q, heat flux density, W/m^2; R, radius, m; r, latent heat of crystallization, J/kg; r^*, latent heat of vaporization, J/kg; ΔT, superheat, K; W, volume, m^3; Π, porosity; Pm, permeability, m^2; α, heat-transfer coefficient, W/(m^2·K); β, angle of inclination of the pouring-channel system, deg; δ, thickness, m; θ, contact angle, deg; μ, viscosity, N·sec/m^2; σ, surface tension, N/m; ρ, density, kg/m^3; τ, time, sec. Indices: in, internal; ℓ, liquid; cn, condenser; cp, capillary-porous; mo, mold (crystallization); crt, critical; s, strip; co, cooling; v, vapor; cd, corrected; s.m, superheat of melt; m, melt; fi, fin; wa, wall.

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POSSIBILITY OF EXPANDING THE STABILITY DOMAIN OF THE FIBER DRAWING PROCESS

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UDC 532.51:532.522

It is shown that the fiber drawing process in the constant viscosity mode becomes more stable when the initial jet rate depends on the tensile force. In the particular case of a directly proportional dependence, the drawing process is stable for any values of the necking factor. Stability patterns of the process and amplitude-frequency characteristics are represented.

It is known that the fiber drawing process becomes unstable when the velocity coefficient (the ratio between the drawing velocity and the supply velocity) exceeds a certain critical value. Thus, the critical value of the rate coefficient is a quantity of the order of 20 [1, 2] for drawing in a constant viscosity mode. Because of buckling the drawing process goes over into a self-oscillatory mode for which the fiber output parameter can differ substantially from the given value. This phenomenon, called "drawing resonance" was detected both theoretically and experimentally [3-5]. However, processes realizable stably for significantly higher velocity ratios than that mentioned above are known in many technical applications. This turns out to be possible because of the action of a number of stabilizing factors in real processes. One such factor is the nonconstancy of viscosity along the jet due to the spatial inhomogeneity of its temperature. Another such factor, although

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less substantial than the first is the influence of the space-time jet velocity fluctuations on its temperature distribution due to heat transfer, and therefore, on the viscosity also.

In this paper we indicate the possibility of realizing still another substantial stabilizing factor, namely: The stability of the process is raised significantly if the supply velocity or drawing velocity depends on the drawing force. Moreover, in one particular case when the delivery velocity is directly proportional to the drawing force the process of drawing with a constant flow remains stable for any values of the rate factor. It is essential here that such drawing conditions, that raise its stability, be realizable easily by passive methods in practice, i.e., without utilization of performance mechanisms requiring external energy sources, and without information feedback channels. Let us note that in the case of fiber formation by a draw-plate method there is always an essential dependence of the initial jet velocity on the drawing force that results in a rise in process stability since the drawing force introduces a contribution to the pressure drop between the draw-plate input and output, which in turn governs the fluid mass flow rate through it.

In conformity with the above, we give the delivery velocity of the glass mass V_s as a linear function of the drawing force F

$$V_s = V_0 + \alpha F, \tag{1}$$

where V_0 and α are constants.

The equation and boundary conditions describing the fiber drawing process have the form [6-8]

$$Y_{ZZ}Y_t - Y_{Zt}Y_Z = \eta Y_Z F/S_0, \tag{2}$$

$$Y(Z, 0) = Y_i(Z),\ S_0 Y_Z(0, t) = S_i(t),\ Y_t(0, t)/Y_Z(0, t) = -V_s,$$
$$Y_t(L, t)/Y_Z(L, t) = -V_d,\ Z \in [0, L],\ t \in [0, \infty]. \tag{3}$$

Here $S_i(t)$, $V_s(t)$, $V_d(t)$ are functions describing the change with time in the initial section of the blank, the supply and drawing rates, respectively, S_0 is the transverse section area of the undeformed blank, $\eta(Z)$ is the glass mass flow, L is the length of the deformation zone, Y(Z, t) is a function designated "motion" [8]. The physical quantities being observed, V and S, the jet velocity and section, are expressed in terms of the function Y(Z, t) by means of the formulas

$$S = S_0 Y(Z),\ V = -Y_t/Y_Z. \tag{4}$$

Let us introduce dimensionless variables and parameters

$$Y^* = Y/L,\ Z^* = Z/L,\ t^* = tV_s^{st}/L,\ V^* = V/V_s,\ S^* = S/S_0,$$
$$F^*(t^*) = F(t)L\eta/V_s^{st}S_0,\ W = \ln(V_d/V_s^{st}),\ \alpha_1 = \alpha S_0/L\eta. \tag{5}$$

