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Regularities of distribution of the relative air humidity in the volume textile fiber material in the production of yarn

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Abstract. Methods for calculating the moistening of textile fibers in the process of yarn production when processing with conditioned air with certain technological parameters based on mathematical modeling and numerical methods are presented. There are appropriate mathematical models, adequately describing the process of distribution of the relative air humidity in the porous medium under consideration. A mathematical model of the process of moistening porous of a textile material in the form of the Cauchy problem for a second-order differential equation for the purpose of numerical modeling of the change in the relative humidity of conditioned air in the volume of a compactly formed semi-finished product of textile production. The classical instability of the problem is shown, methods of its solution are considered, the problem is numerically solved for various options of technological conditions for organizing the humidification process. Numerical calculations have shown that the relative humidity of the air flow decreases monotonically with distance from the surface to a certain limiting value. At the same time, an increase in the specific surface area of a capillary-porous medium leads to a more intense drop in the relative humidity of the conditioned air in a moving air stream. The results of numerical studies show that with an increase in the flow rate of conditioned air, the depth of penetration of moisture into the volume of a porous medium increases, i.e. more moisture settles on the last layers of the volume. Consequently, to optimize the process, one should choose an air flow rate that provides a sufficient intensity of material moistening with deep penetration of moisture into the volume of a porous medium. Mathematical models of changes in the air flow rate in the volume of a porous medium according to linear and exonential laws are presented. It is shown that taking into account the drop in velocity according to the exponential law allows one to obtain good agreement between the calculated and experimental data. Physical and mathematical modeling of the non-stationary process of moisture distribution in a textile material during its humidification with conditioned air for the case of diffusion kinetics of the humidification reaction in the form of a boundary value problem for the diffusion equation has been carried out. On the basis of physical concepts of the processes occurring at the boundary of a porous medium and in its volume, modeling equations and boundary conditions for the problem of calculating the unsteady distribution of moisture in a porous medium are formulated.

1. Introduction

The quality of the flow of technological processes in the production of yarn from semi-finished products (wool top, ribbon, roving) depends on the moisture content, W, % of processed textile fibers.

At the same time, it is known that the value of W, % is determined by the level of relative air humidity φ, %, maintained in the production premises of textile factories.

Most of applied textile fibers are capillary-porous colloidal bodies that actively adsorb moisture from the ambient air. With the increase of φ, % the W, % of fibers increases sharply [1-3].

Figure. 1 shows the graphical dependences of equilibrium moisture content of various textile fibers Wp on the relative air humidity in the shop φ, %, obtained on the basis of experimental studies.

The graphical dependences shown in Figure. 1 were obtained experimentally. During the studies, textile fibers of viscose, wool and capron were in a non-compacted state, while roving and yarn were formed into a dense compacted form, e.g., in bobbins, cops, etc.

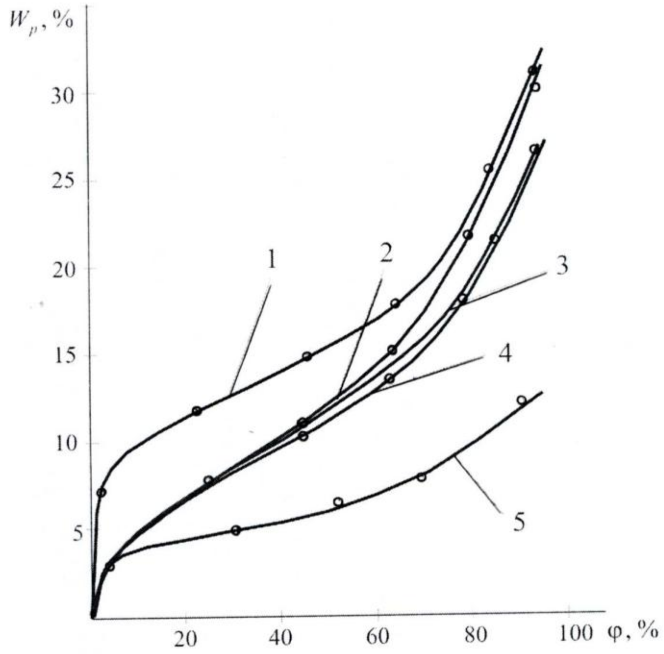

Figure 1. Dependence of the equilibrium moisture content of fibers W_p, % on relative air humidity φ, %: 1 – yarn; 2 – viscose; 3 – wool; 4 – roving; 5 – capron.

