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INFLUENCE OF THE GAS FLOW RATE ON THE DRAWING OF OPTICAL FIBERS FROM FLUORIDE GLASSES

M. V. Gorbunov

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Glasses made from fluorides of heavy metals have earned an excellent reputation as promising materials for long fiber-optic communication lines. One of the indices of quality of an optical fiber is the lengthwise invariance of its geometrical dimensions. It has been shown [1-3] that variations of the fiber–gas heat-transfer coefficient have a far weaker influence than other factors on the diameter of a drawn quartz fiber, but this is not true of fluoride glass (FG) fibers. Heat transfer cannot possibly be cited as the dominant mechanism in the fabrication of FG fibers, because the necking down of FG blank rods into a fiber takes place at temperatures of 300–400°C, so that heat-transfer processes between the neck-down zone of the melt and the gas warrant serious attention.

In the present article the influence of the mass flow rate and temperature of the gas on the dynamics of the formation of a FG fiber is investigated on the basis of the steady-state conjugate problem of gas flow in the furnace duct.

STATEMENT OF THE PROBLEM AND ANALYTICAL METHOD

We consider an axisymmetrical, laminar flow of a viscous, heat-conducting, chemically inert gas in an annular duct formed by the inner surface of the melting furnace and the surface of the neck-down zone of a FG melt during the drawing of an optical fiber. Since the rms velocity of the gas is of the order of 1 cm/sec, we use the subsonic flow approximation [4], which rests on the assumption that the Mach number and the hydrostatic compressibility are small parameters, and terms involving with them can be discarded. It is also assumed that the angle between the tangent to the generatrix R(x) and the x axis (angle of inclination) is much smaller than unity. The temperature dependences of the viscosity and the thermal conductivity are calculated from equations of the molecular-kinetic theory of gases [5]. The system of equations is reduced to dimensionless form using as the velocity scale whichever is greater: the mass flow rate averaged over the cross section of the duct ("bulk velocity") at its inlet or the characteristic velocity obtained from the expression

$$U_* = \frac{\mu_* \sqrt{\mathrm{Gr}}}{2\rho_*(R_+ - R_-)}.$$

Thus normalized, the system of governing equations has the form

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \frac{1}{\mathrm{Re}}\left(2\nabla(\mu \dot{S}) - \frac{2}{3}\nabla(\mu\nabla\mathbf{v})\right) + \frac{1-\rho}{\mathrm{Fr}}\mathbf{g}; \tag{1}$$

$$\rho \frac{dT}{dt} = \frac{1}{\mathrm{Pe}}\nabla(\lambda\nabla T); \tag{2}$$

$$\rho\nabla\mathbf{v} = \frac{1}{T\mathrm{Pe}}\nabla(\lambda\nabla T). \tag{3}$$

The system is augmented with the equation of state and boundary conditions:

$$\rho T = 1,$$
$$U|_{r=R(x)} = V|_{r=R(x)} = U|_{r=R_+} = V|_{r=R_+} = 0,$$
$$T|_{r=R_+} = T_+(x),\ T|_{r=R(x)} = T_-(x).$$

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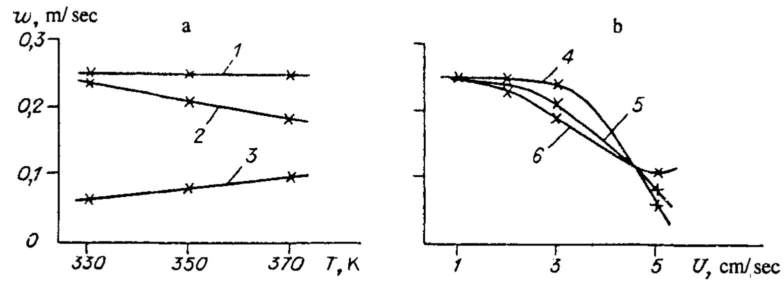

Fig. 1

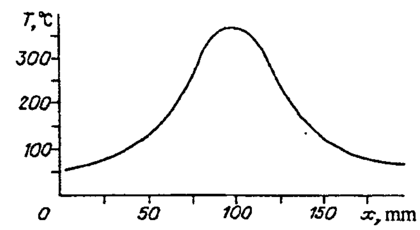

Fig. 2

Uniform distributions of U and T and a zero transverse component of the velocity are adopted at the inlet. Soft boundary conditions are specified at the outlet:

$$\frac{\partial T}{\partial x} = \frac{\partial U}{\partial x} = \frac{\partial V}{\partial x} = 0.$$

The pressure obeys the following condition at all boundaries:

$$\left.\frac{\partial p}{\partial n}\right|_{\Gamma} = 0.$$

The stated problem is unique in that the gas flow strongly influences both the shape of the melt neck-down zone R(x) and its lengthwise temperature distribution $T_-(x)$. The values of these quantities are determined by solving a system of equations given in [6] and closing the conjugate problem.

The inner wall of the duct, being formed by the surface of the melt, is curved; we therefore introduce a transformation of coordinates that maps the analytical domain into a rectangle. We replace the cylindrical coordinates (x, r) by new coordinates (z, y) according to the equations

$$z = x,\ y = (r - R_+)/(R(x) - R_+).$$

The gas flow is calculated by a modified projection method using relaxation computations:

1) The distribution of T and values of the transport coefficients and the density are found by solving the energy equation (2).

