Determination of Temperature of Components of Cotton-Raw Material in a Drum Dryer with a Constant Air Temperature

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Abstract. This article solves one parabolic-type boundary value problem for determining the heat-moisture state of raw cotton in drum dryers at a constant air temperature. Numerical results are obtained by the Bubnov–Galerkin method of the problem under consideration, a comparative analysis is carried out with experimental data. It is shown that the proposed mathematical model and its numerical algorithm adequately describe the drying process of raw cotton.

1. Introduction

Currently, extensive work is being done on programs and activities aimed at the production of yarn and fabrics that meet international standards. A number of events in the country are aimed at introducing new methods of economic management of economic enterprises and increasing their independence in full economic management. The purpose of these activities is to increase the demand of the national economy for light industry products and to improve the quality of the products. Since independence of the Republic of Uzbekistan, the number of joint ventures with foreign countries has grown every year and is equipped with modern technologies and technologies. In addition, many modern types of equipment are being installed in laboratories established under joint ventures to control the quality of the yarn [1].

The main task of drying cotton is to bring its moisture content to normal level. However, this problem is not always solved successfully using modern cotton-raw cotton processing technology. To intensify the drying process, heat carriers of high temperature are used, which lead to a deterioration in the quality of raw materials. By controlling the temperature conditions inside the drum, it is possible to create conditions that ensure uniform and intensive removal of moisture from the components of the raw cotton. Determination of the functional theoretical dependences of heat and mass transfer indicators of fiber and seeds on the conditions and drying conditions and, on this basis, improvement of the equipment and drying technology is an actual scientific problem [2, 3].

The initial processing of cotton consists of a number of technological processes (placement, storage, transportation, drying, cleaning, fiber separation, etc.), which form a unique technological chain. The performance and quality of each piece of equipment in this chain is closely related to the performance and quality of the previous machines. Given this situation, it can be concluded that the impact of each piece of equipment in the technological chain on the quality of cotton products is significant [4].
2. Methods

Considering the convective drying of raw cotton in a direct-flow drum dryer in which a relatively constant temperature of the heat carrier is maintained along the length of the drum during drying. Let the mass of raw cotton move with speed along the length of the drum and let the temperature difference between the components of raw cotton and air over the cross section of the drum be zero. In addition, we assume that convective heat exchange occurs between the raw cotton component and air according to Newton’s law. Then, the temperature of the components of raw cotton, given the evaporation of moisture, can be found by solving the system of differential equations of the parabolic type [5, 6]:

\[
c_i \rho_i \frac{\partial T_i}{\partial \tau} = \lambda_i \frac{\partial^2 T_i}{\partial x^2} - c_i \rho_i v_i \frac{\partial T_i}{\partial x} + \alpha_i (T_2 - T_i) + \alpha_2 (T_3 - T_i) + \epsilon_i \rho_i r_{21} \frac{dU_1}{d\tau} \tag{1}
\]

\[
c_2 \rho_2 \frac{\partial T_2}{\partial \tau} = \lambda_2 \frac{\partial^2 T_2}{\partial x^2} - c_2 \rho_2 v_2 \frac{\partial T_2}{\partial x} + \alpha_2 (T_1 - T_2) + \alpha_3 (T_3 - T_2) + \epsilon_2 \rho_2 r_{21} \frac{dU_2}{d\tau}
\]

with initial.

\[
T_1(x,0) = T_{10}, \quad T_2(x,0) = T_{20} \tag{2}
\]

and boundary conditions for \( x = 0 \)

\[
T_1(0, \tau) = T_{10}, \quad T_2(0, \tau) = T_{20} \tag{3}
\]

and with \( x = L \)

\[
-\lambda_1 \frac{\partial T_1}{\partial x} + \alpha_4 (T_{3L} - T_1) = 0 \tag{4}
\]

\[
-\lambda_2 \frac{\partial T_2}{\partial x} + \alpha_5 (T_{3L} - T_2) = 0
\]

where \( T_1, T_2, T_3 \) - respectively, the temperature of the seeds, fibers, drying agent;

\( \lambda_i, c_i, r_{21} \) - temperature characteristics (i = 1) of fiber seeds (i = 2);

\( \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5 \) - heat transfer coefficients;

\( U_i \) - volumetric average moisture content of seeds and fiber (i = 1, 2);

\( L \) - drum length;

\( \tau \) - drying time;

\( T_{10}, T_{20}, T_{30} \) - initial temperatures of seeds, fiber and air.

