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Analysis of Capillary Coating Die Flow in an Optical Fiber Coating Applicator

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***Abstract*—**Viscous heating becomes significant in the high speed resin coating process of glass fibers for optical fiber manufacturing. This study focuses on the coating resin flows inside the capillary coating die of optical fiber coating applicator and they are numerically simulated to examine the effects of viscous heating and subsequent temperature increase in coating resin. Resin flows are driven by fast moving glass fiber and the pressurization at the coating die inlet, while the temperature dependent viscosity of liquid coating resin plays an important role in the resin flow. It is found that the severe viscous heating near the coating die wall profoundly alters the radial velocity profiles and that the increase of final coating thickness by die pressurization is amplified if viscous heating is present.

***Keywords*—**Optical fiber manufacturing, Optical fiber coating, Capillary flow, Viscous heating, Flow simulation

I. INTRODUCTION

THE manufacturing of optical fibers starts with the preparing of a solid glass rod or a preform made of high purity silica, and a series of well automated inline processes follow such as the drawing of glass fiber from a heated and softened silica preform in a graphite furnace, the cooling of drawn glass fiber in a dedicated fiber cooling system with helium injection, the coating of polymer resins on the bare glass fiber, and the UV curing of the glass fiber coatings. Resin coatings on the fragile glass fiber provide the protection from mechanical damages such as cable bending and prevent the ingress of moisture into microscopic flaws on fiber surface. Generally, double layer coatings are applied to the glass fiber surface. The role of the inner layer is to minimize attenuation due to microbending, and the outer layer protects the inner coating against mechanical damages [1], [2]. In fact, the UV curable fiber coatings on glass fibers have been responsible for the widespread popularity of optical fibers in the areas of telecommunications as a practical alternative to conventional copper wirings [3].

At the time when the mass manufacturing of optical fibers began in 1970s, the fiber drawing speed was merely 300 m/min or less [4], [5]. Since the fiber drawing speed is directly related to higher volume production at a lower manufacturing cost, the fiberoptics industries have been trying to increase the fiber drawing speed. Entering the twenty first century, fiber drawing speed is increased to 1000 m/min, and presently it is exceeding 2000 m/min [6]. Increasing fiber drawing speed poses various kinds of serious problems and it requires the redesign and retooling of almost every process in the aforementioned optical fiber manufacturing system. In the resin coating process on the glass fiber, which is illustrated in Fig. 1, high speed fiber drawing leads to some technical problems such as liquid flow instabilities of resin coating layers and air bubble entrainment at the glass fiber entrance of coating applicator [7]. The other technical problem in the high speed coating process is the severe temperature increase of coating resin due to the viscous heating in the capillary coating die, and it significantly affects the control of the final coating thickness [8].

There have been a few analytic studies on the resin flow in the optical fiber coating. Panoliaskos et al. [5] and Sakaguchi and Kimura [9] presented a simple one-dimensional viscous flow analysis of single layer liquid resin die coating. Yang et al. [10] studied a similar fiber coating problem in unpressurized and pressurized coating applicators. However, the viscous heating effects were not considered and, thus, their analysis could be applicable only to low speed fiber coating process.

On the other hand, the multi-dimensional flow computations have been utilized to study the coating resin flows inside the fiber coating applicator. Ratten and Jaluria [11] investigated the two-dimensional axisymmetric liquid resin flow in an open-cup coating applicator for the fiber drawing speed up to 15 m/s. Yoo and Jaluria [12] also employed the similar approach on the isothermal resin flow up to the fiber drawing speed of 22 m/s.

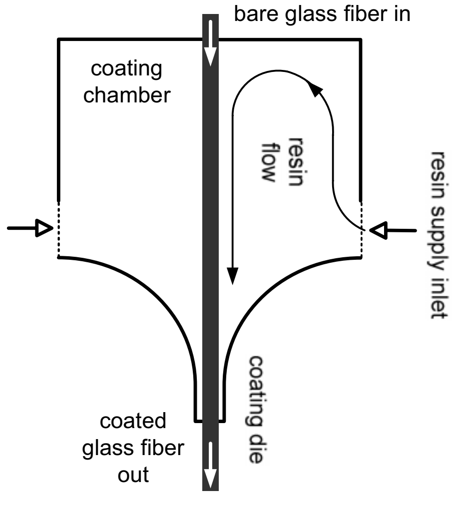

Fig. 1 Schematic of the optical fiber coating applicator

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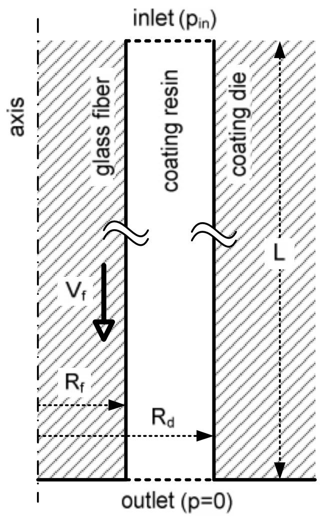

