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THERMOSTABILIZATION AND DRYING OF COMPOSITE CHEMICAL FILAMENTS IN THE PROCESS OF PNEUMATIC TEXTURING

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A method of calculation of the output of a thermostabilization chamber in the process of drying of composite chemical filaments in pneumatic texturing is given.

The process of production of pneumotextured composite chemical filaments in pneumotexturing devices (PTDs) with the use of air heat fluxes occurs simultaneously with drying and thermostabilization [1]. The process of thermostabilization of filaments ensures a high quality of treatment: shrink resistance, stability to deformations, higher-than-average sorption capacity, wrinkle resistance, and strength. The duration of the process of heat treatment of filaments depends on the type of heat-transfer agent used and its temperature; the character of the fiber influences the duration of heat treatment only slightly.

In a PTD (Fig. 1), the prewetted filament interacts with a heated compressed air with a temperature t_a = 120–150°C and a pressure p = 0.35–0.55 MPa. The process of drying and thermostabilization represents a complex process of heat and mass exchange accompanied by the physicomechanical changes in the properties of the filament. Under these conditions, pneumatic texturing of wetted filaments may be considered as a process of high-rate drying of fine capillary-porous materials. As has been shown by the practice of drying of fine woven products and filaments, the process of dehydration occurs in the period of a constant rate of drying up to the equilibrium moisture content.

The heat-flux density for the period of a constant rate of drying (heat treatment) is determined by the following relation [2]:

$$q_1 = r\rho_0 R_V N \,. \tag{1}$$

The drying rate in the first period is found from the initial $\overline{U}_0$ and final $\overline{U}_{\text{fin}}$ or equilibrium $\overline{U}_{\text{eq}}$ moisture content of the filament over the period of heat treatment in the pneumotexturing chamber:

$$N = \frac{\overline{U}_0 - \overline{U}_{\text{fin}}}{\tau_1} \,. \tag{2}$$

The ratio of the volume of the filament to its surface is

$$R_V = \frac{V_{\text{fl}}}{F_{\text{fl}}} = \frac{M_{\text{fl}}}{\rho_0 \pi d_{\text{fl}} l_{\text{fl}}} \,, \tag{3}$$

where $M_{\text{fl}} = V_{\text{fl}}\rho_0$ is the mass of the filament.

Equation (1) with account for expressions (2) and (3) has the following form:

$$q_1 = \frac{M_{\text{fl}}}{\tau_1} r \frac{\Delta\overline{U}}{\pi d_{\text{fl}} l_{\text{fl}}} \,. \tag{4}$$

The ratio M_{fl}/τ_1 represents the output of the PTD as far as the pneumotextured filament is concerned. We denote it by G_{fl}; then Eq. (4) will take the form

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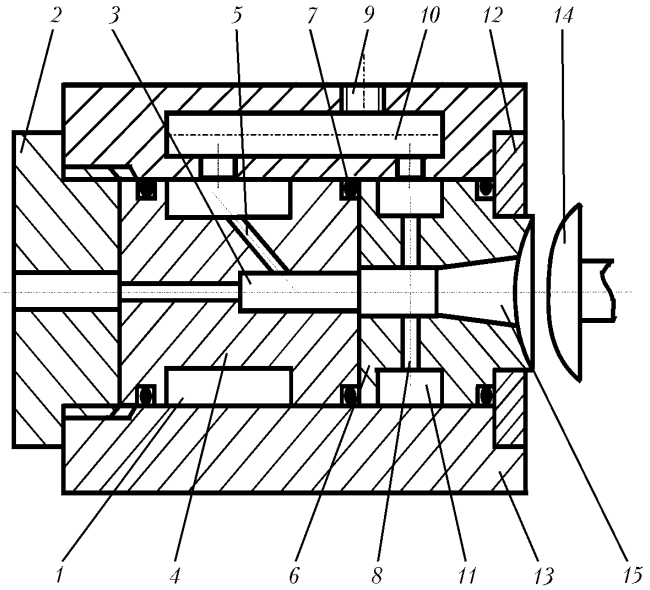