2) Equation (1) is solved by an implicit scheme to obtain preliminary values of the components of the velocity vector from the known pressure field.

3) An iterative process is formulated, where the values of U, V, and p are corrected until Eq. (3) is satisfied within prescribed error limits.

The values of $T_-(x)$ and R(x) are recomputed periodically.

RESULTS

The objective of the calculations is to determine values of the mass flow and temperature of the injected gas (argon) that will minimize the influence of deviations of these parameters from their specified values on the dynamics of the drawing process.

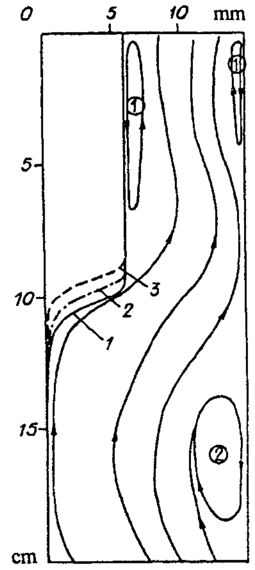

Fig. 3

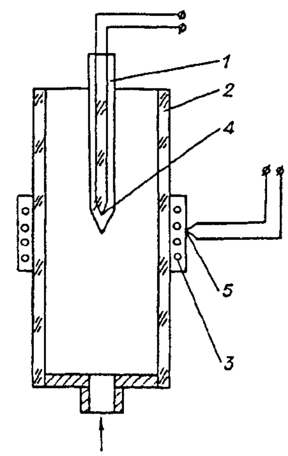

Fig. 4

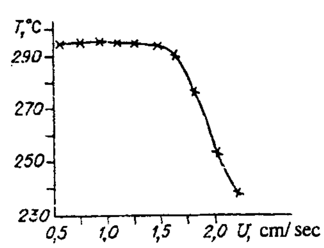

Fig. 5

For this purpose the parameters of the gas flow are varied, while the drawing tension is maintained at a constant value of approximately 25 gf by varying the drawing rate. The fiber drawing rate w as a function of the mass flow and temperature of the gas at the inlet is shown in Fig. 1, where lines 1-3 correspond to bulk velocities of 1 cm/sec, 3 cm/sec, and 5 cm/sec, and curves 4-6 correspond to inlet temperatures of 330 K, 350 K, and 370 K. The calculations are carried out for the necking down of a rod of diameter 12 mm into a fiber of diameter 180 μm. The gas is injected upward from the bottom. The temperature distribution of the inner surface of the furnace is shown in Fig. 2.

Figure 3 shows the variations in the configuration of the furnace duct for various gas flow rates at an inlet temperature of 350 K, the circulation zones that can occur under different gas injection conditions, and some typical streamlines (lines 1–3 correspond to bulk velocities of 1 cm/sec, 3 cm/sec, and 5 cm/sec).

It is clearly visible in Fig. 1b that for bulk velocities of the gas below 2 cm/sec a change in the gas injection conditions at the inlet to the duct has scarcely any influence on heat transfer in the melt neck-down zone or, therefore, on the drawing rate. The existence of a zone in which the drawing rate is slightly dependent on the mass flow is caused by the dominance of natural convection over forced convection, and the temperature independence of line 1 in Fig. 1*a* is attributable to the fact that the gas has ample time, as it approaches the neck-down zone, to warm up equally for different inlet temperatures.

One intriguing features is the decrease in the drawing rate as the argon inlet temperature increases for a bulk velocity of approximately 3 cm/sec (line 2). The following mechanism underlies this phenomenon. As the temperature of the gas at the duct inlet increases, the temperature difference between the furnace wall and the argon increases, inducing return flow past the inner surface of the furnace. As a result, the velocity of the gas near the inner wall of the duct increases, retarding the warming of the gas and intensifying heat transfer between the glass and the gas.

With a further increase in the mass flow (bulk velocity) the influence of natural convection diminishes, and an increase in the temperature reduces heat transfer from the rod and increases the drawing rate (line 3).

A model experiment has also been carried out (Fig. 4) in addition to the calculations. An FG rod 1 with the thermocouple 4 soldered to it is positioned with the tip of the neck-down zone at the center of a melting furnace model in the form of a quartz tube 2 with a Nichrome wire heater 3 wound around it. The temperature of the furnace model is monitored by the thermocouple 5 and is maintained at 300 ± 0.1°C. Room-temperature argon is injected from below, the mass flow is set, and the temperature of the rod is measured. The experimentally determined dependence of the temperature of the FG neck-down zone on the argon injection rate is shown in Fig. 5. The behavior of the curve corroborates the results of the calculations both qualitatively and quantitatively.

It can thus be stated that, from the standpoint of relaxing the equipment requirements of the gas circuit and (or) diminishing the influence of instability of the gas flow parameters on the fiber geometry in the drawing of fluoride glass optical fibers, it is desirable to set the mass flow of the gas so that its bulk velocity in the furnace duct does not exceed 2 cm/sec and the temperature does not exceed the temperature of the bottom cross section of the furnace.

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