While the moist air supply for free fibers is sufficient, for fibers in a dense medium it is more difficult. As a result, there is an uneven moistening of the fibers in the thickness of compacted medium.

It is known that this leads to deterioration in the physical and mechanical properties of fibers and, as a result, an increase in the breakage of threads and a decrease in the quality of yarn and fabric [1].

It is determined that the most promising moistening technology for textile fibers formed into compacted medium is the method of supply of conditioned air with required values of φ, % directly to the processed semi-finished products.

Such method will make it possible to provide the most efficient access of moist air to the fibers inside compactly formed textile materials [12].

2. Materials and methods

2.1. Materials

In order to ensure uniform moistening of the fibers during the production, it is important to study changes in the relative air humidity φ, %, within compacted form, depending on the velocity of air supplied to the materials w, m/s [4-7, 12].

The most convenient tool for this is to conduct experimental and theoretical studies based on mathematical modeling and numerical methods. This will allow to predict physical processes of the moist air movement in the thickness of compacted medium.

Let us review specific methods for calculation of the moistening of capillary-porous colloidal textile material during its treatment with conditioned moist air at various technological stages and perform a numerical study of reviewed regularities in the process.

As a first approximation, the modeling equations for solving the problem of calculation of distribution of conditioned air moistening across the textile fibers can be written as follows (1,2,3):

$$D\frac{d^2\varphi}{dx^2} - w\frac{d\varphi}{dx} = F_{ss}\cdot f(\varphi); \tag{1}$$

$$\varphi(0)=\varphi_0; \tag{2}$$

$$\frac{d\varphi}{dx}(0) = -\frac{1-\varepsilon}{\varepsilon}\cdot\frac{\rho}{Q_{\max}}\left(f(\varphi(0)) - W_0\right). \tag{3}$$

For convenience of programming, let us specify the required relative air humidity function $\varphi(x)$ by identifier $y_0(x)$, and derivative $d\varphi/dx$ by identifier $y_1(x)$. Then the problem for numerical solution will be written as follows:

$$\begin{cases} \dfrac{dy_0}{dx} = f_1(x, y_0, y_1); \\ \dfrac{dy_1}{dx} = f_2(x, y_0, y_1), \end{cases} \tag{4}$$

where $f_1(x, y_0, y_1) = y_1(x, y_0, y_1)$, then it can be written as follows:

$$f_2(x, y_0, y_1) = \frac{y_1\cdot w + K\cdot F_{ss}\cdot\left(C\cdot e^{k_1\cdot(y_0-\varphi_c)} + \dfrac{A}{1+(A/B-1)\cdot e^{-k\cdot y_0}}\right)}{D}, \tag{5}$$

with boundary conditions on the required function y_0 and its derivative:

$$y_0(0)=\varphi_0;\quad y_1(0) = -\frac{1-\varepsilon}{\varepsilon}\cdot\frac{\rho}{Q_{\max}}\left(f(Y_0(0)) - W_0\right). \tag{6}$$

2.2. Methods

Here, the value of φ0 is the humidity of conditioned air at the external boundary of the medium, %; φ(x) is the relative humidity of conditioned air at the point x of the porous medium, %; w is the velocity of air flow through the porous medium, m/s; D is the effective diffusion coefficient, m2/s; Fss is the specific surface area of the unit of porous material mass, m2/kg; l is the thickness of the porous medium, m; ε is the coefficient of porosity; К, A, B, C, k, k1 are regression parameters.

The system of equations (4-6) was solved by the Runge-Kutt method [2-3,8, 13-14].

