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FLOW AND CRYSTALLIZATION OF HOLEY, COMPOUND, OPTICAL FIBERS

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Summary A model of the flow, thermal field and crystallization of axisymmetric, slender, holey, compound optical fibers is developed. The model accounts for the crystallization kinetics and molecular orientation through generalized Avrami and Kikutani equations and their effects on the momentum equations through a dynamic viscosity law that depends on the temperature in an Arrhenius fashion and exponentially on the degree of crystallization. For small Biot numbers, it is shown that the compound holey fiber's geometry, axial velocity component, temperature, molecular alignment and crystallization are governed by one–dimensional equations. It is also shown that the necking and viscosity of the fiber and molecular orientation increase whereas the degree of crystallization decreases as the activation energy of the viscosity law is increased.

INTRODUCTION

In recent years, holey or microstructured polymer fibers have been developed for optical applications [1]. The cross–section of these fibers contains an array of holes running along the fiber length, and these fibers guide light due to the effective refractive index difference between the solid core and the cladding. The presence of air holes in optical holey fibers makes them very useful in applications ranging from nonlinear devices to high–power delivery systems.

Holey fibers are usually manufactured by drawing a preform in a furnace by conventional fiber–drawing processes, and their geometry can be controlled by acting on the parameters used in the fiber–drawing process such as the temperature of the furnace, the drawing speed, the speed at which the preform is injected into the furnace, etc. Since the optical properties of microstructured polymer fibers depend strongly on the the size and locations of the air holes in the cladding, it is of paramount importance to determine the effects of the drawing conditions on the fiber cross–section. In order to achieve this objective, most theoretical and modelling studies of single hollow fibers have considered a *single* material, used a slender or long wavelength approximation, and assumed either isothermal flows [2, 3, 4] or the heat transfer exchanges between the fibers and the surroundings by means of either a constant Biot number approximation or models for the film heat transfer coefficient as a function of the (local) Reynolds and Prandtl numbers [5], but have considered a single material and have not accounted for the polymer molecular orientation and crystallization. In this paper, a model of the flow, thermal field and crystallization of axisymmetric, *compound*, optical holey fibers is developed by means of perturbation methods based on the (small) slenderness ratio.

FORMULATION

Consider a cylindrical furnace of radius R_f and length L_f. On the top wall of this furnace a hollow, compound preform consisting of an inner material (subscript 1) of inner and outer radii equal to $R_1(0,t)$ and $R(0,t)$, respectively, surrounded by an outer material (subscript 2) of inner and outer radii equal to $R(0,t)$ and $R_2(0,t)$, respectively, at temperatures equal to $T_1(0,r,t)$ and $T_2(x,0,t)$ smaller than the melting temperatures of these materials, is pushed in the vertical x–direction into the furnace. Owing to the radiative and convective heat transfer exchanges between the furnace walls and the hollow, compound preform, the fiber's materials reach their melting temperatures and a hollow, compound jet is obtained. The temperatures of the furnace vertical wall and bottom are selected so that the hollow, compound fiber solidifies before reaching the furnace bottom wall, and the solidified fiber is collected downstream at the spinneret at an axial velocity equal to $u_{pu} > u_f$. Let u_p be the axial velocity component at which the preform is introduced into the furnace and L_p the axial distance from the furnace's top wall to the location where the preform melts, and assume that the preform behaves as a rigid solid material until the melting temperature is reached. Assume also that the melting temperatures of the two materials that compose the hollow, compound preform are very similar, and $\max R_2(0,t) << L_f - L_p$ and $\max R_2(0,t) << R_f$ so that the hollow, compound fiber is slender and its diameter is much smaller than the furnace diameter, and that $T_1(0,r,t)$ and $T_2(x,0,t)$ do not differ significantly from each other. Furthermore, assume that the gases surrounding and enclosed by the compound, hollow fiber are dynamically passive, the geometry and flow are axisymmetric, viscous dissipation can be neglected, the materials that compose the fiber are incompressible and Newtonian, the density and thermal properties of the fiber are constant, the dynamic viscosity of the materials that compose the fiber depends on the temperature in an Arrhenius fashion and exponentially on the degree of crystallization through a Kikutani's empirical equation, while the degree of crystallization is governed by an Avrami expression which depends on the molecular alignment which, in turn, can be quantified by a single scalar order parameter s that can be deduced from a Doi closure approximation and corresponds to the ensemble average of the alignments of the molecular directions with respect to the axial one. Under these assumptions and at low Reynolds numbers, it can be easily shown that the continuity, linear momentum and energy equations for the two materials of the compound fiber depend on $O(\epsilon^2)$, where ϵ denotes the slenderness ratio, and, therefore, the fiber's radii, axial and radial velocity components, pressure and temperature can be written in terms of asymptotic expansions in $O(\epsilon^2)$ which, at low Biot numbers, result in one–dimensional equations for the leading–order radii, axial velocity and temperature of the hollow, compound fiber that depend on the Reynolds, Froude, Biot and capillary numbers, the difference between the pressure of the gases enclosed by and surrounding the fiber, the density, surface tension and thermal diffusivity ratios, and Zel'dovich numbers. At high Biot numbers, however, the leading–order temperature field is two–dimensional but the leading–order fiber's geometry and axial velocity field are still governed by one–dimensional equations that depend on the cross–sectional integrals of the dynamic viscosity and may be determined by using the leading–order axial and radial velocity components.