Here V_s^{st} is the stationary value of the supply rate. It is assumed in such a dimensionless formulation that by giving a certain supply rate V_s^{st} for the statinary mode, we select such α and V_0 in (1) that the selected V_s^{st} would satisfy this relationship for an appropriate value of the stationary force. The solution of (2) and the boundary conditions (3) for the stationary mode has the form [8]

$$Y^0(Z, t) = \int_0^Z \exp\left(\frac{\eta F_{st}}{S_0 V_s^{st}} - Z_1\right) dZ_1 - t,\ F_{st} = \frac{S_0 V_s^{st} W}{\eta L}. \tag{6}$$

Substituting (6) into (1), we obtain that α_1 from (5) should be determined from the relationship

$$\alpha_1 = (V_s^{st} - V_0)/(V_s^{st} W), \tag{7}$$

from which it follows that the value $\alpha_1 = 1/W$ corresponds to the case $V_0 = 0$.

Representing the function Y(Z, t) in the form of the sum of its stationary value Y_0 and the nonstationary perturbing addition P(Z, t) multiplied by the smallness parameter ε (here and henceforth we omit the asterisk in writing the dimensionless quantities), we obtain

$$Y(Z,\ t)=Y_0+\varepsilon P(Z,\ t). \tag{8}$$

Substituting (8) into (2), after linearizing we obtain an equation describing the perturbation of the stationary drawing mode

$$\exp(WZ)P_{ZZ}+W\exp(WZ)P_Z+P_{Zt}+WP_t=-\mu(t),\ 0\leqslant Z\leqslant 1, \tag{9}$$

where μ(t) is a function describing the perturbation of the drawing force.

The general solution of (9) is obtained in [8] and has the form

$$P(Z,\ t)=\exp(-WZ)\int\limits_0^Z\left[f\left(\frac{1}{W}\exp(-Wx)_t t\right)-\int\limits_0^t\mu(y)\,dy\right]\exp(Wx)\,dx+\exp(-WZ)\,c(t), \tag{10}$$

where μ, c, f are unknown functions that are determined from the boundary conditions.

Let us examine the problem of the stability of the stationary fiber formation process that is given by the following initial and boundary conditions

$$\begin{gathered}P(Z,\ 0)=P_0(Z),\ P_Z(0,\ t)=0,\ P_t(0,\ t)=-\alpha_1\mu(t),\\ P_t(1,\ t)=-\exp(W)P_Z(1,\ t),\end{gathered} \tag{11}$$

here the function $P_0(Z)$ describes the perturbation of the initial stationary state.

Satisfying the solution (10) by the first three boundary conditions (11) we obtain

$$P(Z,\ t)=\begin{cases}\exp(-WZ)\int\limits_0^Z\left\{WP_0[\varphi(y,\ t)]+\dfrac{\partial P_0[\varphi(y,\ t)]}{\partial y}\right\}\exp(Wy)\,dy+\\ +\dfrac{(1-W\alpha_1)\exp(-WZ)-1}{W}\int\limits_0^Z\mu(s)ds,\ 0\leqslant t\leqslant\dfrac{1-\exp(-WZ)}{W},\\ \exp(-WZ)(1-\alpha_1W)\int\limits_0^Z\left[\int\limits_0^{\frac{\exp(-Wy)-1}{W}+t}\mu(s)\,ds\right]\exp(Wy)\,dy+\\ +\dfrac{(1-\alpha_1W)\exp(-WZ)-1}{W}\int\limits_0^t\mu(s)\,ds,\quad t\geqslant\dfrac{1-\exp(-WZ)}{W},\end{cases} \tag{12}$$

$$\varphi(y,\ t)=-\frac{1}{W}\ln[\exp(-Wy)+Wt],\ P(0)=P_0^{\prime}(0)=0.$$

As is customary in stability theory, we examine the asymptotic of the evolution of a certain initial perturbation $P_0(Z)$ in time and we determine the value of the modal parameters for which the process of fiber formation is stable.