As an example, the following values of parameters and constants in the system of equations (4-6) were chosen as the basis for numerical experiments: D = 200 m2/s; w = 2 m/s; Fss = 200000 m2/kg; l = 0.15 m; φ0 = 80 %;

A = 15; B = 3; k = 15; k1 = 10; K = 0.0001. (7)

Figure. 2 shows an example of calculation of the change in relative air humidity φ (along the vertical axis) in the thickness of the porous medium l (along the horizontal axis).

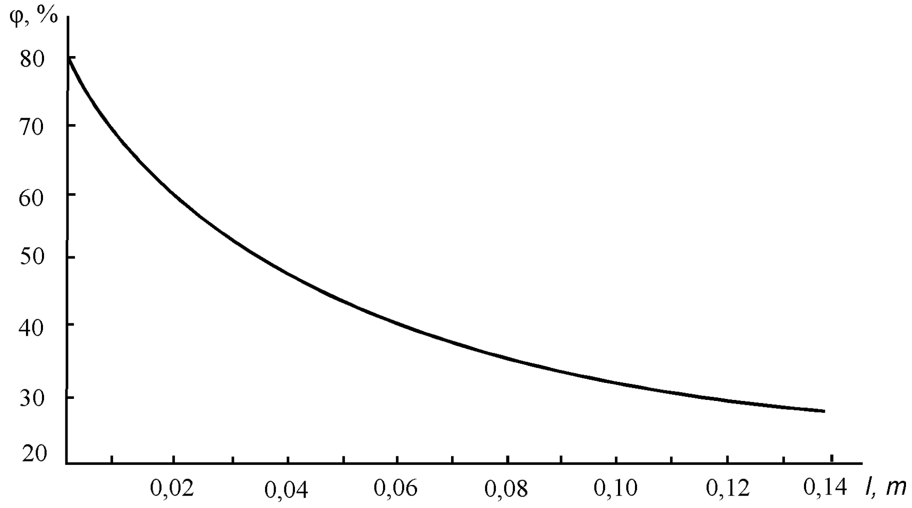

Figure 2. The pattern of the airflow humidity distribution in porous material.

3. Results

Obtained experimental data (Figure. 3) adequately comply with the calculated dependence (5). We observe correspondence between distribution patterns of the calculated and experimental curves and the relative coincidence of numerical characteristics.

However, when carrying out the calculations, the authors noticed some discrepancy between the calculated and experimental data at sufficiently high rates of the moist air supply to the working area. The following explanation was given to this fact.

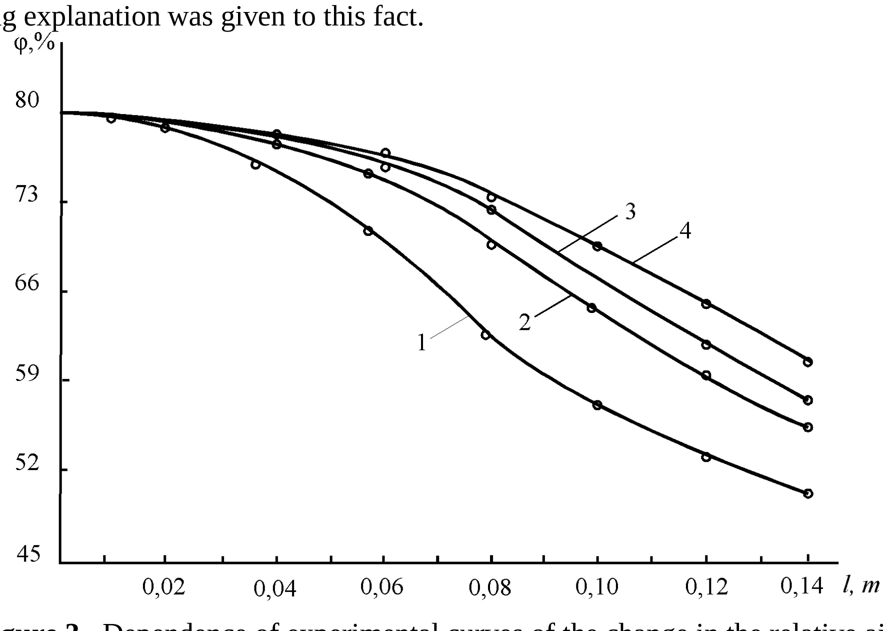

Figure 3. Dependence of experimental curves of the change in the relative air humidity φ in the thickness *l* of a roving bobbin on the airflow velocity: 1– *w* = 2 m/s; 2 – *w* = 4 m/s; 3 – *w* = 6 m/s; 4 – *w* = 8 m/s.

