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SOLUTION OF THE CONJUGATE PROBLEM OF THE GAS FLOW IN THE PULLING OF FLUORIDE FIBER LIGHT GUIDES

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A mathematical model is suggested for the congugate problem of the inert gas flow in a furnace channel during stretching of fluoride glass billets into optical fiber. Based on an analysis of preliminary results of a numerical investigation of gas supply from top to bottom and from bottom to top it is shown that the second variant is more effective for creating a protective atmosphere.

Introduction. A substantial advantage of optical fiber light guides (OLG) made of glasses based on fluorides of heavy metals (FG) over those made of traditional quartz glasses lies in a substantially lower level of theoretical losses (< 0.01 dB/km). Advances in obtaining the FG compositions that are more stable to devitrification as well as progress in decontamination of the initial substances have allowed manufacture of the light guide specimens with total losses of less than 1 dB/km. However, a further decrease in the losses involves substantial difficulties in optimization of the processes of billet preparation and fiber pulling. One of the technological aspects of pulling is creation of an atmosphere of a highly pure inert gas in the glass melting zone in order to avoid interaction of the FG with moisture and oxygen that are present in air. However, a low temperature of stretching (about 300°C) and a strong dependence of the dynamic viscosity on the temperature for FG make heat exchange with a gas during OLG manufacture a rather important factor that may lead to formation of surface defects [1] and may affect the pulling dynamics, while in the manufacture of quartz light guides it is not very important [2].

The most effective method for revealing the basic regularities in a process is mathematical modeling of the process. Since a gas flow exerts a pronounced influence on the shape of a melt bulb and its temperature, in the present work we suggest a conjugate model of an inert gas flow in a furnace channel in the pulling of optical light guides made of FG and discuss some calculation results.

Formulation of the Problem. We consider a laminar axisymmetric flow of a viscous heat-conducting chemically inert gas in an annular channel formed by the inner surface of a melting furnace and the surface of an FG melt bulb during the pulling of an optical fiber light guide.

The solution of the complete Navier-Stokes equations for slow flows requires much computation time but does not give a considerable gain in accuracy compared to the hyposonic flow approximation [3]. In this connection we have taken into consideration that the Mach number and the hydrostatic compressibility are small parameters, and to improve the calculation accuracy we have subdivided the pressure into two terms, namely, the hydrostatic pressure at the initial temperature and the deviation from it due to temperature and velocity changes. We have also assumed that the angle formed by the tangent to the generatrix $R(x)$ and the x axis (the angle of inclination) is much less than 1.

The temperature dependences of viscosity and thermal conductivity were calculated by formulas of the molecular-kinetic theory of gases [4].

The system of equations was reduced to dimensionless form, the higher of the following two velocities was chosen as a velocity scale: the mean mass velocity at the channel inlet or the characteristic velocity obtained from the expression

$$U_0 = \frac{\mu_0 \sqrt{\mathrm{Gr}}}{2\rho_0 (R_{\mathrm{fur}} - R_{\mathrm{f}})} . \tag{1}$$

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Thus, the system of governing equations in dimensionless form is written as

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

$$\rho \frac{dT}{dt} = \frac{1}{\mathrm{Pe}} \nabla (\lambda \nabla T), \quad (2b)$$

$$\rho \nabla \mathbf{v} = \frac{1}{T\,\mathrm{Pe}} \nabla (\lambda \nabla T), \quad (2c)$$

$$\rho T = 1. \quad (2d)$$

The system was closed by the following boundary conditions:

$$U|_{r=R(x)} = V|_{r=R(x)} = U|_{r=R_{\mathrm{fur}}} = V|_{r=R_{\mathrm{fur}}} = 0, \quad (3a)$$

$$T|_{r=R_{\mathrm{fur}}} = T_2(x), \quad T|_{r=R(x)} = T_1(x). \quad (3b)$$

At the inlet a uniform distribution was taken for U and T and the transverse velocity was assumed equal to zero. At the outlet the mild boundary conditions were postulated. For the pressure at all the boundaries it was stipulated that

$$\left(\frac{\partial P}{\partial n} \right) \Big|_{\mathrm{b}} = 0. \quad (3c)$$

The distinctiveness of the problem to be solved lies in the fact that in calculations not only the function T_1 but also the channel configuration, more exactly, its internal boundary $R(x)$, changes. Their values were found by solving a system of equations that is analogous to that in [5].

