APPLICATION OF RESPONSE SURFACE METHODOLOGY (RSM) FOR OPTIMIZATION OF WET-SPINNING PARAMETERS IN ORDER TO IMPROVE THE QUALITY OF HEMP YARNS

Cristina RACU, PhD

"Gheorghe Asachi" Technical University of Iaşi, Romania

REZUMAT. Deși nu au fost apreciate la adevărata lor valoare pentru mult timp, în ultima perioadă fibrele de cânepă sunt recunoscute mai ales pentru calitățile lor ecologice, antibacteriene, antifungice sau termoregulatoare. Cercetările efectuate în ultimii ani au arătat că domeniul de utilizare a fibrelor de cânepă poate fi extins în zone cu valoare adăugată ridicată, inclusiv domeniul firelor și țesăturilor subțiri pentru articole de modă precum şi cel al textilor tehnice. Prezenta cercetare și-a propus să dezvolte o tehnică eficientă pentru producerea firelor de cânepă de înaltă calitate, prin optimizarea parametrilor de filare în stare udă, cu ajutorul metodologiei suprafeței de răspuns. S-a investigat efectul a două variabile independente, cum ar fi lungimea traseului semitortului în cuva cu apă și temperatura apei, asupra coeficienților de variație. S-a propus un model matematic pentru a corela variabilele independente şi coeficienții de variație în condiții optime de proces, folosind metoda designului compozit central (CCD). Studiul dezvăluie că temperatura apei a avut o influenţă mai mare asupra coeficienţilor de variaţie a densităţii de lungime a firului şi a tenacităţii decât lungimea traseului semitortului în cuva cu apă.

Cuvinte cheie: fire tehnice de cânepă, filare în stare udă, metodologia suprafeţei de răspuns.

ABSTRACT. Although they have not been appreciated at their true value for a long time, lately the hemp fibers are recognized mainly for their ecological, antibacterial, antifungal or thermoregulatory qualities. Researches conducted in recent years have shown that the field of use of hemp fibers can be extended to areas with high added value, including the field of fine yarns and fabrics for fashion items as well as that of technical textiles. The present research aimed to develop an efficient technique for the production of hemp yarn of high quality by optimizing the wet-spinning parameters with the help of response surface methodology. The effect of two independent variables, such as the length of the roving path in the vat with water and water temperature, on the coefficients of variation was investigated. A mathematical model was proposed to correlate the independent variables and the coefficients of variation under optimal process conditions by using central composite design (CCD) method. The study reveals that the temperature of the water had a greater influence on the coefficients of variation of yarn length density and tenacity than the length of the roving path in the vat with water.

Keywords: technical hemp yarns; wet-spinning; response surface methodology.

1. INTRODUCTION

Hemp is a natural fiber that can be grown very well in our country, it is environmentally friendly and it can provide the required amount of fiber without resorting to import. From hemp fibers it can be obtained new yarns, with other destinations than the usual ones, including for technical textiles.

Hemp fibers are biodegradable and do not cause harm to the environment at any stage of processing or use. As a spectacular comeback of hemp and an extension of its fields of use are currently occurring worldwide, a manufacturing preparation campaign is required through research related in particular to the tandem characteristics of fiber - applied technology [1,2].

The technical fibers undergo from one technological phase to another modifications that could be directed if one would know how each operation on the fibers interferes, starting with obtaining them from the plant and ending with the spinning. The mechanical forces of the machines applied to the technical fibers, break the bundles of fibers into increasingly fine groups, to which new divisions due to chemical processes are added, in case of the fibers chemical treatment or if the spinning is done in the wet state [3,4].

Different methods of statistical experimental design are used to optimize the process parameters in the field of industrial engineering. Conventional optimization techniques for a system with multiple variables that analyze the influence of each factor separately requires multiple experiments, multiple data and takes a long time. The experimental design techniques follow the optimization of the experimental parameters and provide statistical models that lead to the understanding of the interactions between the parameters. The present research aims to statistically optimize the parameters of the wet spinning process to improve the quality characteristics of hemp yarns. This paper investigates the combined effects of time and temperature of the wet spinning process on the coefficients of variation of the length density and tenacity of hemp yarn. The process parameters were optimized using central composite design (CCD) in conjunction with Response Surface Method (RSM) [5,6]. The models were developed by using the design of experiments to determine the optimum wet spinning conditions where the minimum coefficients of variation were obtained for the hemp yarns.

2. MATERIALS AND METHODS

2.1. MATERIALS

In order to carry out the experiments, a hemp roving with the linear density of 333.3 tex (Nm 3) was used.