Fig. 1. Pneumotexturing device (PTD): 1) cavity for equalization of pressure; 2) nut; 3) transport chamber; 4) transport bushing; 5) sloping channel; 6) pneumotexturing bushing; 7) packing rings; 8) radial channels; 9) channel for supply of air; 10) annular gap; 11) cavity for equalization of pressure; 12) lock washer; 13) casing; 14) gate; 15) pneumotexturing chamber.

$$q_1 = G_{\text{fl}} r \frac{\Delta \overline{U}}{\pi d_{\text{fl}} l_{\text{fl}}} . \tag{5}$$

The heat-flux power supplied in a unit of thermal preparation of air is determined as

$$Q = M_{\text{a}} c_{\text{a}} (t_{\text{a}} - t_0) . \tag{6}$$

The equation of thermal balance for the PTD chamber may be written as follows:

$$Q = q_1 f_{\text{ch}} = M_{\text{a}} c_{\text{a}} (t_{\text{a}} - t_0) , \tag{7}$$

where $f_{\text{ch}} = \pi d_{\text{ch}}^2/4$ is the cross-sectional area of the PTD transport channel. Solving Eqs. (5) and (7), we obtain

$$G_{\text{fl}} = \frac{4 M_{\text{a}} c_{\text{a}} \Delta t}{d_{\text{ch}}^2} \frac{d_{\text{fl}} l_{\text{ch}}}{r \Delta \overline{U}} , \tag{8}$$

here $l_{\text{fl}} = l_{\text{ch}}$ is the filament length.

Equation (8) may be represented in the form

$$G_{\text{fl}} = \frac{4 f_{\text{ch}} W \rho_{\text{a}} c_{\text{a}} \Delta t}{r \Delta \overline{U}} \frac{d_{\text{fl}}}{d_{\text{ch}}^2} l_{\text{ch}} , \tag{9}$$

where $M_{\text{a}} = f_{\text{ch}} W \rho_{\text{a}}$ is the mass flow rate of the air.

Thus, the treated-filament mass output of the PTD chamber depends only on the geometric characteristics of the PTD, the flow rate of compressed air, and the thermophysical parameters of the heat-transfer agent.

The results of numerical solution of Eq. (9) were compared to the experimental data obtained in the process of pneumatic texturing of chemical filaments in drying and thermostabilization. A fairly good coincidence of the ex-

perimental results with the numerical solutions was observed throughout the range of operating parameters (the disagreement did not exceed 3–5% of deviations from experiment).

The velocity of the air flow in the PTD chamber and the air density are determined from the following relations:

$$W = \frac{4M_{\text{a}}}{\rho_{\text{a}} \pi d_{\text{ch}}^2}, \tag{10}$$

$$\rho_{\text{a}} = \frac{p_1}{R_{\text{a}} T_{\text{a}}}, \tag{11}$$

where R_{a} = 287 J/(kg·K) is the gas constant of the air and p_1 is the initial pressure of the compressed air.

The mass flow rate of the compressed air at the PTD-chamber inlet may be determined from the adiabatic conditions of the process of flowing of the air out of the high-pressure cavity into the low-pressure one:

$$M_{\text{a}} = f_{\text{a}} \mu \sqrt{2 \frac{k}{k-1} \frac{p_1}{\upsilon_1} \left[\left(\frac{p_2}{p_1} \right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1} \right)^{\frac{k+1}{k}} \right]}, \tag{12}$$

where μ is the flow coefficient of the PTD channel; it is determined by experiment ($\mu \approx$ 0.2–0.35).

