EVAPORATION OF 'LUBRICATING AGENT' IN THERMAL TREATMENT OF TECHNICAL SYNTHETIC FIBERS

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A mathematical model of the evaporation of a water-emulsion mixture (lubricating agent) in thermal treatment of a synthetic fiber is suggested. It is based on an approximation of interpenetrating continua. A substantial effect of deformation heat losses on the evaporation-front motion is shown.

Introduction. The production of synthetic fibers is a powerful, strategically important, and very energy consuming subbranch of chemical industry [1]. Optimization of the production of synthetic fibers requires a large number of experimental and theoretical investigations of both chemical and heat/mass exchange natures. In the production of synthetic fibers their thermal treatment is of great importance. In the process of thermal treatment a technical fluid called a "lubricant" is used [1] which is applied to the fibers and which is evaporated on heating and drawing of the fibers in a thermal chamber called an "iron." The lubricant is an emulsion consisting of up to 80% water and a variety of polyesters. The process of evaporation of the lubricant from a system of fibers moving along the "iron", whose metal surface temperature is constant, is greatly influenced by the drawing of fibers, which reduces the fiber diameter several times. The process of fiber deformation requires the expenditure of thermal energy transferred from the "iron" and substantially slows down the evaporation process [2]. The present article is devoted to mathematical simulation of lubricant evaporation in a Stefan approximation taking account of the thermal energy loss for the deformation (drawing) of a fiber. Our experimental investigations showed that generally the effervescence of a lubricant is dependent on its composition. Its boiling temperature lies within $93-100^{\circ}$C. Hereafter, we shall ignore this effect to remain within the bounds of the prescribed accuracy and assume that evaporation begins on the attainment of 100°C at a certain point of the fiber. We shall ignore lubricant evaporation at lower temperatures for two reasons: at lower temperatures the partial pressure of the lubricant vapors is substantially lower than atmospheric pressure, and the diffusional resistance of noncondensing gases plays a retarding role [3].

Mathematical Model of the Process of Thermal Treatment of Fiber in Drawing. Let us introduce a Cartesian coordinate system such that the x axis is oriented in the direction of motion of the fiber that enters the "iron." The origin of the coordinate system coincides with the beginning of the heated surface of the "iron." The z axis is perpendicular to the "iron" surface. Let us approximate the dependence of the velocity $v(x)$ of an element of the deformed fiber on the distance x by the following expression:

$$v(x) = v_0 + \alpha x = v_0 (1 + \alpha x / v_0), \tag{1}$$

where v is the initial velocity of the fiber entering the "iron;" the parameter α characterizes the degree of the deformation of the fiber in the "iron." For many polymer fibers and drawing technologies this important parameter is approximately equal to 10. The determination of α is very simple if we know the length of the "iron" and the velocities of the fiber at the entrance to the "iron" and at its exit. Let $d(x)$ be the diameter of the fiber at the distance x. Then, by virtue of the continuity equation [3, 4] and relation (1), considering the cylindrical shape of the fiber, we have
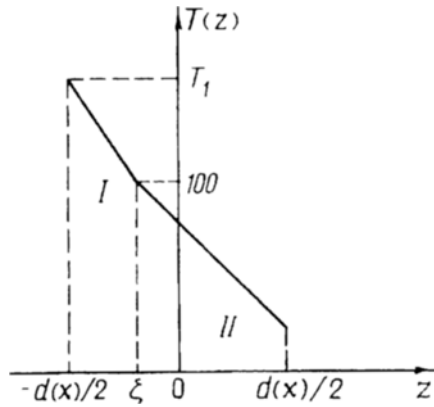

Fig. 1. Distribution of temperature field in section of a deformed fiber at distance x from beginning of "iron."

$$d(x) = d(v_0/v(x))^{0.5},$$ (2)

where d is the fiber diameter at the entrance to the "iron."

