FLUID DYNAMICS AND MASS TRANSFER IN THE FORMATION OF FIBERS

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UDC 532.522:532.135

A theory of the process of wet fiber formation is constructed. Calculated results are compared with experimental data.

In the wet method of fiber formation, a polymer solution is fed through a spinnerette. The polymer emerges from the spinnerette in the form of filaments, which then enter a bath filled with a low-molecular-weight precipitant and a solvent (such as water and sulfuric acid, in the case of fibers of polyoxadiazole). The filaments harden as a result of a change in the composition of the polymer system during counter diffusion of the precipitant and solvent. Here, the precipitant enters the filament material from the bath, while the solvent diffuses into the bath. When the concentration of precipitant inside the filaments reaches a certain value, the polymer system begins to coagulate. The high-polymer phase formed as a result of coagulation flows poorly due to its high viscosity. This leads to the appearance of a hardened layer on the surface of the filament, accompanied by a sharp change in the rheological properties of the fibers and an increase in the variation of these properties over the fiber cross section. The stretching of the fibers has nearly ceased, and they are wound about the receiving roller.

Several monographs [1, 2] have studied – at least quantitatively – many general principles underlying the formation of chemical fibers. However, the quantitative theory of the process remains in need of further development. For example, in theoretical studies of the flow during wet formation [3, 4], investigators used empirical dependences of the viscosity of the filament on the concentration of the precipitant diffusing inside it. Such depenences do not as a whole reflect the physics of the given process. Our goal here is to construct a substantiated physical theory of fiber formation by the wet method.

The rate of coagulation is fairly high for the wet method of fiber formation, and it can be assumed that coagulation occurs almost instantaneously after the precipitant reaches critical concentration in the fiber [5]. Given a sufficiently high concentration of precipitant in the bath, a rigid shell of coagulated polymer appears in the surface layers of the fiber immediately after the polymer leaves the spinnerette. Thus, in such "intensive" regimes of spinnerette extrusion, the growing shell of the fiber is deformed in the bath. This deformation completely determines the tensile force on the forming filament. Meanwhile, the liquid core of the filament remains nearly unstressed. The resulting structure of such fibers is quite nonuniform and is undesirable. As an example, in the formation of fibers from a 5.3% solution of poly-p-phenylene-oxadiazole (POD) in 98% sulfuric acid in precipitating baths containing mixtures of sulfuric acid (solvent) and water (precipitant), "intensive" formation regimes occur at an H_2SO_4 content (by wt.) from 0 to 40%, i.e., at precipitant concentrations greater than 60%.

In "mild" regimes, when the concentration of precipitant in the bath is fairly low, a stable shell appears on the surface of the filament only at a certain distance from the spinnerette, and there is a lengthy liquid section of fiber in which there is appreciable tension of the polymer solution. The tension ends with the appearance of the solid sheath, which undergoes almost no deformation at the values of longitudinal load typical of the fiber-forming operation. Thus, for the example examined above involving the formation of fibers from a POD solution, the liquid section of filament near the spinnerette appears at H_2SO_4 concentrations exceeding 40% (less than 60% precipitant in the bath). The presence of the liquid section sharply reduces the tensile force on the filament and significantly increases the maximum polymer extraction [6, 7]. In this case, the structure of the fiber is more uniform than in "intensive" regimes.

Institute of Problems of Mechanics, Academy of Sciences of the USSR, Moscow. "Khimvolokno" Scientific-Industrial Association, Mytishchi. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 55, No. 1, pp. 50-59, July, 1988. Original article submitted February 9, 1987.

0022-0841/88/5501-0737 $12.50

Here, we will study only "mild" formation regimes. It is assumed that a stable shell is formed in the cross section of the filament at a certain depth under its surface. Here, deformation ceases and the coagulation rate is commensurate with the receiving rate. The polymer system remains liquid up to this section and its rheological charactristics remain constant.