In the low-pressure cavity of the PTD chamber, the pressure p_2 established in adiabatic outflow is such that the ratio p_2/p_1 becomes equal to the critical ratio $\beta_{\text{cr}} \approx$ 0.528, which is calculated as

$$\beta_{\text{cr}} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}}.$$

With allowance for this fact, it is more convenient to represent formula (12) in the form

$$M_{\text{a}} = \mu f_{\text{ch}} \frac{p_1}{\sqrt{T_{\text{a}}}} \sqrt{\frac{2k}{R_{\text{a}} (k-1)} \sqrt{\beta_{\text{cr}}^{2/k} - \beta_{\text{cr}}^{(k+1)/k}}}. \tag{13}$$

To create prescribed temperature regimes of compressed air we use the unit of thermal preparation of air, whose diagram is presented in Fig. 2.

A KR 220 quartz lamp of power 1 kW is used as the thermal radiator 3. The casing of the unit 5 is made in the form of a cylindrical surface (length L = 250 mm and diameter D = 50 mm) from a heat-resistant ceramic material. The end surfaces 1 of the casing are manufactured from a heat-resistant porous material (chamotte). The compressed air, traversing a spiral pneumoline manufactured from a material with a high thermal conductivity (copper), is heated to a prescribed temperature. The temperature regime is controlled by changing the voltage applied to the contacts 4 of the radiator 3. The heat insulation of the unit of thermal preparation of air is made from a material with a low thermal conductivity and is considered to be ideal. As follows from the figure, the process of heat exchange between the thermal radiator 3 and the compressed air in the pneumoline 2 follows the scheme of heat transfer. The transfer of heat from the radiator 3 to the pneumoline surface is by radiation, that via the casing of the tube is by conduction, and the transfer of heat from the tube surface to the compressed air is by convective heat exchange.

The heat flux supplied to the heated compressed air under stationary conditions is determined from the heat-transfer equation

$$Q = KF_{\text{pl}} (t_{\text{rad}} - t_{\text{a}}). \tag{14}$$

The area of the pneumoline heating surface is calculated as

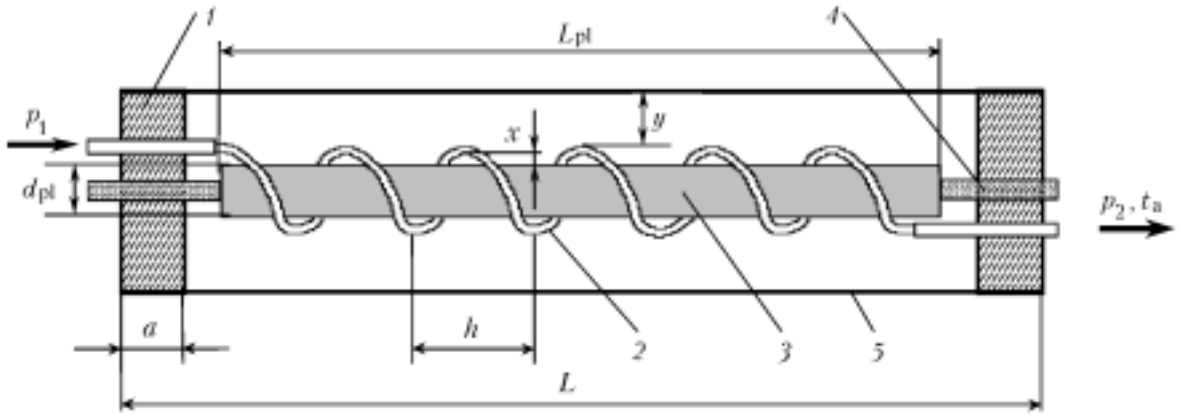

Fig. 2. Block diagram of the unit of thermal preparation of air.

$$F_{pl} = \pi d_{pl} L_{pl} . \tag{15}$$

In accordance with the diagram of the unit of thermal preparation of air (Fig. 2), the pneumoline length is

$$L_{pl} = n\,[2\pi\,(r_{rad} + x) + h]\,, \tag{16}$$

where r_{rad} is the radius of the radiator, m, x is the gap between the radiator and the pneumoline surface, h is the spiral pneumoline, and n is the number of turns.