Calculation Method. Since the internal channel wall formed by the melt surface was curvilinear, we transformed the coordinates so as to map the calculation region into a rectangle. The cylindrical coordinates (x, r) were replaced by the new coordinates (z, y):

$$z = x, \quad y = (r - R_{\mathrm{fur}})/(R(x) - R_{\mathrm{fur}}). \quad (4)$$

The algorithm for gas flow calculation represented determination by the modified projection method:

1) in the first stage energy equation (2b) was solved and the transfer coefficients and the density were determined;

2) using an implicit scheme, preliminary values of the velocity vector were determined from prescribed pressure field (2a);

3) in the final stage, iterations were performed in which $\mathbf{v}$ and P were corrected until Eq. (2c) was fulfilled with the prescribed accuracy.

The values of T_1 and $R(x)$ were periodically recalculated.

Calculation Results. At present when an FG billet is stretched into fiber, an inert gas is pumped through, as a rule, from top to bottom (variant I). However in practice it is also of interest to supply a gas from bottom to top, which is often done in the pulling of quartz light guides (variant II).

We shall consider only characteristic features of flows in these two methods of creating the protective atmosphere (PA) without discussing the effect of the gas on the dynamics of the pulling process. As an example, a billet 12 mm in diameter made of glass with $T_g = 267^{\circ}$C was pulled into fiber 180 μm in diameter in a furnace in the form of a quartz tube with an inner radius of 15 mm with a Nichrome heater wound onto it. The length of

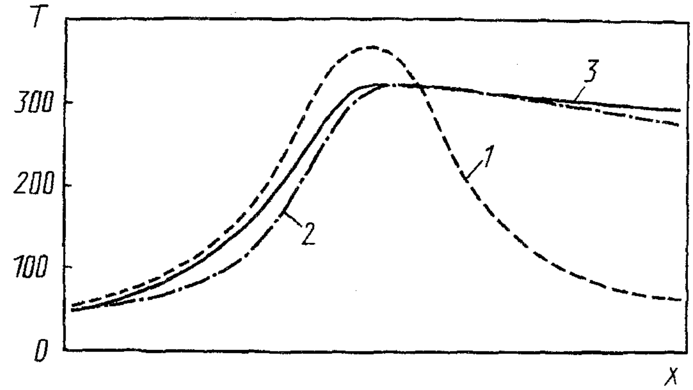

Fig. 1. Temperatures of the channel walls versus the longitudinal coordinate: 1) furnace temperature; 2) billet temperature (variant I); 3) billet temperature (variant II). T, °C.

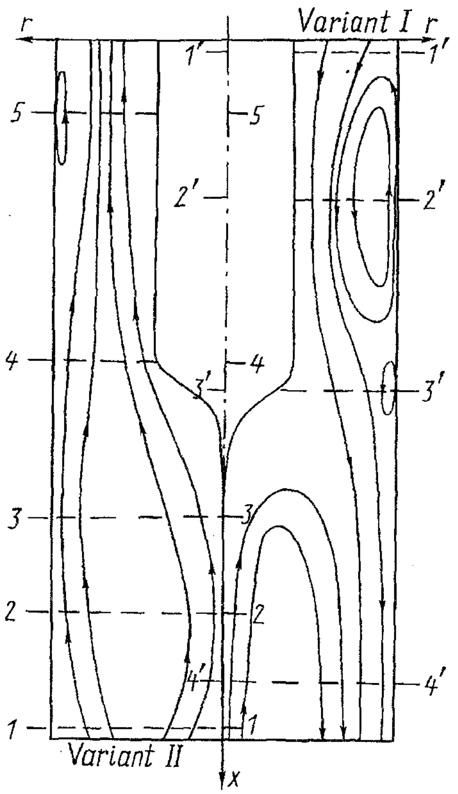

Fig. 2. Configuration of the calculation region and qualitative flow patterns for two variants of gas supply.

the calculation region was 20 cm. Argon was supplied to the channel at a mean mass velocity of 3 cm/sec at 57°C. The pulling force in the both cases was about 25 gf. In Fig. 1 distributions of T_1 and T_2 are shown for variants I and II.