We shall solve the thermal part of the problem in an approximation of interpenetrating continua [5]. This will allow us to use a one-dimensional approximation to describe the temperature field. Thus, the fiber temperature used below has the following physical meaning: this is the mean temperature in the interior of the fiber at a constant z. Let us now determine the effective density of the lubricant ρ_e in the following manner. Assume that a lubricant layer of thickness a is applied to a fiber of diameter d, with the lubricant having the density ρ. Then, the effective density of the lubricant is

$$\rho_e = 4da\rho/(d + a)^2,$$ (3)

As follows from relation (3), when $a \ll d$, the value of the effective density is proportional to the initial thickness of the lubricant. We note that the conservation law (2) shows that the effective density ρ_e does not change in the process of drawing. The designations of the characteristic regions of our problem are given in Fig. 1. In region I, the lubricant is fully evaporated, since the temperature within it is above 100°C. At the moving front $\zeta(t)$ the lubricant is being evaporated; in region II the temperature is not high and there is no evaporation. For region I we have the equation of heat conduction with a sink:

$$c\rho_e \partial_t T(z, t) = \lambda \nabla^2 T(z, t) - I_0.$$ (4)

Physically, I_0 is the volumetric density of the energy spent in elongation of the fiber. The value of I_0 is unknown, however, we may state that the magnitude of this parameter depends on Young's modulus of the fiber E and on the parameter α introduced above. Then, from dimensionality considerations [4] it follows that

$$I_0 = CE\alpha,$$

where C is a numerical constant that cannot be determined within the scope of dimensionality theory and that usually changes within the range of from 1 to 10 [3]. The boundary conditions for Eq. (4) in region I have the form

$$T(-d/2) = T_1; \quad T(\zeta) = 100.$$ (5)

For region II we also have the heat conduction Eq. (4) with the boundary condition

$$\nabla T(d/2) = 0,$$ (6)

which means that we ignore heat exchange between the fiber and the heated air compared with heat exchange with the metal surface of the "iron." To determine the position of the evaporation zone, we have the condition

$$-\lambda \nabla T\big|_{z-\zeta-0} = w_S U \rho_c - \lambda \nabla T\big|_{z-\zeta+0} \, ,\tag{7}$$

$$w_S = \frac{d\zeta}{dt} \, ,$$

where w_S is the Stefan evaporation-front velocity, which actually is of basic interest for our problem. Attention should be given to the fact that the boundaries of the regions change not only because of evaporation of the lubricant, but also as a result of deformation in drawing. To solve Eq. (4) subject to boundary conditions (5) and (6) and condition (7), we shall avail ourselves of the technique suggested in [6]: for each of the regions a stationary solution for temperature is constructed, which is subsequently used in an approximate search of the front velocity with the aid of condition (7). It is not difficult to show that the characteristic time for the temperature profile to attain a quasistationary regime

$$\tau \approx d^2 c\rho / \lambda$$

is very small, i.e., much smaller than the characteristic times of the problem. As a result of application of the technique from [6], we have the following system of ordinary differential equations:

$$\frac{dx}{dt} = v_0 + \alpha x \, ,\tag{8}$$

$$\frac{d\zeta}{dt} = w_S + v_d \, ,\tag{9}$$

where v_d is the rate of change of the boundary between the regions as a result of the fiber drawing. Using Eqs. (1) and (2), it is easy to show that in a laboratory coordinate system

$$v_d = -\zeta\alpha/2 \, .\tag{10}$$

After simple calculations the expression for w_S can be presented in the form

$$w_S = -\frac{\lambda}{\rho_c U}\left[\frac{I\,(3d\,(x) - 2\zeta)}{4\lambda} - \frac{\Delta T}{(\zeta + d\,(x)/2)}\right] \, ,\tag{11}$$

where $\Delta T = T_1 - 100$.

The system of Eqs. (8) and (9) was solved numerically with the initial condition

$$t = 0 \quad x = 0 \quad \text{and} \quad \zeta = \zeta_0 \, ,\tag{12}$$

so that $\zeta_0 \approx -d/2$.

Results of Calculations. Before moving to the results of numerical calculations, we should pay attention to the fact that if we assume in Eq. (11) that $I = 0$ and ignore the change in the fiber diameter due to drawing, then Eq. (11) can be easily ignored. As a result, we have the following expression for the position of the evaporation front as a function of time, having designated it by ζ_s:

$$\zeta_s + d_0/2 = \sqrt{\left(\frac{2\lambda\Delta T t}{\rho_c U}\right)} \, .\tag{13}$$