Substituting (12) in the fourth boundary condition (11), after manipulation we obtain an integral equation in the function μ:

$$(1-\alpha_1W)\int\limits_{\frac{\exp(-W)-1}{W}}^{0}\left[\frac{\exp(-W)}{(Ws+1)^2}-\frac{1}{Ws+1}\right]\mu(s+t)\,ds=\frac{1-\exp(-W)[1-\alpha_1W]}{W}\mu(t). \tag{13}$$

Following the normal mode method, we represent the desired function μ in the form

$$\mu(t)=\mu_0\exp(\sigma t),\ \sigma=\xi+i\omega,\ \mu_0=\text{const}. \tag{14}$$

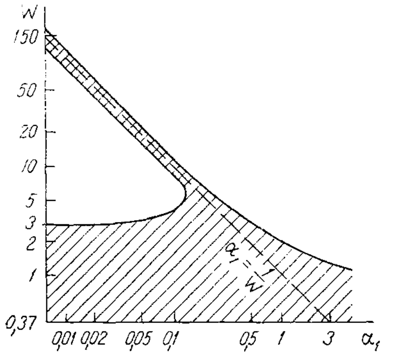

Fig. 1. Stability domain of the process for $V_S = V_0 + \alpha F$.

Substituting (14) into (13) and separating real and imaginary parts of the equation, we obtain a system of transcendental equations in ξ and ω. The roots ξ_0, ω_0 of this system govern the damping and frequency of the appropriate modes. To establish the critical values of the parameters governing the passage of the process from the stable to the unstable mode (ξ changes sign here), we set $\xi = 0$. Consequently, we obtain the following system of transcendental equations

$$\int\limits_{\frac{\exp(-W)-1}{W}}^{0} \left[\frac{\exp(-W)}{(Ws+1)^2} - \frac{1}{Ws+1}\right] \cos \omega_0 s ds = \frac{\exp(-W)[\alpha_1 W - 1] + 1}{W(1-\alpha_1 W)},$$
$$\int\limits_{\frac{\exp(-W)-1}{W}}^{0} \left[\frac{\exp(-W)}{(Ws+1)^2} - \frac{1}{Ws+1}\right] \sin \omega_0 s ds = 0, \tag{15}$$

that can be solved for ω_0 and W. The least of the roots W of this system determines the critical value of W for which buckling of the stationary drawing mode occurs.

Let us note that the system (15) degenerates for $\alpha_1 = 1/W$. To obtain the answer to the question about the stability of the process we again turn to (12) in this case. Substituting $\alpha_1 = 1/W$ therein and determining μ from the fourth boundary condition of (11), we obtain

$$P(Z, t) = \begin{cases} \exp(-WZ) \int\limits_0^Z F(y, t) \exp(Wy)\, dy - \int\limits_0^t \int\limits_0^1 \left[\left(\frac{\partial F(y, s)}{\partial s} \exp(-W) - \right.\right. \\ \left.\left. - WF(y, s) \exp(Wy)\right) dy + \exp(W) F(1, s)\right] ds, \\ 0 \leqslant t \leqslant \frac{1-\exp(-W)}{W}, \\ 0, \quad t \geqslant \frac{1-\exp(-W)}{W}, \end{cases} \tag{16}$$

where $F(y, s) = \frac{\partial P_0[\varphi(y, s)]}{\partial s} + WP_0[\varphi(y, s)]$.

Hence it is seen that for any perturbation of the initial state, the perturbations it caused in the drawing process would seem to be "contracted" with the jet in a time not exceeding $(1 - \exp(-W))/W$. Therefore, any initial perturbations of the process vanish in a finite time for any W and, therefore, the process remains absolutely stable on a curve described by the equation $\alpha_1 = 1/W$ in the plane (α_1, W). The boundaries of the whole stability domain in this plane are determined from the solution of the system (15), as has already been mentioned.