It was processed on a wet spinning machine to which the following parameters were modified, the length of the roving path in the tube with water and the water temperature. The modification of the roving path length through the water tube was achieved by the guide pulleys within the tube and the water quantity introduced in the tube. Through this mode of processing were obtained yarns with an average length density of 100 tex (Nm 10).

The physico-mechanical characteristics of the processed yarns spun in different conditions, different roving path length and different water temperature, were measured according to the standardized methodology [7].

2.2. DESIGN OF EXPERIMENTS WITH MULTIPLE VARIABLES

The parameters used to reduce the coefficients of variation of length density and tenacity were analyzed by standard response surface methodology (RSM) design called central composite design (CCD). The RSM method helps to optimize the process parameters with a minimum number of experiments, as well as to analyze the interaction between the parameters, being a collection of mathematical and statistical techniques useful for developing the empirical model and for optimizing the process parameters. To optimize an answer, respectively an output variable that is influenced by several independent variables called input variables, the RSM statistical method uses quantitative data from the experiment to determine a regression model [5]. CCD consists of a 2^n factorial runs with 2n axial runs, and the experimental error is measured by center runs (n_c). This experimental design is composed of 2^n factorial with coded by ±1 notation augmented by 2n axial points (±a, 0, 0. . .0), (0, ±a, 0. . .0) . . . (0, 0, ±a . . .0) and n_c center points (0, 0, 0 . . . 0) [6].

The optimization by the RSM method involves several major stages, the statistical design of the experiments, the estimation of the coefficients in the mathematical model, the prediction of the response and the verification of the adequacy of the model in the configuration of the experiment.

In this study, two independent variables were chosen for the statistical experiment design as follows: the length of the roving path in the vat with water of the wet spinning machine (X_1, mm), and water temperature in the vat (X_2, °C). The range and level of the factors varied accordingly to the experimental design. In order to reduce the coefficients of variation, these two variables proved to be critical parameters.

$$Y = f(X_1, X_2) \quad (1)$$

where Y is the response of the system and X_1, X_2 are the independent variable called factors.

In the design it is assumed that the independent variables are continuous and that they can be regulated by experiments with negligible errors. A second degree polynomial equation was used to correlate the experimental variables with an empirical model generated by the experimental response (2).

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j + \varepsilon \quad (2)$$

where:

Y is the predicted response;

β_0 - the constant coefficient;

β_i - the linear coefficients;

β_{ii} - the quadratic coefficients;

β_{ij} - the interaction coefficients;

n - the number of factors studied and optimized in the experiments;

X_i and X_j the coded values of the variable parameters for the wet spinning process;

ε - the random error.

The coded values are calculated as a function of the range of interest of each factor as shown in Table 1.

Table 1. **Relationship between the coded and actual value of the variables**

Coded values	**-α**	**-1**	**0**	**1**	**α**
The actual level of variable	X_{min}	$(X_{max} + X_{min})/2 - (X_{max} - X_{min})/2\cdot\sqrt{2}$	$(X_{max} + X_{min})/2$	$(X_{max} + X_{min})/2 + (X_{max} - X_{min})/2\cdot\sqrt{2}$	X_{max}

The total number of tests or experiments required for CCD (N) is given by the relation (3).

$$N = 2^n + 2n + n_c \quad (3)$$

where n is the number of independent variables.

The total number of tests includes the standard factorial points (2^n), the axial points (2n) which are for screening analysis and readability, and (n_c) which is the number of central points which provide an independent estimation of the experimental error.

For two variables in the experiments, four factorial points, four axial points and five replicates at the central points were used for the CCD design. Hence, the total number of tests (N) required for the two independent variables is 13. Once the desired range value of the variables is defined, they are coded to ±1 for the factorial points, 0 for center points and ±α for the axial points [8,9,10].

For the regression analysis of the experimental data, to plot the response surfaces and to outline the contour under optimized conditions, the software package Design Expert 12, Stat-Ease, Inc., Minneapolis, USA was used. Within the same program the statistical significance was verified with the F-test, the accuracy of the polynomial model was determined by the R^2 coefficient and the significant model terms were evaluated by the probability value (*P*-value) at 95% confidence interval.

3. RESULTS AND DISCUSSIONS

3.1. WET SPINNING PROCESSES

When the spinning is done in the wet state, in the drafting zone of the spinning machine an individualization of the technical fibers can be obtained that can reach up to elementary fibers. The destruction of the bonds that unite the elementary fibers into technical fibers, the bonds formed by pectin, waxes, lignin, is achieved by softening these substances, as a result of the passage of the fed roving through a hot water tube and by adopting the rolling gauge smaller than the average length of technical fibers. The more technical fiber will be broken down into more groups of fibers, the better the spinning will take place and the quality of the yarn will be superior [3].