The method of calculation being proposed here can also be used to describe the process of dry—wet formation, when the liquid polymer filament moves in an intervening layer of air between the spinnerette and the bath. The filament then hardens almost instantaneously as it enters the "hard" bath.

First let us examine the flow of concentrated solutions in the channels of a spinnerette (at $-\ell \le x \le -0$). For relatively short spinnerettes with a length/diameter ratio having the value $O(1)$, friction of the solution against the wall is negligible in a number of cases and the motion can be approximately characterized as quasiunidimensional flow under uniaxial tension. This approximation acquires greater validity if we consider the viscosity anomaly typical of viscoelastic spinning solutions. This anomaly has the effect of reducing friction against the wall. The velocities of spinning solutions are low in wet-forming and the inertial forces can be ignored compared to the internal forces in the liquid due to the entropy-related elasticity of the polymer macromolecules. Thus, the balance equation for the momentum of the polymer solution during flow in a spinnerette with the cross section $f(x)$ will be

$$\frac{d}{dx}[(-p+\tau_{xx})f]+p\frac{df}{dx}=0. \tag{1}$$

The channels in the spinnerette are circular in cross section.

In the steady-state case being examined here, the steady-state flow rate in the channel does not change. Thus

$$Vf=q=\text{const}. \tag{2}$$

Now let us proceed to description of the motion of the spinning solution in the forming fiber after it leaves the spinnerette. In the wet method of forming, the tensile force on the fiber may change along the path of its formation. Such a change will be due mainly to the viscous friction created by the contents of the precipitate bath. Wet formation is characterized by low fiber velocities (~0.1 m/sec) and a ratio of the viscosity of the polymer solution to the viscosity of the bath liquid on the order of 10^5. As was shown in [6], the length of the liquid section of fiber is on the order of one-tenth of the path traveled by the fiber in the precipitation bath, i.e., on the order of 0.1 m. Given these conditions, estimation of the friction acting on the liquid part of the fiber from the side of the bath contents yields a value which is more than an order lower than the longitudinal force in the fiber. Thus, in calculating flow in the liquid part of the fiber, we will ignore friction. As a result, the motion of the liquid in the fiber can be examined in a quasiunidimensional approximation [8], ignoring the change in velocity across the fiber. Following custom and also ignoring inertia and interfacial energy, we obtain the momentum balance in the liquid part of the fiber

$$\frac{d}{dx}[(-p+\tau_{xx})f]=0,\quad -p+\tau_{yy}=0, \tag{3}$$

from which

$$f\sigma_{xx}=f(\tau_{xx}-\tau_{yy})=F=\text{const}, \tag{4}$$

with the cross-sectional area of the fiber to be determined in the course of the solution of the problem.

Assuming the volume flow rate of polymer solution to be constant on the liquid section of the fiber being examined — in accordance with the experimental data in [6] — we write the quasiunidimensional mass balance inside the fiber in the form (2). It should be noted that the cross section of the fiber is assumed to be circular and the flow is assumed to be steady.

In contrast to the case of formation from a melt – where the increase in viscosity during fiber cooling is usually greater than the elastic stresses in the liquid (which in several cases makes it possible to restrict investigation to a Newtonian rheological model) – in wet-forming the flow is generally isothermal not only in the spinnerette channels, but also in the fibers. Here, the question of describing the rheological behavior of the solution becomes of fundamental importance. The rates of deformation (tension) during flow in the spinnerette channels are high – on the order of 10^2 1/sec – while the residence time of a fluid particle in the constricted part is ~10^{-2} sec. The rates of deformation in the fiber are relatively low (~1 1/sec), while the characteristic time of deformation is ~1 sec. Under such conditions, the tension of the macromolecular chains in the channel [9] and the associated increase in internal stresses in the polymer liquid are important, as is the diffusion of the macromolecules [9, 10]. The study [11] derived the governing rheological equations, making it possible to describe flow with intensive strains leading to stretching of the macromolecular chains in the spinnerette. The equations simultaneously describe the effect of diffusion of the macromolecules and can be written in the form