The heat-transfer coefficient is determined from the relation

$$K = \frac{1}{\dfrac{1}{\alpha_{rad}} + \dfrac{\delta_{pl}}{\lambda_{pl}} + \dfrac{1}{\alpha_{conv}}} . \tag{17}$$

The thermal resistance δ_{pl}/λ_{pl} may be disregarded, since the thickness of the pneumoline wall is δ_{pl} = 0.5 mm and the thermal conductivity of copper is λ_{pl} = 380 W/(m^2·deg). Then formula (17) will take the following form:

$$K = \frac{\alpha_{rad}\alpha_{conv}}{\alpha_{rad} + \alpha_{conv}} . \tag{18}$$

It follows from Eq. (18) that the value of the heat-transfer coefficient K is always lower than the lowest of the values of α.

To determine the order of magnitude of the coefficients of heat transfer in the chamber of the unit of thermal preparation of air we used the well-known procedure of calculation of heat exchange by radiation and convection [3]. The coefficient of heat exchange in a closed space is computed from the equation

$$\alpha_{rad} = \varepsilon_{red} C_0 \frac{\left[\dfrac{T_{rad}}{100}\right]^4 - \left[\dfrac{T_a}{100}\right]^4}{T_{rad} - T_a} , \tag{19}$$

here C_0 = 5.67 W/(m^2·K^4) is the emissivity.

The reduced emissivity factor for heat exchange by radiation in a closed space is determined as

$$\varepsilon_{red} = \frac{1}{\varepsilon_1 + \dfrac{F_1}{F_2}\left(\dfrac{1}{\varepsilon_2} - 1\right)} , \tag{20}$$

where $\varepsilon_1 = 0.9$ is the emissivity factor of the quartz radiator, $\varepsilon_2 = 0.85$ is the emissivity factor of the oxidized copper, and F_1 and F_2 are the smaller and larger surfaces of the unit of thermal preparation of air.

To calculate convective heat exchange in the pneumoline of the unit of thermal preparation of air in the turbulent regime of motion we used the equation

$$\mathrm{Nu}_{\mathrm{liq}} = 0.018\mathrm{Re}_{\mathrm{liq}}^{0.8} . \tag{21}$$

In solving (21), we took the diameter of the pneumoline as the governing linear dimension and the temperature of the heated air as the governing temperature.

The analysis of the solutions of Eqs. (19) and (21) has shown that the order of values of the coefficients of heat exchange by radiation α_{rad} and convection α_{conv} in the pneumoline is the same. The heat-exchange coefficients took values of $\alpha_{\mathrm{rad}} \approx$ 80–120 W/(m^2·deg) and $\alpha_{\mathrm{conv}} \approx$ 90–150 W/(m^2·deg) throughout the range of variation of the compressed-air temperature from 60 to 150°C, the air velocity in the pneumoline $W \approx$ 25–75 m/sec, and the radiator-surface temperature from 500 to 650°C.

The high values of the convective component of heat exchange α_{conv} are attributed to the high velocities of motion of the compressed air. The intensity of heat exchange in traversal of the PTD by the filament for the period of a constant rate of drying with the simultaneous process of thermostabilization was calculated from the equation

$$q_1 = \alpha_{\mathrm{a}} (t_{\mathrm{a}} - t_{\mathrm{s}}) = \mathrm{Nu} \frac{\lambda_{\mathrm{a}}}{l_{\mathrm{ch}}} (t_{\mathrm{s}} - t_{\mathrm{s}}) . \tag{22}$$