When studying the movement of the fibers in the drafting zone of the spinning machine, it was found that the large-length technical fibers, at the contact line of the feed cylinders, move with the speed of these cylinders. They cannot have another speed because their possibility of sliding between the cylinders is excluded. The complexes of elementary fibers detached from these technical fibers acquire from the moment of their separation the speed of the drafting cylinders, under the action of the forces due to which they were detached. In this way, the above-mentioned fiber groups move normally in the drafting zone [3].

Short fibers whose length is less than the distance between cylinders, as long as they are under the control of the feed cylinders, move with their speed. If, however, the anterior end did not come under the action of the drafting cylinders, then the movement of the short fibers becomes disordered and it is largely conditioned by the adhesion by friction with the neighboring fibers. This group of fibers which, when forming the yarns, moves at an arbitrary speed and depends on random causes, is a source of formation of yarn defects. In order to prevent the accidental movement of these fibers it is necessary to create conditions that prevent it from feeding and drafting areas [3].

3.2. DEVELOPMENT OF MODEL

The required experimental range and coded level of variables are given in Tables 2.

Table 2. **Experimental independent variables and their coded levels for the central composite design**

Independent variable	**Symbol**	**Levels of coded variables**				
		-α	**Low**	**Medium**	**High**	**α**
		-1.4142	**-1**	**0**	**1**	**1.4142**
The length of the roving path (mm)	X_1	48.17	119	290	461	531.83
Water temperature in the vat (°C).	X_2	19.64	30	55	80	90.36

The final empirical model in terms of a coded factor for the coefficient of variation of length density (Y_1, %) and the coefficient of variation of tenacity (Y_2, %) are shown in Equation (4) and (5). where the positive sign indicates the synergistic effects.

$$Y_1 = 6.37 + 0.1746X_1 + 0.1977X_2 + 0.0025X_1X_2 + 0.2912X_1^2 + 0.1562X_2^2 \quad (4)$$

$$Y_2 = 14.88 + 0.334X_1 + 0.4475X_2 + 1.68X_1^2 + 2.48X_2^2 \quad (5)$$

3.3. COMBINED EFFECT OF THE LENGTH OF THE ROVING PATH IN THE VAT WITH WATER OF THE WET SPINNING MACHINE AND WATER TEMPERATURE ON THE COEFFICIENT OF VARIATION OF LENGTH DENSITY

For the model expressed by the equation (4), the linear and square components were successively analyzed. For the linear component of the equation (4), one can conclude that the two observed parameters demonstrated almost similar effects on the response, the temperature of the water having an influence slightly greater than the length of the roving path on the coefficient of variation of length density. The signs of the coefficients of the linear components are positive for both parameters; taking into account that the resultant is the coefficient of variation of length density, I have obviously aimed at minimizing this function, therefore the behavior of the model for the simultaneous variation towards the limits of the experimental region of the two parameters X_1 and X_2 is the one shown in Figures 1 and 2.

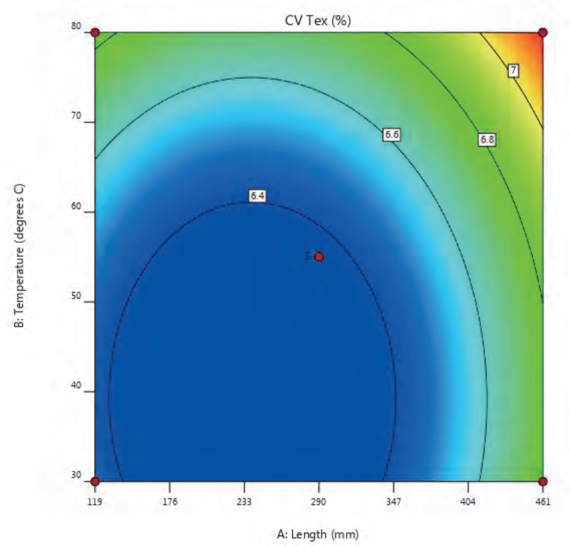

Fig. 1. Constant contour lines of the coefficient of variation of length density

The coefficient of interaction corresponding to the term X_1X_2 has a small value, meaning that the effect of the simultaneous variation of the two parameters is cumulative but in an unimportant manner. The presence of the square terms for both X_1 and X_2 has confirmed the existence of a well outlined surface, a rotation ellipsoid with a minimum point. There is a difference between the absolute values of the square term coefficients, X_1^2 having a coefficient almost twice greater than that corresponding to X_2^2.