$$\frac{d\boldsymbol{\tau}}{dt} = \nabla\mathbf{v}\cdot\boldsymbol{\tau} + \boldsymbol{\tau}\cdot\nabla\mathbf{v}^T + \frac{2}{3}G_0\mathbf{D} - \frac{1}{\tau_B}(\boldsymbol{\tau} - \boldsymbol{\tau}_2) - \frac{\boldsymbol{\tau}}{\tau_C}, \tag{5}$$

$$\boldsymbol{\tau}_2 = \frac{G_0}{\tau_C}\int\limits_{-\infty}^{t} d\tau \exp\left(-\frac{t-\tau}{\tau_C}\right)\left[\mathbf{Q}(\tau,\ t) - \frac{\mathbf{I}}{3}\right], \tag{6}$$

$$\mathbf{Q} = \int \frac{d^2\mathbf{u}_0}{4\pi}\left\{\frac{[\mathbf{F}_\tau(t)\cdot\mathbf{u}_0]\,[\mathbf{F}_\tau(t)\cdot\mathbf{u}_0]}{|\mathbf{F}_\tau(t)\cdot\mathbf{u}_0|^2}\right\}.$$

Equations (5) and (6) generalize the Doi–Edwards governing rheological relation [10] (in the one-mode variant) to the case of intensive strains leading to stretching of macromolecular chains in the spinnerette.

Here, it is assumed that the moment of the beginning of deformation of a fluid particle (at the inlet of the spinnerette channel) corresponds to t = 0.

Equations (5) and (6) were obtained in [11] on the basis of the macromolecular dynamics of concentrated polymer systems. The relaxation times τ_C and τ_B entering into these equations are related by the equality $\tau_C = 3N\tau_B$. The number of subchains in a macromolecule N depends on the number of bonding points in the macromolecule, which is in turn dependent on the solution concentration.

In a quasiunidimensional approximation, the fluid particle undergoes tension both in the channel and in the fiber. Thus, the components of the tensor Q needed for calculations using (6) have the form:

$$\begin{gathered} Q_{xx} = \frac{\lambda^3}{\lambda^3 - 1}\left(1 - \frac{\operatorname{arctg}\sqrt{\lambda^3 - 1}}{\sqrt{\lambda^3 - 1}}\right), \\ Q_{yy} = \frac{\operatorname{arctg}\sqrt{\lambda^3 - 1}}{2\sqrt{\lambda^3 - 1}} - \frac{1}{2(\lambda^3 - 1)}\left[1 - \frac{\operatorname{arctg}\sqrt{\lambda^3 - 1}}{\sqrt{\lambda^3 - 1}}\right], \quad \lambda = \frac{V(t)}{V(\tau)}. \end{gathered} \tag{7}$$

In the spinnerette channels, the stresses are calculated by integrating differential equations obtained from (5):

$$\begin{gathered} V\frac{d\tau_{xx}}{dx} = 2\tau_{xx}\frac{dV}{dx} + \frac{2}{3}G_0\frac{dV}{dx} - \frac{1}{\tau_B}(\tau_{xx} - \tau_{2xx}) - \frac{\tau_{xx}}{\tau_C}, \\ V\frac{d\tau_{yy}}{dx} = -\tau_{yy}\frac{dV}{dx} - \frac{G_0}{3}\frac{dV}{dx} - \frac{1}{\tau_B}(\tau_{yy} - \tau_{2yy}) - \frac{\tau_{yy}}{\tau_C}, \end{gathered} \tag{8}$$

where the velocity V is known from (2) [since f(x) is assigned in the channel].

At the channel inlet, at $x = -\ell$, we assume that $\tau_{xx} = \tau_{yy} = 0$.