RESULTS

Some sample results illustrating the hollow, compound fiber's geometry (R_1, R, R_2), axial velocity component (B), temperature (T), dynamic viscosity of the inner material (visc1), degree of crystallization (Xc) and orientation factor (s) are shown in Figure 1 for three different (nondimensional) activation energies of the dynamic viscosity law of the compound fiber's inner material. This figure indicates that the fiber's neckning, viscosity and molecular orientation increase whereas the degree of crystallization decreases as the activation energy increases. It also shows that, at low activation energies, the fiber cools rapidly and its axial velocity increases rapidly near the take–up point. However, at high activation energies, the axial velocity increases rapidly from the die's exit and the fiber reaches an almost constant geometry.

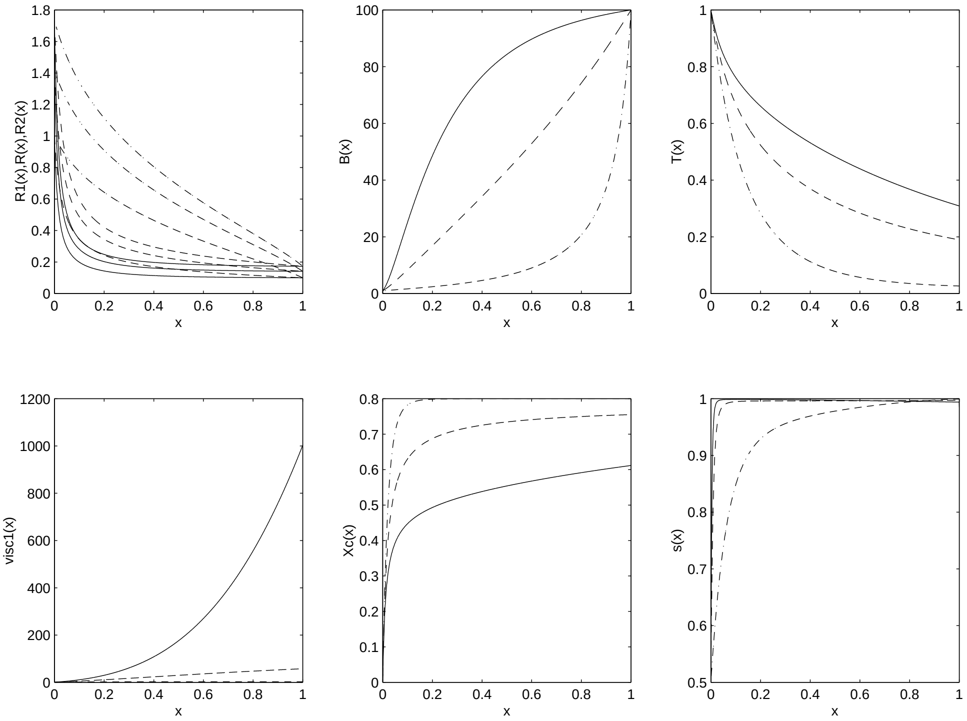

Figure 1. Fiber's geometry (top left), axial velocity component (top middle), temperature (top right), dynamic viscosity of the inner material (bottom left), degree of crystallization (bottom middle) and molecular orientation (bottom right)as functions of the coordinate along the fiber.(The solid, dashed and dashed–dotted lines corespond to nondimensonal activation energies equal to 50, 10 and 1, respectively).

CONCLUSIONS

A slender approximation has been used to determine the leading–order equations of holey, compound, optical fibers at low Reynolds numbers by including the polymer molecular orientation and crystallization and their effects on the dynamic viscosity of the two materials that compose the fiber. It is shown that the activation energy of the viscosity law plays a paramount role in determining the necking, solidification and crystallization of holey compound fibers at low Biot numbers.

References

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