If denote by \( \rho_B, \rho_C \) - the true density of the fiber and seeds, then the values \( \rho_1, \rho_2 \) can be calculated by the formulas

\[
\rho_1 = \delta \cdot \rho_C, \quad \rho_2 = (1-\delta)\cdot \rho_B, \quad \delta = \frac{V_1}{V}, \quad V = V_1 + V_2
\]

here \( V, V_1, V_2 \) - the volumes occupied by raw cotton, pulp and seeds in the drum.

Volumetric heat transfer coefficients \( \alpha, \alpha_1, \alpha_2 \) can be determined, if they are unknown, through the volumetric heat transfer coefficient \( \alpha \) between raw cotton and air using the formula:

\[
\alpha_2 = \frac{c_1 \cdot \rho_1}{c_1 \cdot \rho_1 + c_2 \cdot \rho_2} \cdot \alpha, \quad \alpha_1 = \frac{c_2 \cdot \rho_2}{c_3 \cdot \rho_3} \cdot \alpha_2, \quad \alpha_3 = \frac{c_2 \cdot \rho_2}{c_1 \cdot \rho_1 + c_2 \cdot \rho_2} \cdot \alpha
\]

In addition, the following relations are true:

\[
\overline{\alpha}_2 = \frac{\alpha_2}{\delta}, \quad \overline{\alpha}_3 = \frac{\alpha_3}{1-\delta}, \quad \alpha = \alpha_2 + \alpha_3 = \delta \cdot \overline{\alpha}_2 + (1-\delta) \cdot \overline{\alpha}_3
\]
where are the true $\overline{\alpha}_1$, $\overline{\alpha}_2$, $\overline{\alpha}_3$ heat transfer coefficients between the components of raw cotton and air.

In the system (1) - (4), changing the variables [7-12]

$$\overline{T}_i = T_i - T_{i0}, \quad i = 1, 2$$

we get the task:

$$c_1 \rho_1 \frac{\partial T_1}{\partial \tau} = \lambda_1 \frac{\partial^2 T_1}{\partial x^2} - c_1 \rho_1 \nu \frac{\partial T_1}{\partial x} + \alpha_1 (T_2 - T_1) + \alpha_2 T_1 + f_1(\tau)$$

$$c_2 \rho_2 \frac{\partial T_2}{\partial \tau} = \lambda_2 \frac{\partial^2 T_2}{\partial x^2} - c_2 \rho_2 \nu \frac{\partial T_2}{\partial x} + \alpha_2 (T_2 - T_1) + \alpha_3 T_2 + f_2(\tau)$$

with initial

$$T_1(x, 0) = 0, \quad T_2(x, 0) = 0$$

and boundary conditions

$$T_1(0, \tau) = 0, \quad T_2(0, \tau) = 0$$

$$-\lambda_1 \frac{\partial T_1(L, \tau)}{\partial x} + \alpha_4 (T_{3L} - T_{10} - T_1) = 0$$

$$-\lambda_2 \frac{\partial T_2(L, \tau)}{\partial x} + \alpha_5 (T_{3L} - T_{20} - T_2) = 0$$

where

$$f_1(\tau) = \varepsilon_1 \rho_1 r_{21} \frac{dU_1}{d\tau} + \alpha_1 (T_{20} - T_{10}) + \alpha_2 (T_3 - T_{10})$$

$$f_2(\tau) = \varepsilon_2 \rho_2 r_{21} \frac{dU_2}{d\tau} - \alpha_1 (T_{20} - T_{10}) + \alpha_3 (T_3 - T_{20})$$

We will solve the resulting problem by the variational-grid method, for which we choose the coordinate functions $\varphi_i(x), \quad i = 1, N$ so that they satisfy the main boundary condition $\varphi_i(0) = 0$. We will look for approximate solutions in the form:

$$T_1 = \sum_{k=1}^{N} A_k(\tau) \cdot \varphi_k(x), \quad T_2 = \sum_{k=1}^{N} B_k(\tau) \cdot \varphi_k(x)$$

where the coefficients of the differential equations:

$$\sum_{k=1}^{N} \alpha_{jk} \frac{dA_k}{d\tau} = \sum_{k=1}^{N} \beta_{jk} A_k + \sum_{k=1}^{N} \gamma_{jk} B_k + F_{1j}(\tau) \quad (5)$$

$$\sum_{k=1}^{N} \alpha_{jk} \frac{dB_k}{d\tau} = \sum_{k=1}^{N} \beta'_{jk} A_k + \sum_{k=1}^{N} \gamma'_{jk} B_k + F_{2j}(\tau)$$

with initial conditions

$$\sum_{k=1}^{N} \alpha_{jk} A_k(0) = 0, \quad \sum_{k=1}^{N} \alpha_{jk} B_k(0) = 0 \quad (6)$$