The stresses up to the channel outlet (x = –0) are thus calculated.

Now let us examine the calculation of the flow in the fiber on the formation section. We use (2) and (4) to obtain

$$\tau_{xx}-\tau_{yy}=VF/q. \tag{9}$$

The stresses τ_{xx} and τ_{yy} and the velocity V are found by simultaneous solution of Eqs. (8) and (9) using (6) and (7). The calculations are performed by means of iterations up to self-consistency of the fields of τ_{xx}, τ_{yy}, and V.

In the quasiunidimensional model we are using, the expansion of the jet of solution (Barris effect) occurs instantaneously after the solution leaves the channel. In reality, the expansion occurs over a section of a length less than 10^{-3} m from the edge of the channel. Here, the total length of the liquid fiber-formation section is ~10^{-1} m, which fully justifies the use of the instantaneous expansion model adopted here. Consequently, calculation of flow in the filament at the formation stage is begun at the section x = +0, corresponding to the maximum expansion of the jets of solution after they leave the spinnerette channels.

Let us proceed to calculation of the parameters of the filament at x = +0. Assuming that df/dx = 0 at the end of the channel (near x = −0), we use Eqs. (1)-(3) and (5) to obtain the conservation conditions at the discontinuity corresponding to expansion of the filament upon discharge from the spinnerette:

$$[fV]_{x=-0}^{x=+0}=0,\qquad [(\tau_{xx}-p)f]_{x=-0}^{x=+0}=0,$$
$$\left[\left(\tau_{xx}+\frac{G_0}{3}\right)\frac{1}{V^2}\right]_{x=-0}^{x=+0}=0,\qquad \left[\left(\tau_{yy}+\frac{G_0}{3}\right)V\right]_{x=-0}^{x=+0}=0. \tag{10}$$

From here, we use Eqs. (2) and (4) to obtain a cubic equation for determination of the velocity V_+ in the initial section of the filament:

$$\left(\frac{V_+}{V_-}\right)^3\left(\tau_{xx}^-+\frac{G_0}{3}\right)-\left(\frac{V_+}{V_-}\right)^2\frac{F}{f_-}-\left(\tau_{yy}^-+\frac{G_0}{3}\right)=0. \tag{11}$$

The values of the stresses τ_{xx}^- and τ_{yy}^- in the outlet section of the channel are known from the results of integration of Eqs. (8). Of course, the outlet cross section of the spinnerette channel f_- is also known. Accordingly, from (2) we also know the velocity $V_- = V(x = -0)$. The longitudinal force in the filament can also be assigned in place of V_1. The final value of F is determined during iteration in order to obtain the necessary fiber receiving velocity V_1 (in practice, the velocity V_1 rather than the force F is prescribed on the receiving device). Taking the value of V_+ obtained from Eq. (11), we use (2) to find $f_+ = q/V_+$ and, thus, the expansion of the filament at the outlet of the spinnerette $b = f_+/f_-$.

We use the second condition of (10), the second equation of (3), and Eq. (4) to find the pressure at the channel outlet

$$p_-=\tau_{xx}^--\frac{F}{f_-}. \tag{12}$$

Integrating Eq. (1) with allowance for the results of integration of the first equation of (8) and (12), we find the pressure distribution along the channel and, in particular, the pressure P at the channel inlet that is needed to maintain flow at the rate q with the prescribed force F (or, with allowance for the iterative process, with the velocity V_1):

$$P=p(x=-l)=-\frac{F}{f_-}+\int_{-0}^{-l}\tau_{xx}\frac{d\ln f}{dx}\,dx. \tag{13}$$

By virtue of the last two conditions of (10), the stresses in the initial section of the filament are equal to

$$\tau_{xx}^+=b^{-2}\left(\tau_{xx}^-+\frac{G_0}{3}\right)-\frac{G_0}{3},\qquad \tau_{yy}^+=b\left(\tau_{yy}^-+\frac{G_0}{3}\right)-\frac{G_0}{3}. \tag{14}$$

It is natural that Eqs. (14) satisfy Eq. (9) with allowance for (11).

