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Feasibility and optimization of the hollow optical fiber drawing process

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ABSTRACT

The drawing process for the fabrication of a hollow optical fiber involves the flow of glass, which is largely heated by thermal radiation, in an inert gas environment. It is critical to maintain the central core, which can collapse if the thermal conditions are not properly imposed and controlled. This paper presents the analysis and simulation of this complicated process. A numerical model is developed, validated, and applied to simulate the hollow optical fiber drawing process under a wide range of boundary conditions, particularly draw speed, tension, and temperature. A feasible domain of the drawing process is identified to give the range of the drawing parameters for which the geometry of the fiber is maintained and collapse of the core and viscous rupture of the fiber are avoided. The effects of drawing temperature and feeding speed, which are crucial factors in determining the geometry and quality of the fiber, are investigated in detail. A multi-variable unconstrained optimal design problem is posed and considered in terms of the feasible domain. An appropriate objective function, comprised of the maximum velocity lag, thermally induced defect concentration and draw tension, is proposed to quantify the quality of the hollow fiber. The univariate search method is then applied to obtain the optimal drawing temperature and feeding speed. This study provides a basis for the optimization of hollow fiber drawing process and indicates that a substantial improvement in fiber quality can be achieved.

1. Introduction

Hollow optical fibers have a wide range of applications, from sensors to power delivery and medical applications. A high quality hollow optical fiber is desirable in order to achieve low signal loss. Hollow optical fibers are typically fabricated by drawing a specially manufactured hollow glass preform to the desired fiber diameter in a conventional fiber-drawing tower. The quality of the final hollow fiber can be characterized by many factors, such as draw tension, which can cause stresses and microcracks in the fiber, radial non-uniformity in temperature and velocity, and concentration of drawing-induced defects. Small values of these factors are desirable for high fiber quality. All of these factors strongly depend on the drawing conditions, such as the furnace temperature, the drawing speed, and the preform feeding speed. Therefore, optimizing the hollow fiber drawing system can significantly improve the quality of hollow optical fiber.

A number of studies have been carried out on the solid-core fiber drawing process. Among these, only a few considered the optimal design of the fiber drawing system. For instance, Cheng and Jaluria [1] developed an optimization algorithm. In addition, compared with solid-core fiber drawing, very few researchers [2–5] have investigated the simulation of the hollow optical fiber drawing process. No investigations have been directed at the optimization of the hollow optical fiber drawing process or of the relevant system. However, optimization in hollow optical fiber drawing is strongly needed due to the interest in high quality fiber at high draw speeds. Compared to experimental work, numerical simulation provides a convenient and practical way for optimization because of the cost and effort involved with the former.

This paper presents the optimal design of the hollow optical fiber drawing process, considering the feasible domain of the process. The numerical model of the hollow optical fiber drawing process, presented by Yang and Jaluria [6], is used for optimization. As shown in the earlier study, on the one hand, the central hole in the hollow fiber may collapse completely at high furnace temperatures or at low drawing speeds. On the other hand, lower furnace temperatures or high drawing speeds may cause failure in the drawing process due to viscous rupture, which causes the fiber to break. Hence, the feasible domain for hollow fiber drawing, in which a successful fiber drawing is obtained, must be identified before the drawing system can be optimized to get high quality hollow fibers. Among the main drawing parameters, the furnace temperature and the preform feeding speed significantly affect the drawing process and can be easily and realistically controlled. So the temperature of the drawing furnace and the preform feeding speed are chosen for detailed investigation and optimization of the hollow optical fiber drawing process. The effects on draw tension, maximum temperature and velocity lags, and drawing-induced

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Nomenclature

C_r	collapse ratio in hollow fiber drawing	z	axial coordinate distance
c_p	specific heat at constant pressure	λ	absorbing wavelength band
g	acceleration due to gravity	μ	dynamic viscosity
H	height	ν	kinematic viscosity
K	thermal conductivity	Φ	viscous dissipation term
L	preform length	ρ	density
n	refractive index	τ	shear stress
$\vec{n}$	unit normal vector		
p	pressure	*Subscripts*	
$\vec{q}$	heat flux	f	fiber
r	radial coordinate distance	F	furnace
R	radius	in	inlet
S_r	radiation source term		
t	time	*Superscripts*	
T	temperature	(1)	core
u	radial velocity	(2)	cladding
v	axial velocity		

defect centers are investigated. Based on these results, an appropriate objective function for optimization is formulated and a multi-variable and non-constrained optimal design problem is presented. Finally, a simple optimization procedure is carried out to solve the problem.

