefficients are determined:

$S^2\{b_0\}$=0,2*747,7=149,54 S(b_0)=12,23

$S^2\{b_i\}$ =0,125*747,7=93,46 S(b_0)=9,67

$S^2\{b_{ij}\}$ =0,25*93,46=23,37 S(b_0)=4,83

Table 2. Working matrix of a rotatable central composition experiment.

№	Working Matrix					Y_1 – continuously unwinding length of cocoon thread, m			Y_2 – yield of raw silk, %		
	x_1	x_2	x_1^2	$x_1 x_2$	x_2^2	Y_{1u}	Y_{1Ru}	$(Y_u - Y_{Ru})^2$	Y_u	Y_{Ru}	$(Y_u - Y_{Ru})^2$
1	-1	-1	1	1	1	410	598,72	35616,03	28	30,89	8,33
2	1	-1	1	-1	1	538	687,30	22290,97	29,7	31,88	4,74
3	-1	1	1	-1	1	617	723,97	11443,35	31	32,67	2,79
4	1	1	1	1	1	699	766,55	4563,42	32,7	33,66	0,92
5	-1,414	0	2	0	0	767	608,77	25035,82	33,3	30,77	6,39
6	1,414	0	2	0	0	804	701,50	10505,78	33,7	32,17	2,33
7	0	-1,414	0	0	2	849	660,85	35402,01	34,7	31,81	8,34
8	0	1,414	0	0	2	878	805,43	5266,49	35,5	34,33	1,36
9	0	0	0	0	0	900	876,20	566,44	36,2	35,80	0,16
10	0	0	0	0	0	898	876,20	475,24	36,1	35,80	0,09
11	0	0	0	0	0	885	876,20	77,44	36,1	35,80	0,09
12	0	0	0	0	0	863	876,20	174,24	35,5	35,80	0,09
13	0	0	0	0	0	835	876,20	1697,44	35,1	35,80	0,49

$S^2\{b_{ij}\}$ =0,1438*23,37=3,36 S(b_0)=1,83

To determine the significance of regression coefficients, we use the Student's test. For the calculated coefficients, the calculated values of the Student criterion are determined:

$t_R\{b_0\}$ =876,2/12,23=71,65; $t_R\{b_1\}$=32,79/9,67=3,39;

$t_R\{b_2\}$=51,13/9,67=5,29; $t_R\{b_{12}\}$=11,50/4,83=2,38;

$t_R\{b_{11}\}$=110,53/1,83=60,3; $t_R\{b_{22}\}$=71,53/1,83=39,01

Then the calculated values of Student's t-test are compared with the table values that are given in Appendix 3 [6].

$$t_{жад}\ [P=0,95; f\{S_M^2\}=5-1=4]=2,776$$

A comparative analysis shows that all coefficients, with the exception of the regression coefficient b_{12}, are significant. Consequently, the relationship between the continuously unwinding length of the cocoon thread, the coefficients of water temperature and the duration of steaming has the form:

$$Y_{1R} = 876{,}2 + 32{,}79x_1 + 51{,}13x_2 - 110{,}53x_1^2 - 71{,}53x_2^2$$

Next, we check the hypotheses about the adequacy of the second-order RMM obtained from the RCCE using the Fisher criterion. To do this, we determine the dispersion of inadequacy and the calculated value of the Fisher criterion using the formulas [6]:

$$S_{nad}^2\{Y\} = \frac{9943 - 2990{,}8}{13 - 5 - (3 - 1)} = 1158{,}7$$

$$F_R = \frac{S_{nad}^2\{Y\}}{S_M^2\{Y\}} = \frac{1158{,}7}{747.7} = 1{,}55$$

The tabular values of the Fisher criterion are found in Appendix 4 [6]:

$$F_{т}\ [P_{д} = 0{,}95;\ f\ \{S_{nad}^2\{\mathrm{Y}\}\} = 13\text{-}5\text{-}(5\text{-}1) = 4;\ f\ \{S_M^2\} = 5\text{-}1 = 4] = 6{,}39$$

If $F_R < F_{tab}$. the inequality of the models is considered adequate. In our case we have the following inequality:

$$F_R = 1{,}55 < 6{,}39 = F_{tab.}$$

Consequently, the resulting regression mathematical model quite accurately determines the process under study and is considered adequate. Based on the data obtained using the Maple program, graphs were constructed of the dependence of the continuously unwinding length of the cocoon thread on the water temperature and the duration of steaming.