The heat-exchange Nusselt number was determined from (21), where the length of the PTD transport channel (length of the treated filament) was taken as the governing dimension. The coefficient of heat transfer from the compressed air to the filament surface in the process of thermostabilization was

$$\alpha_{\mathrm{a}} = \mathrm{Nu} \frac{\lambda_{\mathrm{a}}}{l_{\mathrm{ch}}} . \tag{23}$$

The filament-surface temperature t_{s}, equal to the wet-bulb temperature t_{w}, was determined from the law of convective heat exchange

$$t_{\mathrm{s}} = t_{\mathrm{w}} = t_{\mathrm{a}} - \frac{q_1}{\alpha_{\mathrm{a}}} . \tag{24}$$

In calculations of the heat exchange in the unit of thermal preparation of air and in the PTD chamber, we must take into account that the heat-exchange coefficients will always have different values, since we have heat transfer in the first case and heat exchange complicated by mass exchange in the second case.

The above procedure of calculation of the PTD output under the conditions of wet and heat treatment makes it possible to determine the basic regimes of the process of pneumatic thermostructuring of chemical filaments with allowance for their properties and to calculate the unit of thermal preparation of air. The procedure may be used in designing the process of pneumatic thermostructuring of chemical filaments of different raw-material composition.

NOTATION

a, thickness of the end surface of the unit of thermal preparation of air, mm; c_{a}, heat capacity of air, J/(kg·deg); d_{ch}, diameter of the PTD transport channel, m; d_{fl}, diameter of the filament, m; d_{pl} and L_{pl}, diameter and total length of the spiral pneumoline, m; F_{fl}, area of the filament surface, m^2; F_{pl}, area of the pneumoline heating surface, m^2; $G_{\mathrm{fl}} = M_{\mathrm{fl}}/\tau_1$, output of the thermostabilization chamber, kg/sec; *k*, adiabatic exponent for air; *K*, coefficient of heat transfer from the radiators to the air in the pneumoline, W/(m^2·deg); *L* and *D*, length and diameter of the unit of thermal preparation of air, mm; $l_{\mathrm{ch}} = l_{\mathrm{fl}}$, governing dimension, m; l_{fl}, length of the filament in the thermostabilization chamber, m; $N = d\bar{U}/d\tau$ = const, drying rate in the first period; Nu, Nusselt number; *p*, pressure, MPa;

Q, power of the heat flux in the unit of thermal preparation of air, W; q_1, heat-flux density for the period of a constant rate of drying (heat treatment), W/m^2; r, specific heat of vaporization, kJ/kg; R_a, gas constant of air, J/kg·deg); Re, Reynolds number; R_V, ratio of the body's (filament) volume to the filament-surface area, m; T, absolute temperature, K; t_0 and t_a, initial and final temperature of the heated air, ^{o}C; t_{rad}, surface temperature of the radiator in the pneumoline, ^{o}C; t_w, wet-bulb temperature, ^{o}C; $\bar{U}$, moisture content; $\bar{U}_0$ and $\bar{U}_{fin}$, initial and final moisture content of the filament; V_{fl}, volume of the filament, m^3; W, velocity of air in the PTD channel, m/sec; y, size of the annular gap between the wall of the unit of thermal preparation of air and the spiral pneumoline; α, heat-exchange coefficient; β_{cr}, critical ratio of the pressures p_2/p_1; δ_{pl}/λ_{pl}, thermal resistance of the copper pneumoline, m^2·deg/W; ε_{red}, reduced emissivity factor; λ_a, thermal conductivity of air, W/(m^2·deg); ρ_0, density of a dry body, kg/m^3; ρ_a, density of compressed air; kg/m^3; τ_1, time of drying (heat treatment) of the filament, sec; υ_1, specific volume of compressed air at the pressure p_1, m^3/kg. Subscripts: cr, critical; pl, pneumoline; red, reduced; a, air; fl, filament; w, wet; fin, final; eq, equilibrium; s, surface; ch, channel; conv, convection; rad, radiator; liq, liquid.

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