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# NUMERICAL MODELING OF PHYSICAL EFFECTS IN THE DRAWING OF A GLASSY MATERIAL INTO A FIBER

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UDC 532.6.011.72

This article is devoted to the numerical modeling of the physical effects which take place in the conversion of a glassy substance from a semifinished product into a fiber by drawing while it is in the hot, viscoplastic state. The problem being examined relates to a number of so-called "problems with a free boundary," since the surface of the highly viscous molten material, not in contact with any other surface, changes form in accordance with the laws governing the dynamic equilibrium between gravitation, surface tension, and other forces. A characteristic feature of the problem is the presence of large gradients of temperature, viscosity, and fluid velocity in the drawing zone. We studied the effect of stable drawing of the semifinished product into a fiber, as well as the conditions, character, and causes of underheating or overheating. The effects of drop formation and fiber rupture are also examined. The problem being considered is of great practical interest, since it helps answer a key question in one of the most rapidly developing high-precision technologies – the stability of the drawing of optical fibers from quartz glass [1-4].

The drawing of quartz glass was studied as the axisymmetric vertical flow of a highly viscous fluid with a free boundary and variable viscosity. Viscosity unambiguously depends on the temperature of the quartz glass [5] in the drawing zone and changes from $10^4$ to $10^{20}$ P. The conditions of entry of heat into the semifinished product are assumed to be given.

We will study coupled nonlinear nonsteady equations describing the heat transfer and flow of a viscous incompressible liquid and its free boundary, along with the continuity equations [2, 4, 6]:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+v\frac{\partial T}{\partial z}=-\frac{1}{\rho C_p}\left(\frac{\partial}{\partial r}+\frac{\partial}{\partial z}\right)k(T)\left(\frac{\partial}{\partial r}+\frac{\partial}{\partial z}\right)T+\frac{1}{\rho C_p}k(T)\left[\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}\right]T; \quad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+v\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+\eta(T)\left[\frac{\partial^2 u}{\partial r^2}+\frac{\partial^2 u}{\partial z^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{u}{r^2}\right]+2\frac{\partial u}{\partial r}\frac{\partial \eta(T)}{\partial r}+\frac{\partial \eta(T)}{\partial z}\left(\frac{\partial v}{\partial r}+\frac{\partial u}{\partial z}\right),$$
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+v\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\eta(T)\left[\frac{\partial^2 v}{\partial r^2}+\frac{\partial^2 v}{\partial z^2}+\frac{1}{r}\frac{\partial v}{\partial r}\right]+g+2\frac{\partial v}{\partial z}\frac{\partial \eta(T)}{\partial z}+\frac{\partial \eta(T)}{\partial r}\left(\frac{\partial v}{\partial r}+\frac{\partial u}{\partial z}\right); \quad (2)$$

$$\frac{\partial u}{\partial r}+\frac{\partial v}{\partial z}+\frac{u}{r}=0; \quad (3)$$

$$\frac{\partial a}{\partial t}=-v\frac{\partial a}{\partial z}+u. \quad (4)$$

Here, the z axis is directed along the drawing axis; the r axis is perpendicular to the drawing axis; v and u are the longitudinal and transverse velocities of the molten quartz

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 153-156, November-December, 1988. Original article submitted February 27, 1987.

 

glass; T is its temperature; $\eta = \eta(T)$ is viscosity, which is approximated in accordance with [5]; $\rho$ and $C_p$ are the density and heat capacity of the substance; k(T) is its thermal conductivity, which, with allowance for heat transfer due to radiation, is dependent on temperature [2, 3]; p is pressure; t is time; g is acceleration due to gravity; $a(z,t)$ is the form of the drawing zone. The following boundary conditions are imposed on heat-transfer equation (1)

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0, \quad \left.\frac{\partial T}{\partial z}\right|_{z=z_N, z_N \gg z_1} = 0, \quad \left.\frac{\partial T}{\partial r}\right|_{r=0} = 0,$$
$$\left.\frac{\partial T}{\partial r}\right|_{r=a} = \frac{1}{k(T)}\left[h(z)(T - T_0) + \varepsilon\sigma\left(T^4 - T_0^4\right)\right]\frac{a(z)}{a_0}[1 + (a')^2]^{-1/2} + a'\frac{\partial T}{\partial z}, \tag{5}$$

where $T_0 = 293$ K; $z_1 - L/2 \le z \le z_1 + L/2$; $T_0 = T_1$; $T_1$ is the temperature of a heater of the length L; $z_1$ is the coordinate of the center of the drawing zone; h(z) is the heat-transfer coefficient [2, 3]; $\varepsilon$ is the emissivity of the quartz; $\sigma$ is the Stefan–Boltzmann constant; $a_0$ is the radius of the semifinished product; $a' = da/dz$.