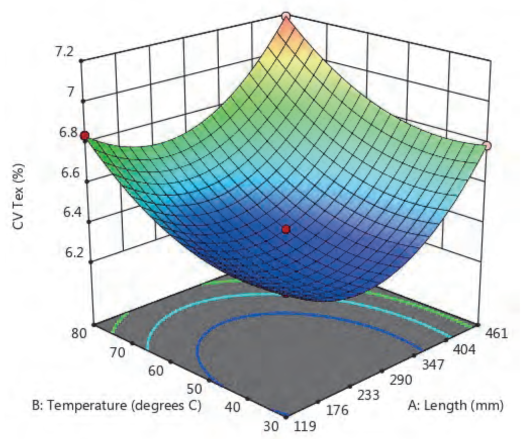

Fig. 2. The 3-D response surface for the resultant characteristic (Y_1), the coefficient of variation of length density

3.4. COMBINED EFFECT OF THE LENGTH OF THE ROVING PATH IN THE VAT WITH WATER OF THE WET SPINNING MACHINE AND WATER TEMPERATURE ON THE COEFFICIENT OF VARIATION OF TENACITY

For the model expressed by the equation (5), a ration similar to that used for the analysis of equation (4) was used. Analyzing the linear terms of the equation (5) it can be concluded that the temperature of the water had a greater influence on the coefficient of variation of tenacity than the length of the roving path. The signs of the coefficients of the linear components are positive for both parameters. Taking into account that the resultant is the coefficient of variation of tenacity, in the experiment it is obvious that the minimization of the result was aimed, therefore the behavior of the model for the simultaneous variation towards the limits of the experimental region of the two parameters X_1 and X_2 is the one shown in Figures 3 and 4.

The coefficient of interaction corresponding to the term X_1X_2 is missing, meaning that the effect of the simultaneous variation of the two parameters is not cumulative. The presence of the square terms for both X_1 and X_2 has confirmed the existence of a well outlined surface, a rotation ellipsoid with a minimum point shown in Figure 4. There is a difference between the absolute values of the square term coefficients, X_2^2 having a coefficient with 47.6% bigger than the one corresponding to X_1^2. The signs of the coefficients of the square terms are positive, therefore the influences consist in the increasing of the coefficient of variation of tenacity.

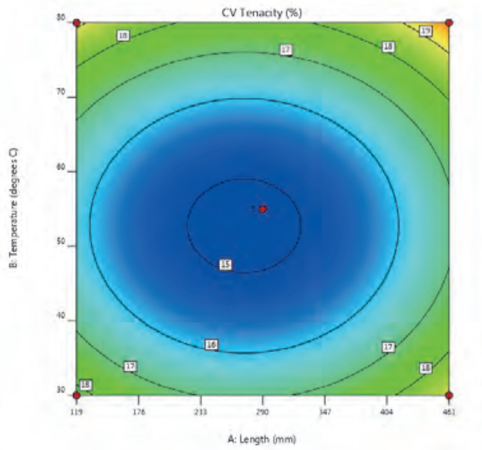

Fig. 3. Constant contour lines of the coefficient of variation of tenacity

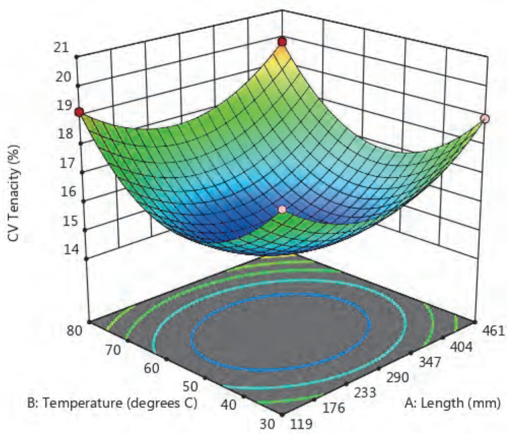

Fig. 4. The 3-D response surface for the resultant characteristic (Y_2), the coefficient of variation of tenacity

3.5. OPTIMIZATION BY RESPONSE SURFACE MODELING

The vital part of the experimental study was to determine the optimum spinning process condition where minimum coefficient of variation of length density and minimum coefficient of variation of tenacity can be obtained. Optimization of the spinning variable parameter was carried out in a numerical optimization method. The contour plot at optimum spinning condition for minimum coefficient of variation of length density was shown in Figure 5 and Table 3.