To solve the above-formulated dynamic problem, it is necessary to determine the time during which a stable shell is formed by diffusion of the precipitant and coagulation of the polymer and the velocity reaches its maximum value – the receiving velocity V_1. To do this, we examine the equation of diffusion of the precipitant in an individual element of the fiber

$$\frac{\partial c}{\partial t} = \frac{D}{y} \frac{\partial}{\partial y} \left(y \frac{\partial c}{\partial y} \right) \tag{15}$$

with boundary conditions in the form

$$\left.\begin{aligned} y = 0 \qquad & \frac{\partial c}{\partial y} = 0 \\ y = R(t) \qquad & -D \frac{\partial c}{\partial y} = q_w(t) \end{aligned}\right\} t > t_0. \tag{16}$$

An evaluation made with the use of laminar boundary-layer theory [12] shows that the thickness of the diffusion layer near the fiber surface in the bath is on the order of one-tenth of its radius. Thus, the characteristic time over which a steady-state concentration profile is established in the boundary layer is approximately one-hundredth the time required inside the fiber (the coefficients of diffusion of the precipitant in the bath and inside the fiber are the same [13]). Thus, the precipitant concentration profile in the boundary layer near the fiber surface in the bath can be considered quasistationary, and we can use the following relation [4] to determine the precipitant flow rate:

$$\begin{gathered} q_w = -k[c_\infty - c(R, t)], \\ \frac{kR}{D} = 0{,}47\, \mathrm{Re}^{\frac{1}{3}} \mathrm{Sc}^{\frac{1}{3}}, \quad \mathrm{Re} = \frac{RV}{\nu}, \quad \mathrm{Sc} = \frac{\nu}{D}. \end{gathered} \tag{17}$$

We will use an integral method which is widely employed in boundary-layer theory [12], representing the solution of (15) in the form

$$c(t, y) = A(t) + B(t)\, y^2, \tag{18}$$

where A(t) and B(t) are coefficients dependent on time.

Polynomial (18) obviously satisfies boundary condition (16) at y = 0.

Using Eqs. (15), (16), and (18), we obtain a differential equation to determine A:

$$\frac{dA}{dt} = \frac{c_\infty - A}{4D + kR} \left\{ \left[\frac{4k}{R} (2D + kR) - R \frac{dk}{dt} \right] + \frac{k}{2D + kR} \left[R^2 \frac{dk}{dt} + 2(D + kR) \frac{dR}{dt} \right] - 4k^2 \right\}. \tag{19}$$

The coefficient B is connected with A by the relation

$$B = \frac{k(c_\infty - A)}{R(2D + kR)}. \tag{20}$$

We write the initial conditions $t = t_0$, $A = 0$ for Eq. (19). In accordance with (18), these conditions correspond to zero concentration of the precipitant on the fiber axis at the moment of discharge of the particle from the spinnerette channel.

At the same time, we use (18) and (20) to find that at $t = t_0$

$$B(t_0) = \frac{kc_\infty}{R(2D + kR)}, \quad c(R, t_0) = \frac{c_\infty kR}{2D + kR}. \tag{21}$$

Thus, it is assumed that a certain amount of precipitant is already present inside the filament at the moment it leaves the channel. This corresponds to nearly instantaneous matching of the precipitant concentration profiles in the bath and the fiber element immediately after discharge of the element from the channel. It should be noted that for the actual values of the quantities entering into (21), $c(R, t_0)$ is appreciably lower than the concentration c_* at which polymer coagulation occurs on the fiber surface. The coagulated shell will be stable (will not decompose) only when it has reached a certain thickness, i.e., when the concentration of precipitant c_* is realized a certain depth under the fiber surface. Only at this moment of time does deformation of the fiber cease.