Analysis of the calculations and plotted graphs shows that the best results for the length of a continuously unwinding cocoon thread (876.2 m) are obtained when steaming in the following processing modes: process water temperature 52^0 C, steaming duration 5 minutes.

After this, we make calculations for the yield of raw silk – Y_2.

To determine the regression coefficients, we first find the following values using the data given in Table 2:

$\sum x_{1u}Y_u = 3{,}96$;

$\sum x_{2u}Y_u = 7{,}13$;

$\sum x_{1u}^2 Y_u = 255{,}4$;

$\sum x_{1u}x_{2u}Y_u = 0$;

$\sum x_{2u}^2 Y_u = 261{,}8$;

$\sum Y_u = 437{,}6$;

$\sum_{u=1}^{N_M}(Y_{uM} - \overline{Y_M})^2 = 56{,}2$;

$\overline{Y_M} = 35{,}8$;

$\sum_{u=1}^{N}(Y_u - \overline{Y_{Ru}})^2 = 36{,}113$.

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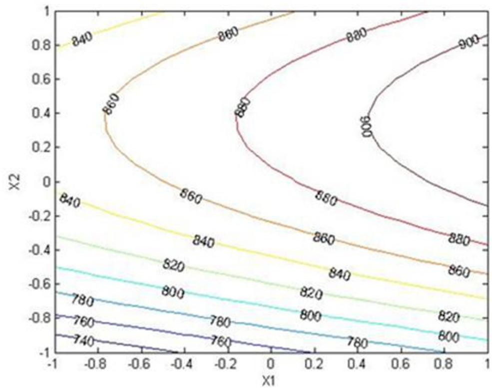

Fig. 1. Graph of the dependence of the continuously unwinding length of the cocoon thread (Y_1) on the water temperature (X_1) and the duration of steaming (X_2) (graphs were constructed using the Maple program).

Then we determine the regression coefficients:

b_0 =0,2*437,6-0,1*517,2=35,8;

b_1 =0,125*3,96=0,5;

b_2 =0,125*7,13=0,89;

b_{12} =0,25*0=0;

b_{11} =0,125*255,4+0,0187*517,2-0,1*437,6=-2,16;

b_{22} =0,125*261,8+0,0187*517,2-0,1*437,6=-1,36.

The variance of the output parameter is determined using the following formula:

$$S^2 = \{Y\} = S_M^2\{Y\} = \frac{56,2}{5-1} = 14,05$$

Using formula (5), the dispersion of regression coefficients is determined:

$S^2\{b_0\}$=0,2*0,23=0,046 S(b_0)=0,21

$S^2\{b_i\}$ =0,125*0,23=0,029 S(b_0)=0,17

$S^2\{b_{ij}\}$ =0,25*0,29=0,007 S(b_0)=0,08

$S^2\{b_{ij}\}$ =0,1438*0,007=0,001 S(b_0)=0,03

To determine the significance of regression coefficients, we use the Student's test. For the calculated coefficients, the calculated values of the Student criterion are determined:

$t_R\{b_0\}$ =35,8/0,21=170; $t_R\{b_1\}$=0,50/0,17=2,94;

$t_R\{b_2\}$=0,89/0,17=5,24; $t_R\{b_{12}\}$=0/0,08=0;

$t_R\{b_{11}\}$=2,16/0,03=72; $t_R\{b_{22}\}$=1,36/0,03=45

Then the calculated values of Student's t-test are compared with the table values given in Appendix No. 3 [6].