The domain of the parameters α_1, W, in which the drawing process remains stable (shaded domain) is represented in a logarithmic scale in Fig. 1. The line $\alpha_1 = 1/W$ is superposed by dashes. As is seen from the figure, for small W the stability domain extends from zero values of α_1 far beyond the absolute stability line. As W grows the stability domain is compressed and drawn out in the form of a narrow strip (in the logarithmic scale) along the line $W = 1/\alpha_1$. In this domain ($W \geq 7$) the stability domain boundaries are described approximately by the following expressions

$$W = 1{,}17/\alpha_1, \; W = 0{,}86/\alpha_1. \tag{17}$$

Let us note that for $\alpha_1 \simeq 0.13$ the drawing process remains stable for any $W \leq 8.6$ while for every $\alpha_1 \leq 0.13$ two stability domains in W exist that can provisionally be called normal and anomalous. The normal stability domain boundaries in W extend from zero to values close to the classical stability boundary for an isothermal drawing process ($W = 3$) and weakly dependent on α_1. The anomalous stability domain lies near $W = 1/\alpha_1$ and its boundaries are determined by (17). For the case of drawing from a cylindrical draw-plate, it can be shown that in the case of constant viscosity the parameter α_1 is determined entirely by the draw-plate geometry and the length of the deformation zone by the relationship

$$\alpha_1 = 3r_0^2/8Ll,$$

where r_0, ℓ are the draw-plate radius and length. Consequently, even for large W, we obtain a stable drawing mode with constant viscosity by selecting the parameters so as to satisfy

$$1{,}17 \geqslant \frac{3Wr_0}{8Ll} \geqslant 0{,}86.$$

In connection with the fact that the drawing process in which $\alpha_1 = 1/W$ is stable, investigation of the reaction of the process to technological parameter perturbation is of interest. This class of problems is described by the following boundary conditions

$$P_Z(0, t) = \varphi(t), \; P_t(0, t) = -\varphi(t) - \mu(t)/W,$$
$$P_t(1, t) = -\exp(W) P_Z(1, t) - \varkappa(t). \tag{18}$$

Here $\varphi(t)$, $\kappa(t)$ are functions of the time that describe perturbations of the initial transverse section and the drawing rate.

Let us consider the reaction of the process to a perturbation in the drawing rate ($\varphi = 0$). Satisfying the solution (10) by the boundary conditions (18), we obtain

$$P(Z, t) = -\exp(-W) \int_0^t \mu(s)\, ds. \tag{19}$$

Since the function P defined by the equality (19) is independent of the space variable Z, then according to (4) and (8) we obtain

$$\delta S = 0.$$

This means that although the drawing rate fluctuations indeed occur they result in such synchronized changes in the supply rate because of the natural feedback through the drawing force according to the relationship $V_S = \alpha F$ that the output section does not change. Therefore, the case with zero parameter V_0 in (1), being special in the absolute stability sense, is moreover still insensitive to drawing rate perturbations.

Let us determine the fiber output section perturbations in the case of fluctuations in the initial section of the glass blank ($\kappa = 0$). Using the first two boundary conditions in (17), we obtain

$$P(Z, t) = \exp(-WZ) \int_{t+\frac{\exp(-WZ)-1}{W}}^{t} \left[\varphi(x) - W \int_0^x \varphi(s)\, ds\right] \frac{dx}{[W(x-t)+1]^2} -$$
$$- \int_0^t \left[\exp(-WZ)\varphi(s) + \frac{\mu(s)}{W}\right] ds. \tag{20}$$

It follows from (20) that perturbations of the jet output diameter in the case of initial section fluctuations are independent of drawing force oscillations that are felt only in

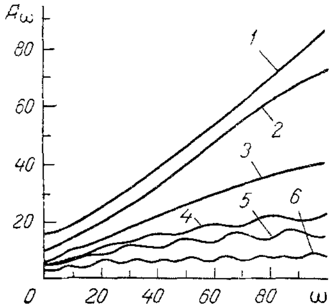

Fig. 2

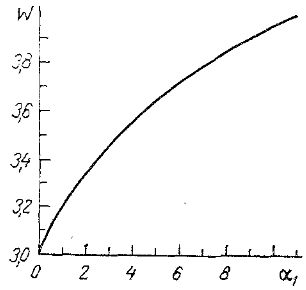

Fig. 3

Fig. 2. Amplitude–frequency characteristics for different W in the case of periodic initial section perturbations: 1, 2, 3, 4, 5, 6) W = 15, 10, 5, 3.5, 3, 2, respectively.