Increase in the airflow velocity has a double effect on the moisture adsorption rate. On the one hand, at high velocity of the flow, the contact time of moisture particles with the porous material decreases, the process is “pushed” inside the porous mass. On the other hand, the increase in velocity enhances the convective mixing of moist air, which contributes to a decrease in the thickness of diffusion-adsorption layer, increases the rate of moisture delivery to the surface of the porous medium material and, as a result, increases the rate of material moistening [15].

The mutual influence of these two circumstances makes it possible to assume that there is some optimal value for the rate of an airflow supply to the working area, at which the moistening process proceeds at sufficient depth of penetration into the porous medium at a high rate of the medium volume moistening [9-11].

In the context of mathematical modeling, the consequence of such reasoning is, firstly, the need to take into account the influence of an airflow velocity on the source function $W = f(\varphi)$, expression (5). I.e., the function f shall depend on both the air humidity φ and the airflow velocity w: $f = f(\varphi, w)$. Secondly, it is necessary to correct the mathematical model of distribution of the relative conditioned air humidity in a porous medium, taking into account the possible decrease of the airflow velocity due to resistance to its movement within the medium.

4. Discussion

At first, let us review the influence of a change in velocity on the source function. In physical chemistry, there is the concept of “mass-transfer coefficient” Km, equal to the ratio of the substance diffusion coefficient to the thickness of reaction medium diffusion layer. Actual value of this coefficient depends on the airflow velocity, and when solving some problems in the field of physical chemistry it is accepted that “effective” values for such a coefficient are described by the following regression dependence

Km = α·wβ. (8)

The numerical experiments performed by us for the solution of the porous medium moistening problem have shown efficiency of the following formula

Km = 0.0001·w–0.7. (9)

In this case, Km is used as a linear coefficient in the source function.

$$W_p = K_m \left(k_2 \cdot e^{k_1(\varphi - \varphi_c)} + \frac{W_i}{1 + \left(\frac{W_i}{W_l} - 1 \right) e^{-k\varphi}} \right), \qquad (10)$$

where Wp – equilibrium moisture content of textile fibers;
Wi – a constant characterizing the initial equilibrium moisture content of the fibers;
Wl – a constant characterizing the limiting moisture content of a porous material.

Then equation (5) will be written as follows:

$$f_2(x, y_0, y_1) = \frac{y_1 \cdot w + K_m \cdot K \cdot F_{ss} \cdot \left(C \cdot e^{k_1 \cdot (y_0 - \varphi_c)} + \frac{A}{1 + (A/B - 1) \cdot e^{-k \cdot y_0}} \right)}{D}. \qquad (11)$$

An even greater influence on the results of calculation is exerted by the value of effective moisture diffusion coefficient in the process of the porous medium moistening. It is known that the porous medium is a good agitator for the moist air flow, consequentially there is a phenomenon of convective diffusion. Simultaneously, the actual value of effective diffusion coefficient D may differ from the true value by several orders of magnitude Di. When calculating D, we used a correction factor that depends on the moist air flow velocity. A good compliance between the results of calculations and experiments was provided by the following formula

D = Di·q·wp, (12)

where p, q – some dimensionless constants.

In our case, the values p = 0.3, q = 71 were obtained.

Let us now turn to the modeling of relative air humidity distribution in a porous medium at a varying flow velocity in the medium thickness.

In that case we will obtain the equation:

$$D \frac{d^2\varphi}{dx^2} - w \frac{d\varphi}{dx} - \varphi \frac{dw}{dx} = F_{ss} \cdot f(\varphi). \qquad (13)$$

Let us consider two possible models of the change in the airflow velocity in a porous medium volume: linear and exponential decay of the airflow velocity.