$$t_{\text{tab.}}\ [P=0,95;\ f\{S_M^2\}=5-1=4]=2,776$$

A comparative analysis shows that all coefficients, with the exception of the regression coefficient b_{12}, are significant. Consequently, the relationship between the yield of raw silk, the coefficients of water temperature and the duration of steaming has the form:

$$Y_{2R} = 35{,}8 + 0{,}5x_1 + 0{,}89x_2 - 2{,}16x_1^2 - 1{,}36x_2^2$$

Next, we check the hypotheses about the adequacy of the second-order RMM obtained from the RCCE using the Fisher criterion. To do this, we determine the dispersion of inadequacy and the calculated value of the Fisher criterion using the formulas [6, pp. 169-172]:

$$S_{nad}^2\{Y\} = \frac{437{,}6 - 56{,}2}{13 - 5 - (3 - 1)} = 63{,}56$$

$$F_R = \frac{S_{nad}^2\{Y\}}{S_M^2\{Y\}} = \frac{63{,}56}{14{,}05} = 4{,}52$$

The tabular values of the Fisher criterion are found in Appendix 4 [6]:

$$F_{tab.}\ [P_д = 0{,}95;\ f\{S_{nad}^2\{Y\}\} = 13\text{-}5\text{-}(5\text{-}1) = 4;\ f\{S_M^2\} = 5\text{-}1 = 4] = 6{,}39$$

If $F_R < F_{tab.}$ the inequality of the models is considered adequate. In our case we have the following inequality:

$$F_R = 4{,}52 < 6{,}39 = F_{tab.}$$

Consequently, the resulting regression mathematical model quite accurately determines the process under study and is considered adequate.

Based on the data obtained using the Maple program, graphs were constructed depending on the yield of raw silk thread on the water temperature and the duration of steaming.

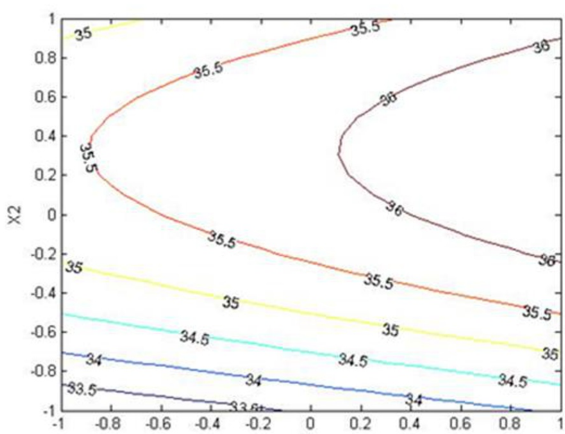

Fig.2. Graph of the dependence of the yield of raw silk (Y_2) on the water temperature (X_1) and the duration of steaming (X_2) (graphs were constructed using the Maple program).

An analysis of the calculations and plotted graphs shows that the best results for the yield of raw silk (36.2%) are obtained when steaming in the following processing modes: process water temperature 52^0 C, steaming duration 5 minutes.

4 Conclusions

At present, in the coco-processing enterprises of the republic, when preparing silkworm cocoons, they use Chinese-made vacuum-steaming devices, which have some disadvantages, one of which is the processing time, as well as large dimensions and power consumption.

Based on the study of available literary sources and long-term production experience at the Andijan Mechanical Engineering Institute, a first domestic universal small-sized vacuum-steaming device was created, which is fundamentally different from analogues in the method of steaming.

To optimize steaming parameters on small-sized universal vacuum steaming devices, a second-order Regression Multifactor Mathematical Model (RMMM) was used based on the results of the Rotatable Central Composition Experiment (RCCE).

Based on the experimental studies carried out, the optimal parameters for steaming on these devices were established, which are equal to: process water temperature 52^0C, steaming duration 5 minutes. During optimization, the main technological indicators of cocoons were taken as output factors - the length of the continuously unwinding cocoon thread and the yield of raw silk.

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