Where

$$\alpha_{jk} = \int_{0}^{L} \varphi_j(x) \cdot \varphi_k(x) dx, \quad \gamma_{jk} = \frac{\alpha_1}{c_1 \rho_1} \alpha_{jk}$$
\[
\beta_{jk} = \left[ \frac{\lambda_1}{c_1 \rho_1} \int_0^L f_j(x) \cdot \varphi_k(x) \, dx + \frac{\alpha_4}{c_1 \rho_1} \cdot \varphi_k(L) \cdot \varphi_j(L) + \frac{\alpha_2}{c_1 \rho_1} \cdot \alpha_j k + v_1 \right] \varphi_j(x) \cdot \varphi_k(x) \, dx
\]

\[
\gamma'_{jk} = \left[ \frac{\lambda_2}{c_2 \rho_2} \int_0^L f_j(x) \cdot \varphi'_k(x) \, dx + \frac{\alpha_5}{c_2 \rho_2} \cdot \varphi'_k(L) \cdot \varphi_j(L) + \frac{\alpha_3}{c_2 \rho_2} \cdot \alpha_j k + v_2 \right] \varphi_j(x) \cdot \varphi'_k(x) \, dx
\]

\[
\beta_{jk} = \frac{\alpha_1}{c_2 \rho_2} \cdot \alpha_j k, \quad F_1(\tau) = \frac{f_1(\tau)}{c_1 \rho_1} \int_0^L \varphi_j(x) \, dx, \quad F_2(\tau) = \frac{f_2(\tau)}{c_2 \rho_2} \int_0^L \varphi_j(x) \, dx
\]

Solving the system of ordinary differential equations (5) with initial conditions (6), we determine the temperature of the raw cotton components in the drying process.

3. Results and Discussions

As an example, drying of raw cotton in an experimental drum dryer installed at the Bozsky ginnery is considered. We studied raw cotton of machine harvest with an initial humidity of 13.35% and 27.4% at an air temperature of 1100 °C, 1500 °C, 2000 °C, with a capacity of 6 t/h, 10 t/h, 12 t/h. The changes in humidity and temperature of raw cotton and its components were determined throughout the experiment.

Figure 1. shows the calculated and experimental data on changes in the temperature of the fiber and seeds at an air temperature of 1100 °C, 2000 °C, productivity 12 t/h. and with an initial moisture content of raw cotton of 13.35%.

Moisture evaporation rates from raw cotton components were determined from the kinetics equation

\[
\begin{align*}
-\frac{dW}{d\tau} &= K(W - W_M) \\
W_{\tau = 0} &= W_0
\end{align*}
\]

Solving the problem we get

\[
W = W_M + \frac{W_E - W_M}{1 + K(W_E - W_M) \cdot \tau}
\]

\[
q = -\frac{dW}{d\tau} = K \cdot \left[ \frac{W_E - W_M}{1 + K(W_E - W_M) \cdot \tau} \right]^2
\]

Numerical calculations are carried out with the following values of the drying coefficients of seeds \(k_1\) and fiber \(k_2\):

\[
k_1 = \begin{cases} 0,028 \text{ min}^{-1} & \text{at } T_B = 1100^\circ C \\ 0,025 \text{ min}^{-1} & \text{at } T_B = 2000^\circ C \\ \end{cases}
\]

\[
k_2 = \begin{cases} 0,0024 \text{ min}^{-1} & \text{at } T_B = 1100^\circ C \\ 0,0083 \text{ min}^{-1} & \text{at } T_B = 2000^\circ C \\ \end{cases}
\]
An analysis of the results shows that the use of a direct-flow drum dryer with a constant coolant temperature increases the heating rate of raw cotton by 25-30%.

4. Conclusions
A comparison of the calculated and experimental data (Figure 1) indicates that the proposed method for calculating the temperature field of the components of raw cotton is sufficiently accurate (error not more than 5-6%) and reliably describe the process of moisture and heat transfer in raw cotton when drying in a direct-flow drum dryer with constant coolant temperature.
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