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Convection and radiation effects in hollow, compound optical fibers ☆

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Abstract

A coupled model for the study of hollow, compound optical fiber drawing processes that accounts for the heat transfer in the preform and fiber and for the motion of the gases surrounding the preform and fiber by means of two-dimensional equations, employs a net radiative model for the radiative heat exchanges amongst the preform, fiber, irises and furnace walls, and uses asymptotic one-dimensional equations for the geometry, axial velocity component and temperature along the fiber for small Biot numbers is presented. It is shown that the coupled model predicts that radiative heat exchanges are about three times larger than forced convection effects, and free convection is not important. It is also shown that the fiber's geometry, axial velocity and temperature predicted by the coupled model are in remarkable good agreement with those obtained with only the one-dimensional model for hollow, compound fibers using a properly chosen constant Biot number. The results of the one-dimensional model for hollow, compound fibers show that, as the heat transfer losses from the fiber increase, the fiber's dynamic viscosity increases, the fiber exhibits a strong necking phenomenon and the fiber's axial velocity increases rapidly from its value at the die's exit to a constant value downstream and then remains constant. For the boundary conditions considered in this paper, it is shown that the activation energies of the viscosity laws for the inner and outer materials of the hollow, compound fiber do not have very strong effects on the fiber's geometry, axial velocity component and temperature, whereas the fiber's solidification point moves towards the die as the thermal Péclet number is decreased. It is also shown that the pre-exponential factor and activation energy of the dynamic viscosity law do not play a key role in determining the fiber's geometry and temperature for the conditions analyzed in this paper.

Keywords: Optical fibers; Holey fibers; Hollow, compound fibers; Radiative heat transfer; Perturbation methods

1. Introduction

In recent years, holey or microstructured 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. These fibers may be made of a single material, such as pure silica, and their effective index contrast can be a strong function of the light guided through the fiber. In addition, depending on the cladding configuration, holey fibers can display anomalous dispersion throughout the visible spectrum.

The presence of air holes in optical holey fibers makes them very useful in applications ranging from nonlinear devices to high-power delivery systems.

Another type of optical holey fibers is the photonic bandgap fiber [2,3] which guides the light by making use of the photonic bandgaps that occur in a periodic structure. Microstructured fibers also include atom-guiding fibers [4] where metal wires are inserted into four electrodes in the fiber and, by running currents along these wires, a magnetic potential can be established. This potential can then guide atoms.

Holey fibers are usually manufactured by drawing a preform in a furnace by conventional fiber-drawing processes. The preform can be made in several ways, including the

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Nomenclature

A	cross-sectional area
B	leading-order axial velocity component, function of x and t
Bi	Biot number
C	function of x and t
Ca	capillary number
C_p	specific heat at constant pressure
D	function of x and t
E	activation energy of the dynamic viscosity law
F	leading-order temperature, function of x and t
Fr	Froude number
g	gravity acceleration
$\bar{h}$	film heat transfer coefficient
h	effective heat transfer coefficient for convection and radiation
k	thermal conductivity
L	axial length
M	Mach number
n	unit outward normal
p	pressure
Pe	thermal Péclet number
Pr	Prandtl number
q	heat flux
Q	energy dissipation rate
r	radial coordinate
R	radius
$\mathbf{R}$	gas constant
Re	Reynolds number
S	pre-exponential factor in the dynamic viscosity law
t	time
T	temperature
x	axial coordinate measured from the furnace top wall or from the furnace exit
u	axial velocity component
v	radial velocity component

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
ε	slenderness ratio
ε'	emissivity
μ	dynamic viscosity
ρ	density
σ	Stefan–Boltzmann constant
θ	nondimensional temperature

Subscripts

B	bottom (iris) of furnace
c	convection
ex	gases surrounding the outer annular jet
f	furnace
g	gases surrounding the preform
in	gases enclosed by the inner annular jet
p	preform
pu	spinneret
r	radiation
ref	reference
T	top (iris) of furnace
0	reference value
1	inner annular jet
12	interface between the inner and outer annular jets
2	outer annular jet

Superscript

$*$	dimensional variable

stacking of small capillaries around a solid rod which forms the fiber core, and drilling directly in a solid glass; the latter is frequently used in the manufacture of atom-guiding fibers. In any case, the geometry of the holey fiber 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 or fed into the furnace, etc.

Since the optical properties of microstructured fibers depend strongly on 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 [5–8] or the heat transfer exchanges between the fibers and the surroundings by means of either a constant Biot number approximation [9] or models for the film heat transfer coefficient as a function of the (local) Reynolds and Prandtl numbers [10]. Radiative heat exchanges have also been considered in these one-dimensional models by correlating these exchanges through a temperature-dependent Biot number. In addition, these one-dimensional models have frequently been derived by means of asymptotic expansions in the slenderness ratio and are only valid for small Biot numbers, have not considered the preform, and have not accounted in a detailed manner for the effects of the radiation and convective flow effects of the gases surrounding the fiber on its dynamics and solidification. Moreover, most of these models employ a constant viscosity and consider Newtonian fluids with either a constant dynamic viscosity [5–8] or a viscosity law of the Arrhenius type [10].

Multidimensional models of optical fiber drawing processes include that of Lee and Jaluria [11] who considered the two-dimensional free-surface flow of fused silica with