Since we are examining the flow of a highly viscous fluid, we used the following approximation [2, 4, 6]: longitudinal velocity depends only on z, while the pressure $p = -\alpha H - \eta(T)\partial v/\partial z$ (H is the curvature of surface tension [2], $\alpha$ is the surface tension). The boundary conditions for the equations [2, 4] were stated in the form

$$v|_{z=0} = v_f, \quad v|_{z_N, z_N \gg z_1} = v_0, \quad u|_{z=0} = 0, \quad \left.\frac{\partial a}{\partial z}\right|_{z_N} = 0, \quad a|_{z=0} = a_0 \tag{6}$$

($v_f$ and $v_0$ are the rate of feed of the semifinished product and the rate of extraction of the fiber). Methods for numerically solving problem (1)-(6) were examined in detail in [7, 8].

We observed two effects that led to destabilization of the drawing operation. First, overheating of the drawing zone caused the surface tension to break the fiber up into drops [4] (if the viscosity of the quartz glass was relatively low). Second, if the glass was underheated, then the viscous forces were extremely strong and interfered with the timely drawing of new masses of material in order to realize stable fiber formation. This in turn led to a situation whereby the entire supply of sufficiently heated glass was used up and new material had not yet arrived at the drawing zone, causing the fiber to thin excessively near the neck and begin to rupture. Figure 1 (a – underheating at $T_1 = 2100$ K, b – overheating at $T_1 = 2700$ K) shows patterns of transformation of the drawing zone at L = 4.5 cm, $2a_0 = 1$ cm, and $v_f = 0.002$ cm/sec. The numbers next to the lines show the heating time in seconds. Figure 2 (1 – initial conditions; 2 – form of drawing zone with stable drawing; 3 – breakup into drops; 4 – rupture upon underheating), where the scale is greatly enlarged along the x axis, shows the difference in the forms of the drawing zone in these situations. In actual cases, when the quartz glass contains various types of defects, rupture during underheating begins earlier – when the drawing force exceeds the strength of the fiber. Nevertheless, as the numerical experiment showed, rupture was observed even in the case of "ideal" quartz glass, i.e., the mechanism of rupture of optical fibers in the case of underheating of the drawing zone has to do with the very nature of the drawing operation. Such rupture cannot be avoided simply by removing defects from the quartz glass.

It should be noted that our algorithm makes it possible to perform calculations just in a simply connected region. We thus recorded situations in which the simple-connectedness of the region is violated (rupture) and is not violated (stable regime). The algorithm was constructed so that the calculations were stopped after the region was no longer simply-connected.

Stable drawing of optical fibers is possible within a broad range of process parameters lying between underheating and overheating. Here, quartz glass is capable of forming a stable stream which forms an optical fiber upon hardening. Figure 3 ($T_1 = 2300$ K) shows the transformation of an optical fiber into such a stream as modeled in the present study. The form of the stream in the steady-state regime is shown in Fig. 2. Comparison with empirically obtained forms of the drawing zone under conditions close to the model conditions demonstrated that the agreement is very good (Fig. 4, experiment conducted by V. A. Bogatyrev). It should be noted that the drawing regime is unstable against small fluctuations of the main process parameters – such a change in $T_1$ by several degrees or in $v_0$ by several percents – near the critical regions. Thus, only a drawing regime far from these

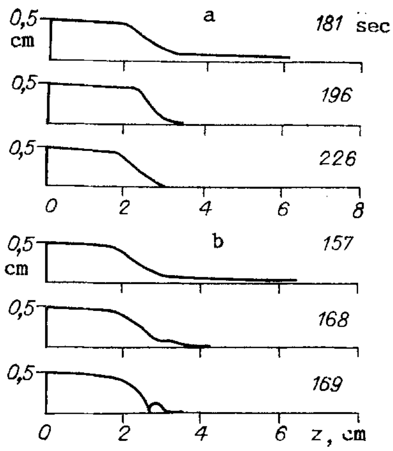


Fig. 1

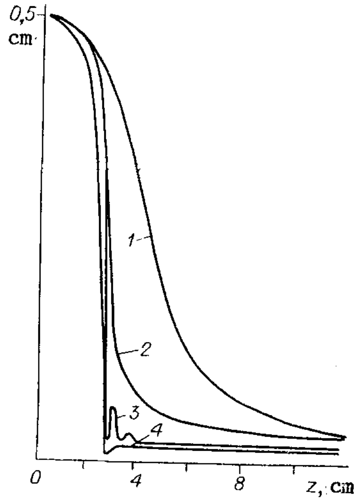


Fig. 2

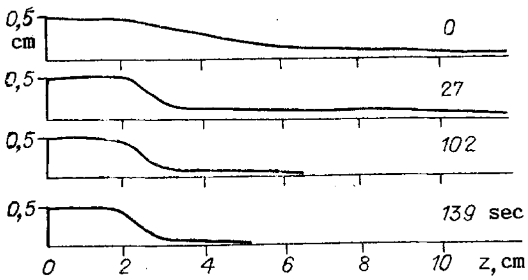


Fig. 3

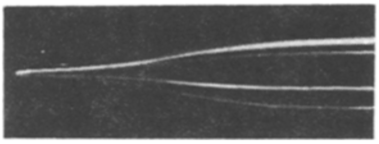

Fig. 4

regions can be considered optimal. In fact, the regime corresponding to Fig. 3 withstands an instantaneous fluctuation in the parameter $T_1$ by 100 K and a fivefold change in $v_f$ and $v_0$ without fiber rupture.

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