Fig. 3. Stability domain of the process for $V_d = V_0 - \alpha F$.

the velocity perturbations. Differentiating (20) with respect to the space coordinate and setting Z = 1, we write

$$\delta S = P_Z(1, t) = \varphi\left[t + \frac{\exp(-W) - 1}{W}\right] + W\exp(-W)\int_0^t \varphi(s)\,ds - $$
$$- W \int_0^{t + \frac{\exp(-W)-1}{W}} \varphi(s)\,ds - W\exp(-W) \times \tag{21}$$
$$\times \int_{t + \frac{\exp(-W)-1}{W}}^{t} \left[\varphi(s) - W\int_0^s \varphi(x)\,dx\right] \frac{ds}{[W(s-t)+1]^2}.$$

Using the solution (21) we determine the reaction of the fiber formation process to periodic perturbations of the initial transverse section. To do this, we represent the functions P(Z, t) and φ (t) in the form

$$\varphi(t) = \exp(-i\omega t),\ P(Z, t) = \exp(-i\omega t),\ F(Z) = F_1(Z) + iF_2(Z). \tag{22}$$

Substituting (22) into (21) and separating real and imaginary parts of the expression obtained, we find

$$F_1'(1) = \exp(-W) + \exp(-W)A(\omega)\int_{\frac{\omega}{W}\exp(-W)}^{\frac{\omega}{W}} \frac{\sin x}{x}\,dx +$$
$$+ \exp(-W)B(\omega)\int_{\frac{\omega}{W}\exp(-W)}^{\frac{\omega}{W}} \frac{\cos x}{x}\,dx, \tag{23}$$

$$F_2'(1) = \exp(-W)A(\omega)\int_{\frac{\omega}{W}\exp(-W)}^{\frac{\omega}{W}} \frac{\cos x}{x}\,dx - \exp(-W)B(\omega)\int_{\frac{\omega}{W}\exp(-W)}^{\frac{\omega}{W}} \frac{\sin x}{x}\,dx,$$

where

$$A(\omega) = \exp(-W)\left[\sin\frac{\omega}{W} + \frac{\omega}{W}\cos\frac{\omega}{W}\right],$$
$$B(\omega) = \exp(-W)\left[\cos\frac{\omega}{W} - \frac{\omega}{W}\sin\frac{\omega}{W}\right].$$

The results of the solution are represented in the form of amplitude—frequency characteristics that describe the ratio between the amplitude of the relative jet output section perturbations and the amplitude of the relative initial transverse section perturbations

$$A_\omega = \left| \frac{\partial S_{out}/S_{out}}{\partial S_{in}/S_{in}} \right| = \exp(W) \sqrt{F_1^2(1) + F_2^2(1)}\,. \tag{24}$$

There follows from an analysis of the solutions (23) in the case $\omega/W \ll 1$ that

$$A_\omega = \sqrt{(W+1)^2 + \omega^2}\,. \tag{25}$$

The expression (25) yields the gain coefficient of the jet output section fluctuation amplitude in the low frequency domain $\omega \le 10^{-3}$ Hz, most characteristic for the case of perturbation of the blank section. The results of computing A_ω for different W are displayed in Fig. 2. It is seen from the figure that as the rate coefficient increases the reaction to the initial section perturbation grows. Let us note that for $W \ge 5$ the dependence of A_ω on the frequency ω is practically linear. A numerical computation showed that for these values of W the linearity is not spoiled up to $\omega = 5000$ (50 Hz). As W ($W < 4$) diminishes the amplitude—frequency characteristics are explicitly nonlinear in nature, here the process reaction to the initial section perturbatins diminishes. Let us note that the peak AFC (amplitude—frequency characteristic) values are independent of the perturbation frequency for $W \le 3$.