In the first case, we can assume that

$$w(x) = \gamma x + \mu, \tag{14}$$

where w(0) = w, i.e., μ = w, and the value of γ makes it possible to track the magnitude of the airflow velocity decrease.

For example, γ = –w/(2·l) leads to a twofold linear decay in the airflow velocity at a distance l from the porous medium boundary.

In this case, equation (13) will be written as follows:

$$D\frac{d^2\varphi}{dx^2} - w\frac{d\varphi}{dx} - \varphi \cdot \gamma = F_{ss} \cdot f(\varphi). \tag{15}$$

In the second case, we will consider the law of velocity decay exponential:

$$w(x) = \gamma \cdot \exp(-\mu \cdot x). \tag{16}$$

Then the γ = w(0), and the value of parameter μ adjusts the airflow velocity decay w(x), where x is the coordinate along the thickness of the porous medium.

Equation (13) will be written as follows:

$$D\frac{d^2\varphi}{dx^2} - w\frac{d\varphi}{dx} + \gamma \cdot \mu \cdot \exp(-\mu \cdot x) = F_{ss} \cdot f(\varphi). \tag{17}$$

Figures. 4, 5, and 6 show the results of calculation of the change in relative air humidity in the volume of a porous medium under linear and exponential velocity change laws, respectively.

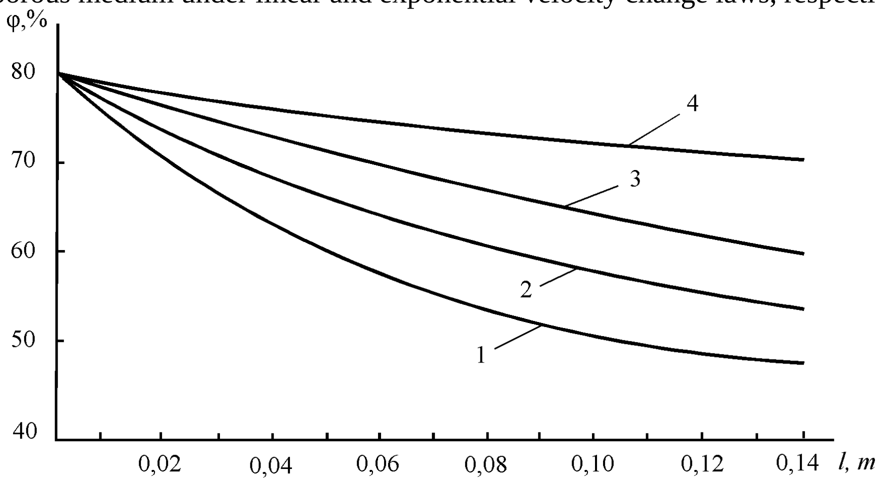

Figure 4. Influence of initial airflow velocity *w* on distribution of the relative air humidity in the volume of a porous medium with due consideration of linear decay of the airflow velocity γ = *w*/(2·*l*): 1 – at *w* = 2 m/s; 2 – at *w* = 4 m/s; 3 – at *w* = 6 m/s; 4 – at *w* = 8 m/s.