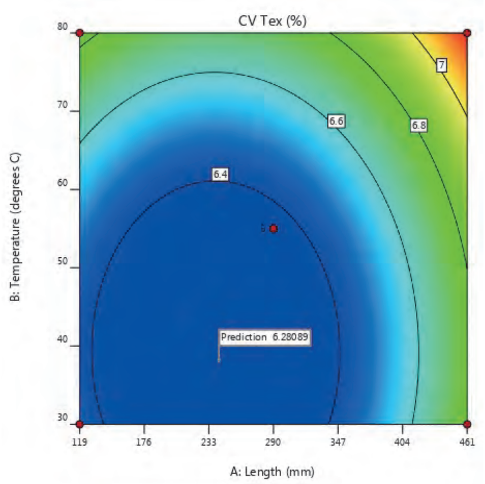

Fig. 5. Contour plot of the length of the roving path in the vat with water of the wet spinning machine and water temperature on the coefficient of variation of length density at optimum condition

The contour plot at optimum spinning condition for minimum coefficient of variation of tenacity was shown in Figure 6 and Table 4.

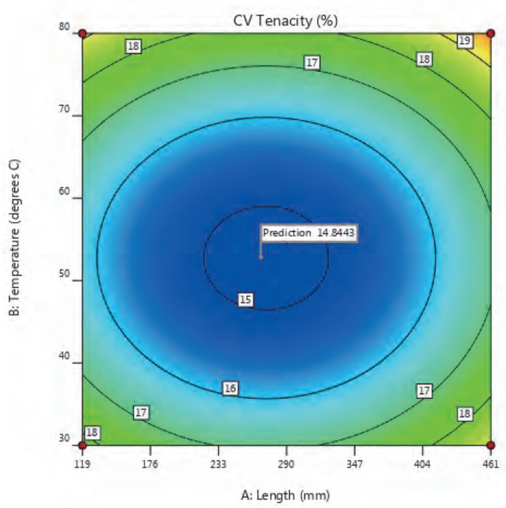

Fig. 6. Contour plot of the length of the roving path in the vat with water of the wet spinning machine and water temperature on the coefficient of variation of tenacity at optimum condition

Analyzing the data presented in Tables 3 and 4 it can be concluded that the optimum wet spinning conditions that resulted in the lowest coefficients of variation for the length density and for tenacity were the length of the roving path of 273 mm and the water temperature of 52.7°C.

From the results, it was concluded that the developed model could accurately predict the coefficients of variation for the length density and for tenacity.

Table 3. **Optimal processing conditions for the reduction of the coefficient of variation of length density**

Parameters	Length of the roving path X_1 (mm)	Water temperature X_2 (°C)	Coefficient of variation of length density Y_1(%)	Coefficient of variation of tenacity Y_2(%)
Optimum conditions	243	38.2	6.28	15.7

Table 4. **Optimal processing conditions for the reduction of the coefficient of variation of tenacity**

Parameters	Length of the roving path X_1 (mm)	Water temperature X_2 (°C)	Coefficient of variation of tenacity Y_2(%)	Coefficient of variation of length density Y_1(%)
Optimum conditions	273	52.7	14.84	6.33

4. CONCLUSIONS

The regression analysis and optimization of variables are calculated by using design expert for predicting the response in the experimental regions. The values obtained experimentally under variable processing conditions of the hemp rovings were used for the regression analysis and the response surface analysis. The analyzes regarding the reduction of the coefficients of variation for the length density and for the tenacity under optimum conditions of wet spinning were carried out by applying RSM in conjunction with CCD.

A model was formulated to correlate the wet spinning experimental variables to the responses. The water temperature was found to have the most significant effect on the coefficients of variation for the length density and for tenacity. Optimal conditions for minimizing the coefficients of variation for the length density and for tenacity were obtained at the length of the roving path of 273 mm and the water temperature of 52.7 °C.

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Despre autor

Şef lucr. dr. ing. **Cristina RACU**
Universitatea Tehnică "Gheorghe Asachi" din Iaşi, România

Absolventă a Universităţii Tehnice "Gheorghe Asachi" din Iaşi, Facultatea de Textile - Pielărie şi Management Industrial - 1988, doctor inginer din anul 1999; în prezent cadru didactic la facultatea pe care a absolvit-o. Domenii de competenţă: tehnologii mecanice textile, grafică asistată de calculator, fire tehnice, textile medicale, testarea produselor textile şi controlul calităţii.