Qualitative flow pictures are depicted in Fig. 2. The temperature distribution is shown in Fig. 3, and changes in the longitudinal velocity distribution are depicted in Fig. 4. In variant I a free convective flow caused by heating is in the opposite direction to the forced flow. In connection with this in the region where T_2 increases due to an advanced increase in it compared to T_1, a return flow (2′–2′) develops that becomes weaker as the billet and the gas become heated. Upon further heating of the billet, formation of a melt bulb begins, which leads to an increase in the cross-sectional area of the channel. This occurs opposite the point of the maximum temperature of the furnace and causes the development of a second circulation zone (3′–3′), which, however, is small since a local change in area is quickly compensated by the stabilizing action of mass forces in the cooling of the flow. In the lower part of

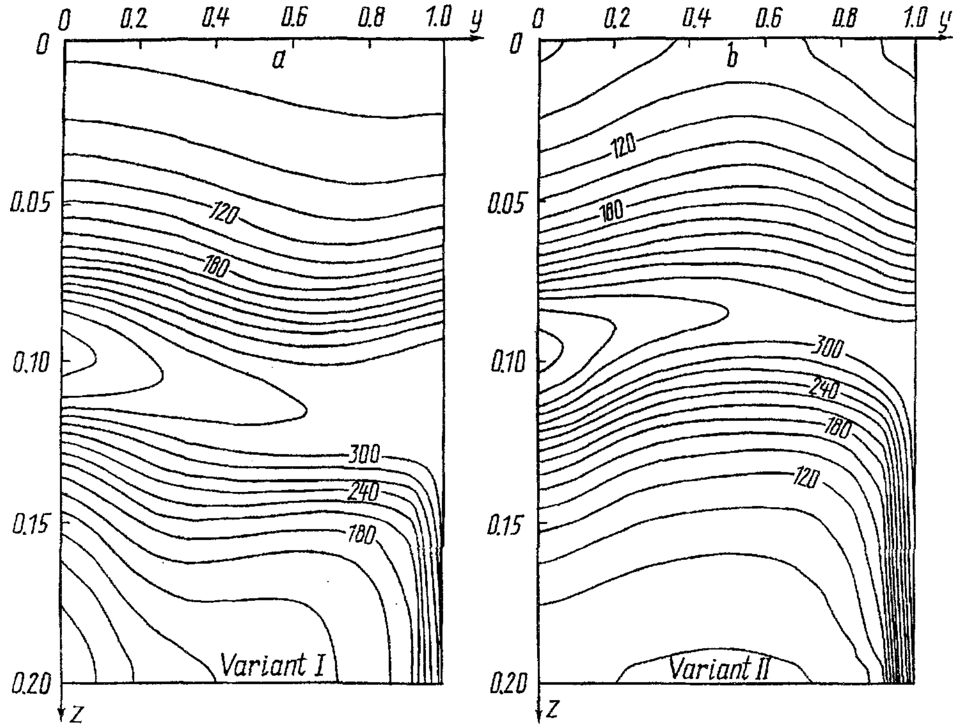

Fig. 3. Temperature field distribution of the gas flow for variants I and II of gas supply. z, m.