Investigation of the stability of the process in which the drawing rate also depends on the drawing force

$$V_d = V_0 - \alpha F,\ V_0,\ \alpha - \text{const} \tag{26}$$

is of interest. In this case the boundary conditions have the form

$$P_Z(0,\ t) = 0,\ P_t(0,\ t) = 0,\ P_t(1,\ t) = -\exp(W) P_Z(1,\ t) + \alpha_1 \mu(t). \tag{27}$$

The solution (10) that satisfies the first two boundary conditions in (27), has the form

$$P(Z,\ t) = a + \frac{1}{W} \int\limits_t^{t + \frac{\exp(-WZ)-1}{W}} \mu(s)\,ds - \frac{\exp(-WZ)}{W} \int\limits_t^{t + \frac{\exp(-WZ)-1}{W}} \frac{\mu(s)\,ds}{W(s-t)+1}\,. \tag{28}$$

Substituting (28) into the third boundary condition in (27), using the representation (14), we obtain a characteristic system of transcendental equations for the spectrum of the eigenvalues ξ and ω:

$$\int\limits_{\frac{\exp(-W)-1}{W}}^{0} \left[\frac{\exp(-W)}{(Wy+1)^2} - \frac{1}{Wy+1} \right] \exp(\xi,\ y) \cos \omega y\,dy = \frac{1 + \alpha_1 W - \exp(-W)}{W}\,,$$

$$\int\limits_{\frac{\exp(-W)-1}{W}}^{0} \left[\frac{\exp(-W)}{(Wy+1)^2} - \frac{1}{Wy+1} \right] \exp(\xi y) \sin \omega y\,dy = 0. \tag{29}$$

The result of a numerical computation are represented in Fig. 3. There follows from the graph of the dependence of the critical values of the rate coefficient W on the parameter α_1 that the stabilizing effect is very much weaker in this case than when utilizing the boundary conditions (1). It is seen from (29) that as α_1 grows the domain of W for which the drawing process is stable is expanded and an α_1 can always be found for which drawing can be performed in a stable mode for any given W. However, the technical realization of such a process is made difficult because of the high values of the parameters V_0 and α_1 because of the weak dependence of W on α_1.

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THIXOTROPIC PROPERTIES OF ELECTRORHEOLOGICAL SUSPENSIONS IN CONTINUOUS DEFORMATION

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UDC 665.45:532.135

The article studies the peculiarities of the mechanical behavior of suspensions, structure-sensitive to electrical effects, in steady and transient regimes under continuous shear strain. It was found that the destruction of the structural carcass is preceded by an induction period, and the dependence of its time on the shear stress is described by the ratio between time to rupture and load for solids.

The authors of [1-4] showed that on the basis of the electrorheological effect (ERE) it is possible to devise various kinds of devices and elements: relays, regulators, adjusting mechanisms, dampers, braking devices, locking devices, stopping elements of hydraulic systems, electromotors, kilovoltmeters, resonators, etc. The use of the ERE for fastening mechanically unstable, pliable, weak materials to be machined, which are widely used in practice [5], is extremely important in machine and instrument construction.

At the Institute of Heat and Mass Exchange extensive research has been carried out for the last 35 years to determine the suitability of dielectric disperse systems to respond to electric impulses [6-9]. The investigations were complex and concerned a wide range of problems, aiming at the discovery of the inherent regularities of ERE and at working out physical concepts of its nature. It was shown that the magnitude and kinetic traits of the ERE are determined by the structural and rheological state of the medium. This state is characterized by the number of particles of the solid phase included in the interaction, by the detectability of the structure, the strength of the necks determined by a certain magnitude of mutual adhesion of particles and adhesion to the electrodes, and also by the length of their existence [7-9].

The regularities of the effect of an electric field on the processes of transfer in electrorheological suspenisons (ERS) were studied by many authors [6, 10-14], the research being carried out with the aid of capillary, rotational, and vibration viscometers. The following features were discovered: nonlinearity of the hydraulic characteristics of flow rate vs. head in an electric field, pseudoplastic behavior of the medium, an increase of the effective viscosity and of the modulus of elasticity by several orders of magnitude, the appearance of initial shear stress on the flow curves.

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