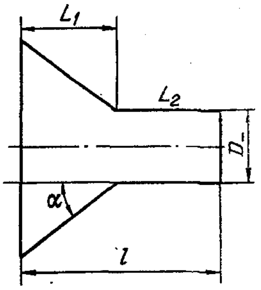

Fig. 1

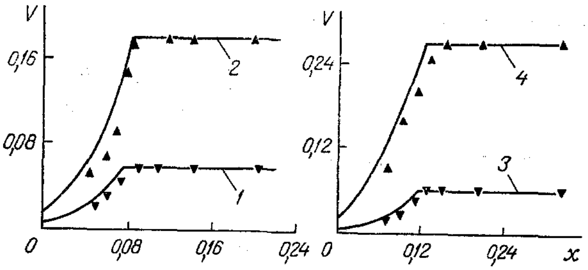

Fig. 2

Fig. 1. Diagram of spinnerette channel.

Fig. 2. Change in the velocity of the solution in the fiber along the path of formation with different fiber receiving velocities: 1) $V_1 = 0.05$ m/sec; 2) 0.178; 3) 0.06; 4) 0.27. For curves 1 and 2, the volume flow rate of spinning solution $q = 0.32 \cdot 10^{-9}$ m³/sec; 3, 4) $0.485 \cdot 10^{-9}$ m³/sec. The results of the calculations are shown by curves 1-4, the experimental data in [6] is shown by the triangles; the calculations were performed with $D_- = 0.15 \cdot 10^{-3}$ m. V, m/sec; x, m.

The system of equations of the problem (2), (7)-(9), (11), (14), (17)-(20) is closed and makes it possible to find the moment of formation of a stable shell and the distribution of velocity and stress on the formation section.

The longitudinal coordinate of the liquid element is determined by the integral

$$x = \int_0^t V dt - l.$$

The proposed method of calculation of the process of wet formation was realized for the case of formation of fibers from a POD solution whose rheological characteristics – measured in a shear flow – were reported in [14]: $\eta_0 = 200\text{-}320$ Pa·sec, $(2\tau_{xy}^2/N_1)|_{\dot{\gamma}\to 0} = 600\text{-}1000$ N/m². Using the Doi–Edwards governing rheological equation [multimodal analog (6)], we find that $(2\tau_{xy}^2/N_1)|_{\dot{\gamma}\to 0} = G_0/6$. We find from this that the elastic modulus $G_0 = 3600\text{-}6000$ N/m². Also, using the Doi–Edwards relation again we find that $\tau_C = 60\eta_0/(\pi^2 G_0) = 0.19\text{-}0.53$ sec. The calculated values of elastic modulus and maximum relaxation time can be regarded only as estimates in terms of order of magnitude, since the polydispersity of the polymer may have affected the rheological behavior of the POD solution in the experiments in [14]. Also, the number of bonds in the macromolecule in [14] was small, so that $N \sim 1$. The same applies to the experimental data in [6] on fiber formation with which we are comparing our calculated results. Thus, proceeding on the basis of the best agreement between the theoretical data and the experimental data in [6], we chose the following values of the parameters in one of the variants of the calculations: $G_0 = 8 \cdot 10^3$ N/m², $\tau_C = 1.1$ sec, $\tau_B = 0.3$ sec. These values are close to the estimates presented above using the results of rheological measurements [14]. They remain the same in other calculation variants.

The critical concentration of precipitant (water) in the fiber at which coagulation of the polymer system occurs is 30% [15]. The coefficient of diffusion of water in the water–sulfuric-acid system is $0.6 \cdot 10^{-9}$ m²/sec both inside the fiber and in the bath (see [16], for example).