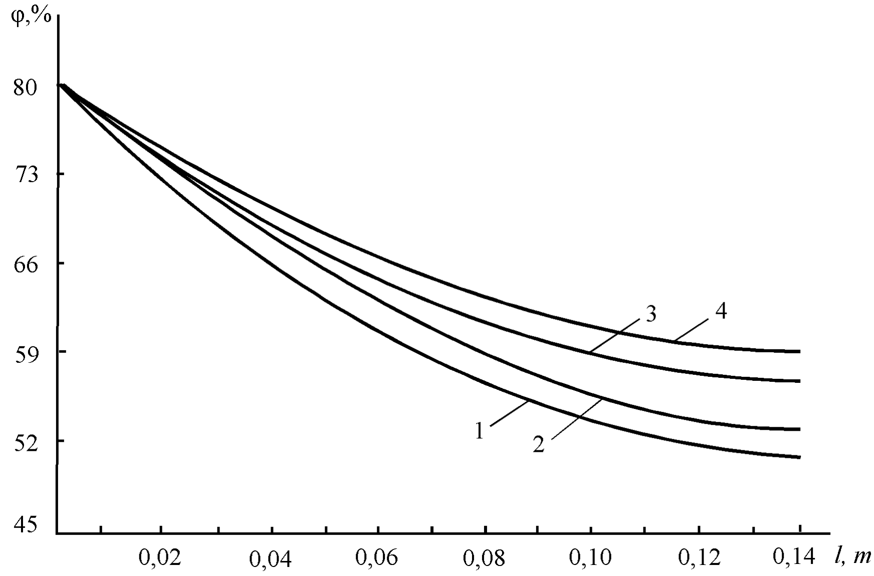

Figure 5. Influence of initial airflow velocity *w*on distribution of the relative air humidity in the volume of the porous medium with due consideration of exponential decay of the airflow velocity (γ =0.1):1 – at *w* = 2 m/s; 2 – at *w* = 4 m/s; 3 – at *w* = 6 m/s; 4 – at *w* = 8 m/s.

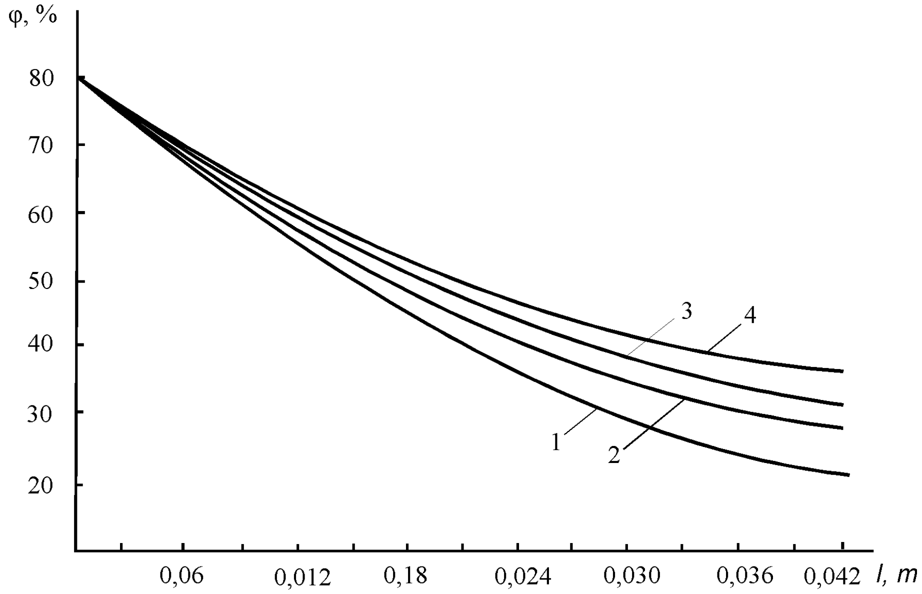

Figure 6. Change in relative air humidity φ along the thickness *l* of the roving bobbin depending on the airflow velocity: 1 – *v* = 2 m/s; 2 – *v* = 4 m/s; 3 – *v* = 6 m/s; 4 – *v* = 8 m/s.

5. Summary

1. The results of theoretical studies show that increase of conditioned air flow velocity leads to the increase of the depth of moisture penetration into the volume of the porous medium, i.e., a greater moisture settlement on the last layers of the volume. Therefore, in order to optimize the process, it is necessary to choose such an airflow velocity that will provide adequately intense moistening of the material with a deep moisture penetration into the volume of a porous medium.

2. Also the analysis of the graphical dependences depicted in Figures. 3, 4, and 5, shows that a

sufficiently good compliance between the calculated and experimental data is observed while using the mathematical model of expression (7), plotted with due consideration of exponential decay of the conditioned air flow velocity in the thickness of the porous medium, the basis of which is a compactly formed semi-finished textile product (roving).

3. Therefore, the mathematical model (17), (2), (3), (5) for the given values of the process parameters used in the ratios and determined experimentally or computationally quite adequately describes the process of the relative air humidity distribution in considered porous medium and can be used for theoretical and practical calculations.

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