2. Mathematical and numerical modeling

A conjugate problem, involving conduction, convection, and radiation heat transfer mechanisms in hollow optical fiber drawing process, is considered. The mathematical model and the numerical scheme have been presented in the earlier papers. For more details, see Yang and Jaluria [6,7]. Fig. 1 illustrates the geometry and coordinate system for the cylindrical drawing furnace. Only half of the axisymmetric domain is shown for convenience. The flows of glass, and of the internal and external gases in the cylindrical furnace are all taken as laminar, incompressible, and axisymmetric. The buoyancy effects are neglected here on the basis of results obtained earlier [6]. The full governing equations for the gases and the glass are given as:

$$\frac{\partial v}{\partial z}+\frac{1}{r}\frac{\partial (ru)}{\partial r}=0 \quad (1)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+v\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial z}+\left(\frac{1}{r}\frac{\partial}{\partial r}\left(\mu\left(\frac{\partial v}{\partial r}+\frac{\partial u}{\partial z}\right)\right)\right)+2\frac{\partial}{\partial z}\left(\mu\frac{\partial v}{\partial z}\right) \quad (2)$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+v\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial r}+\left(\frac{2}{r}\frac{\partial}{\partial r}\left(\mu r\frac{\partial u}{\partial r}\right)\right)+\frac{\partial}{\partial z}\left(\mu\left(\frac{\partial v}{\partial r}+\frac{\partial u}{\partial z}\right)\right) \quad (3)$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+v\frac{\partial T}{\partial z}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)+\Phi+S_r \quad (4)$$

where Φ is the viscous dissipation term and S_r is the radiation source term, which is obtained from radiation analysis within the glass and the furnace. The viscous dissipation term Φ is retained only for the glass flow due to the high viscosity of glass, typically being of the order of a few million times that of water at room temperature

$$\Phi=\mu\left(2\left[\left(\frac{\partial u}{\partial r}\right)^2+\left(\frac{u}{r}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]+\left(\frac{\partial v}{\partial r}+\frac{\partial u}{\partial z}\right)^2\right) \quad (5)$$

For the boundary conditions, at the top of the preform, uniform velocity and temperature are assumed. At the fiber exit, axial diffusion is neglected in the energy and momentum transport. The temperature distribution is specified at the furnace wall, using typical data available on such optical fiber draw furnaces. Along the axis of the furnace and perform/fiber, symmetry is employed. Along the free surfaces ($r = R_1$ and $r = R_2$), the streamfunction values are set equal to constant values and continuity of velocity, temperature and heat flux is applied. The two neck-down profiles are computed on the basis of the balance of the surface forces and mass conservation [6,7].

The vorticity–streamfunction approach is used for solving this problem. The zonal method [8] is applied to model the radiative transport within the glass. The two-band model presented by Myers [9] and adapted by Chen and Jaluria [8] for the absorption coefficient of pure silica is used here. The glass properties are functions of the temperature and are taken from Fleming [10]. The properties of the gas, taken as air, are computed using the state equation of an ideal gas and power law correlations [11], which are expressed as follows:

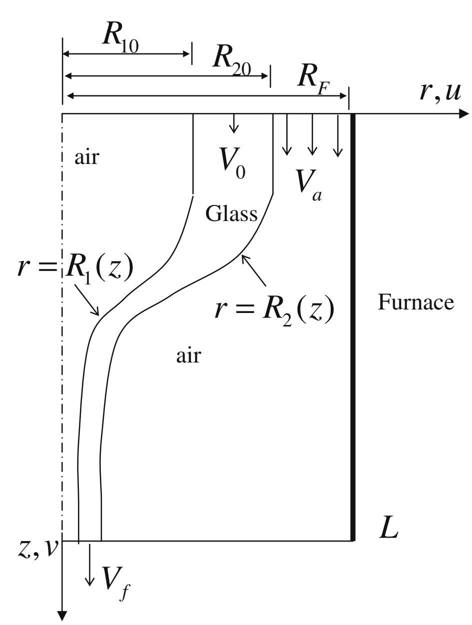

Fig. 1. Schematic diagram of hollow fiber drawing in a furnace.