Finally we shall consider deformation heat losses of the fiber using Eq. (11). It is obvious that we can introduce the dimensionless criterion M:
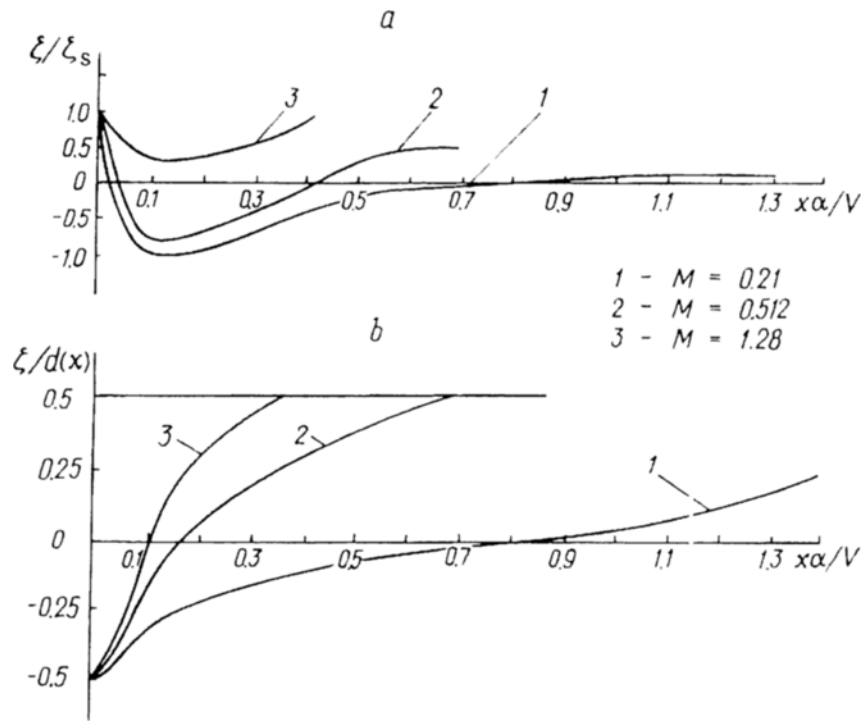
Fig. 2. Dependence of dimensionless coordinate of lubricant evaporation front position $\zeta(x)/\zeta_s(x)$ and of the parameter $\zeta/d(x)$ on x at different values of M.

$$M = \frac{\lambda \Delta T}{d_0^2 I}.\tag{14}$$

If $M \gg 1$, then we can ignore the influence of deformation heat losses. When $M \ll 1$, naturally, there is no evaporation at all. It is important that the influence of deformation heat losses is inversely proportional to the square of the fiber diameter, Young's modulus of the substance, and to the parameter α. Thus, as was proved by numerical calculations, in a number of cases the evaporation front starts to move only after the deformation-induced decrease in the fiber diameter. This conclusion has a great applied significance. Of the parameters available in the problem considered, we can form a dimensionless complex xd/v that characterizes the dimensions of the "iron" and the kinematics of the fiber (see Eq. (1)).

Figure 2 presents the dependence of the position of the dimensionless variable ζ/ζ_s and of the important technological parameter $\zeta/d(x)$ on the dimensionless length covered by the fiber in the "iron" at different values of M. It is seen that already when $M < 0.5$ the motion of the evaporation front differs substantially from the regime in which deformation heat losses are not taken into account.

Conclusion. Numerical investigation conducted with the aid of the mathematical model developed showed that lubricant evaporation is greatly influenced by the thermal energy losses in fiber deformation, which are determined by the parameter α introduced in the present work and by Young's modulus of the fiber. It is shown that the velocity of the evaporation front is inversely proportional to the initial thickness of the lubricant film and to the effective latent heat of the evaporation of the lubricant and is directly proportional to the initial diameter of the fiber. For technological purposes of considerable importance is the dimensionless length of the "iron," which is directly proportional to its length and parameter α and is inversely proportional to the initial velocity of the fiber.

NOTATION

x, path covered by small element of fiber along "iron;" t, current time; $d(x)$, current diameter of a fiber in drawing; v, initial velocity of fiber at entrance to "iron;" ρ_e and U, effective density and latent heat of evaporation

of lubricant; λ and E, thermal conductivity coefficient and Young's modulus of fiber material; M, dimensionless similarity parameter (see Eq. (14)); $\zeta(x)$ and $\zeta_s(x)$, coordinates of evaporation front calculated with and without allowance for deformation heat losses.

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