The article by G. A. Belinskii et al. in the same issue of this journal compares theoretical and experimental methods of determining the flow in the channels of a spinnerette and the expansion of free jets at the outlet of the spinnerette. The article also examines semiempirical methods of allowing for two-dimensional effects in the case of flow in a spinnerette channel. Thus, we will proceed immediately to calculation of the flow as a whole. The geometry of the spinnerette channel is the same as in the article by Belinskii (Fig. 1). The parameters of the spinnerette had the following values: $\ell = 0.2 \cdot 10^{-3}$ m, $2\alpha = 60°$, $L_1 = L_2 = 0.107 \cdot 10^{-3}$ m, $D_- = 0.8 \cdot 10^{-4}$ m or $0.15 \cdot 10^{-3}$ m. In the calculations, we set $2\alpha = 42°$ to allow for the effect of the formation of the inlet jet (see the article by Belinskii).

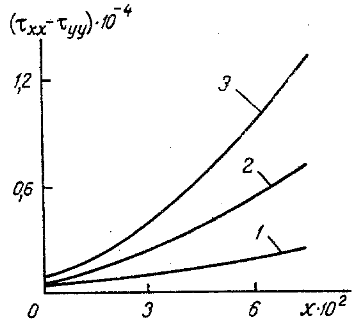

Fig. 3

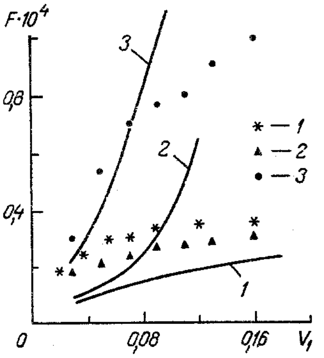

Fig. 4

Fig. 3. Change in the tensile stresses in the fiber along the region of formation in relation to the receiving velocity V_1: $V_1 = 0.05$ m/sec (fiber extrusion ratio $E = V_1/V_+ = 5.7$); 2) $V_1 = 0.1$ m/sec ($E = 11$); 3) $V_1 = 0.178$ m/sec ($E = 19$); the calculations were performed with $D_- = 0.15\cdot 10^{-3}$ m, $q = 0.32\cdot 10^{-9}$ m³/sec. $(\tau_{xx} - \tau_{yy})$, N/m².

Fig. 4. Dependence of the tensile force in the fiber on the receiving velocity V_1. Theoretical curves: 1) concentration of precipitant in the bath $c_\infty = 0.4$, $q = 0.32\cdot 10^{-9}$ m³/sec, $D_- = 0.15\cdot 10^{-3}$ m; 2) $c_\infty = 0.4$, $q = 0.95\cdot 10^{-10}$ m³/sec, $D_- = 0.08\cdot 10^{-3}$ m; 3) $c_\infty = 0.53$, $q = 0.95\cdot 10^{-10}$ m³/sec, $D_- = 0.08\cdot 10^{-3}$ m; the symbols with the corresponding numbers show experimental data [7]. F, N.

Figure 2 shows calculated profiles of velocity in the filament and the corresponding experimental data [6] (the outlet diameter of the spinnerette hole $D_- = 0.15\cdot 10^{-3}$ m). The results shown in Figs. 2 and 3 correspond to a precipitating bath containing 60% sulfuric acid and 40% water. This is the bath composition most often employed in practice. The coefficient of expansion of the filaments upon discharge from the spinnerette channels under the conditions corresponding to Fig. 2 ($D_- = 0.15\cdot 10^{-3}$ m) changed in the calculations within the range $1.39 \le B_* \le 1.42$ ($B_* = D_+/D_- = \sqrt{b}$). In the case of the calculations discussed below, with $D_- = 0.8\cdot 10^{-4}$ m, the expansion coefficient B_* ranged from 1.65 to 1.77.

There is currently no data on the thickness at which the shell of the fiber becomes stable. Thus, in one calculation variant in which the theoretical and experimental relations $V = V(x)$ agreed, we chose the condition $c(0.85\,R, t_*) = c_*$ as the condition for determining the moment of formation of a stable shell, i.e., we reasoned that the shell becomes stable when it reaches the thickness 0.15 R. This value remained the same in all of the other calculation variants.