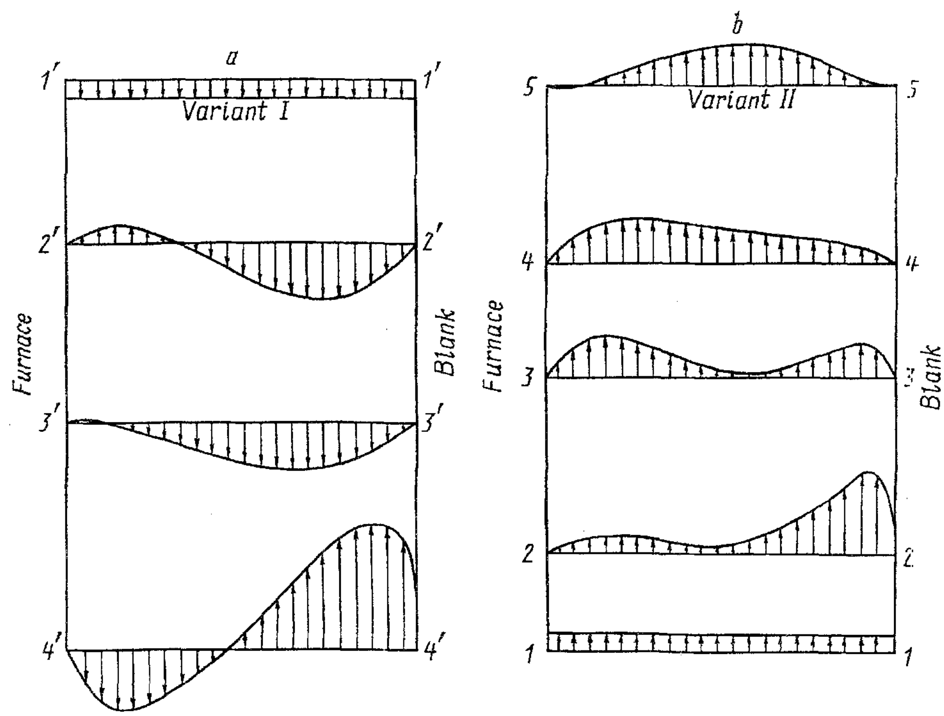

Fig. 4. Distribution of the dimensionless longitudinal component of the velocity vector in different cross sections for variants I and II of gas supply.

the channel a return flow develops near the inner wall, i.e., on the fiber, because of its substantially higher temperature (4′–4′).

If the outlet cross section corresponds to the lower section of the furnace, this indicates that gas from the outside may be sucked into the channel, thus substantially increasing the concentration of limiting gases (water and oxygen) and dust on the hot and, consequently, reactive part of the fiber molding.

For case II the flow picture is substantially simpler. In the region near the channel inlet the gas, coming in contact with the hot fiber, becomes more accelerated than at the furnace boundary and forms an axisymmetric profile that is distorted as the gas moves along the fiber (2–2 and 3–3). Channel narrowing at the site of bulb formation causes rapid rearrangement of the profile, making the latter close to a parabola (4–4). When the gas cools on the channel walls, the internal layers virtually practically preserve their velocity while the near-wall layers become strongly retarded and form stagnant zones (5–5).

Thus, it may be inferred from a comparison of the two flow modes that variant II is preferable for creation of a protective atmosphere due to the substantially higher flow stability. This owes to the fact that the flow in the hot, most important, region is subjected to the action of two stabilizing (accelerating) factors, namely, smooth narrowing of the channel and free-convective flow acceleration. In variant I the change in the cross-sectional area and the influence of bulk forces cause retardation of the flow and, as a consequence, development of several circulation zones, which is especially undesirable in the lower part of the channel at the site of fiber stretching.

NOTATION

t, time; r, y, transverse coordinates; x, z, longitudinal coordinates; v, velocity vector; T, temperature; P, pressure; U, V, longitudinal and transverse components of the velocity vector; μ, ρ, λ, dynamic viscosity, density, and thermal conductivity of the gas; Gr, Re, Fr, Pe, characteristic Grashof, Reynolds, Froude, and Peclet numbers; S, tensor of deformation rates; R_{fur}, R_{f}, furnace and fiber radii; $R(x)$, radius distribution of the melt bulb; T_1, T_2, temperature distribution of the billet and the furnace; **g**, unit vector of the force of gravity; T_{g}, glass transition temperature; 0, subscript of the characteristic value.

REFERENCES

1. P. McNamara and D. R. MacFarlane, Materials Science Forum, 32–33 (1988), pp. 219-224.
2. V. N. Vasil'ev, G. N. Dul'nev, and V. D. Naumchik, Inzh.-Fiz. Zh., 58, No. 3, 499-504 (1990).
3. Yu. V. Lapin and M. Kh. Strelets, Internal Flows of Gas Mixtures [in Russian], Moscow (1989).
4. R. Reed, J. Prousnits, and T. Sherwood, Properties of Gases and Liquids [Russian translation], Leningrad (1982).
5. V. D. Naumchik, Energy Transfer in Convective Flows [in Russian], Collected Papers of the Heat and Mass Transfer Institute of the Academy of Sciences of Belarus, Minsk (1985), pp. 67-76.