Figure 3 shows the change in the tensile stresses in the fiber along the path of formation in relation to the receiving velocity or fiber extrusion ratio. In rheological model (5) and (8), the longitudinal stresses are linearly related to the longitudinal orientation of the macromolecule in the fiber. Thus, Fig. 3 also illustrates the longitudinal orientation of the macromolecules in the fiber at the spinnerette extrusion stage. Since there is a direct connection between the longitudinal orientation of the macromolecules of the polymer in the fiber and its strength [17], Fig. 3 also gives information on the increase in the strength of the fiber with an increase in receiving velocity.

Figure 4 shows theoretical and experimental dependences [7] of the tensile force in the fiber on the receiving velocity with different values of POD solution flow rate and different precipitating-bath compositions. We should point out the sharp increase in the force F as the composition of the bath approaches the boundary of the region of "intensive" regimes of fiber formation (with $c_\infty \to 0.6$).

The results obtained, when compared with the experimental data, permit the conclusion that, on the whole, the proposed theoretical model satisfactorily reproduces the characteristics of the wet formation process and can be used in practical calculations.

In constructing the method used to calculate the fiber-formation process with allowance for flow in the spinnerette channel, we proceeded on the basis of a quasiunidimensional model similar to the model used in [18].

NOTATION

p, pressure; V, flow velocity; f, cross-sectional area of spinnerette channel (at $-\ell \leq x \leq -0$); at $x \geq +0$, f and R denote the area and radius of the fiber cross section ($f = \pi R^2$); Ox and Oy, longitudinal and radial coordinate axes; $\sigma_{xx} = \tau_{xx} - \tau_{yy}$; τ_{xx} and τ_{yy}, longitudinal and radial components of the deviator of the stress tensor τ; v, velocity vector; D, strain-rate tensor; τ_2, tensor of the stresses due to disequilibrium of the system of bonding points of a macromolecule; τ_C, maximum relaxation time of stresses due to disequilibrium of the system of bonding points of the macromolecule (characteristic time of relaxation by diffusion); G_0, elastic modulus; $\mathbf{Q}$, tensor dependent on the strain history; $\mathbf{F}_\tau(t)$, tensor of strain gradient from the moment τ to the actual moment of time t; $\mathbf{u}_0$, unit vector randomly oriented in space; $\mathbf{I}$, unit tensor; N, number of subchains of the macromolecule; q, fluid flow rate; F, tensile force in the fiber; V_1, fiber-receiving velocity; b, expansion of fiber at outlet of spinnerette channel; ℓ, length of spinnerette channel; P, pressure at inlet of channel; t_0, moment of discharge of fluid particle from the spinnerette, c, concentration of precipitant; A and B, coefficients; c_∞, concentration of precipitant in the bath far from the fiber; c_*, concentration at which polymer coagulation occurs; D, diffusion coefficient; q_w, flow of precipitant in the direction of an external normal to the fiber surface; k, mass-transfer coefficient; ν, kinematic viscosity of the liquid in the precipitating bath; Re and Sc, Reynolds and Schmidt numbers; η_0, viscosity at zero shear rate; τ_{xy}, shear stress; N_1, first difference of normal stresses in shear; $\dot{\gamma}$, shear rate; L_1 and L_2, lengths of the conical and cylindrical parts of the spinnerette channel; D_+ and D_-, diameter of the free jet after discharge from the spinnerette channel and diameter of the outlet section of the channel; α, inlet angle of spinnerette; B_*, coefficient of expansion of the free jet; t_*, moment of attainment of a stable shell; E, fiber extrusion ratio. Indices: $-$ and $+$ denote quantities in the final cross section of the spinnerette channel (before expansion of the fiber) and in the initial cross section of the fiber (after expansion).

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