Fig. 2 Computational domain of coating resin flow in the capillary coating die of fiber coating applicator

Later, Yoo and Jaluria [13] considered the energy equation with the viscous heating in the resin flow simulations in order to appreciate the thermal effects on the resin flow patterns inside a coating applicator. However, their study is limited to the relatively low fiber drawing speed up to 18 m/s.Since the fiber drawing speed now exceeds 2000 m/min and approaches 3000 m/min in a modern optical fiber drawing system, viscous heating effects are expected to be significant and they should be included in the analysis of coating resin flow, especially, in the capillary coating die. This article presents the numerical simulations of the coating resin flow inside the capillary coating die of fiber coating applicator at high fiber drawing speed in order to examine the viscous heating effects on the increase of resin temperature and the final coating thickness on the glass fibers.

II. Numerical Modeling

A. Numerical Model of Coating Die Flow

Fig. 1 shows the simplified internal view of single layer resin coating applicator. A bare glass fiber drawn from the heated preform in the furnace and cooled in the glass fiber cooling unit enters the coating applicator. It passes through the liquid coating resin and exits coating applicator through coating die with a thin resin coating layer on the surface of glass fiber. Coating resin is supplied constantly through the chamber inlet.

A capillary coating die is attached at the end of coating applicator and the present computational study focuses on the resin flow inside the coating die, as illustrated in Fig. 2. The radius of the glass fiber is industry standard 62.5 μm (R_f). The length of capillary coating die is 1 mm (L), while the radius of the coating die is set to be 125 μm (R_d).

Resin flows inside the capillary coating die are assumed to be two-dimensional axisymmetric. Also, the flows are considered to be steady and incompressible. Due to exceptionally high resin viscosity and narrow gap between the glass fiber and die wall, the liquid resin flow is expected to be laminar. A commercial FEA simulation software package, COMSOL Multiphysics 3.4, has been employed in solving the governing equations of continuity, momentum, and energy conservation principles for the numerical simulations of velocity and temperature fields in coating die resin flow.

The structured computational mesh system of 30×200 is used in all the computations here in this study. More mesh points are placed near the coating die wall to accurately resolve the extremely large flow velocity gradient that arises due to severe viscous heating effects and subsequent variation of viscosity near the die wall. Glass fiber surface and coating die wall are treated as the conventional no-slip conditions, and the glass fiber surface is sliding at the velocity of fiber drawing speed (V_f). At the die outlet, the pressure condition is given as zero gauge pressure. Pressurization of the coating chamber is required for controlling the coating thickness as well as preventing meniscus collapse at the fiber entrance of coating chamber [7]. The gauge pressure of the coating die inlet is prescribed in order to include this pressurization effect.

Both temperatures of glass fiber surface and the coating resin at the die inlet are set to be 40°C. Coating die wall is considered to be adiabatic. Since the coating applicator is usually designed to minimize the heat loss, this adiabatic condition might be the reasonable approximation. At the die outlet, convective flux condition is suitable for the convective energy equation of resin flow.

B. Properties of Coating Resin

Viscosity of liquid resin for optical fiber coatings exhibits a drastic variation even with the small resin temperature change. Therefore, temperature dependence of coating resin viscosity should be considered in the flow simulations, especially when the viscous heating becomes significant in the case of high speed fiber drawing. Desotech DeSolite 950-106, the urethane acrylate resin, has been commonly used for fiber coatings in the fiberoptics industry and this study adopted its viscosity. Resin viscosity is given as a function of temperature such as

$$\mu\,(\text{Pa·s}) = \exp(3.345 - 5.609\times10^{-2}\,T\,(°\text{C})) \qquad (1)$$

Note that resin viscosity drops to approximately one tenth when the resin temperature rises from 40 to 80°C. Mass density of resin is 1010 kg/m^3, while its specific heat and thermal conductivity are constant at 2234 J/kg·K and 0.176 W/m·K, respectively.

III. Results and Discussion

For the coating resin flows inside the coating die of a single layer coating applicator, a series of two-dimensional flow and thermal analysis have been performed in order to investigate the effects of resin temperature increase due to severe viscous heating at high fiber drawing speed. The resin flow is driven by the fast moving glass fiber as well as the pressurization at the

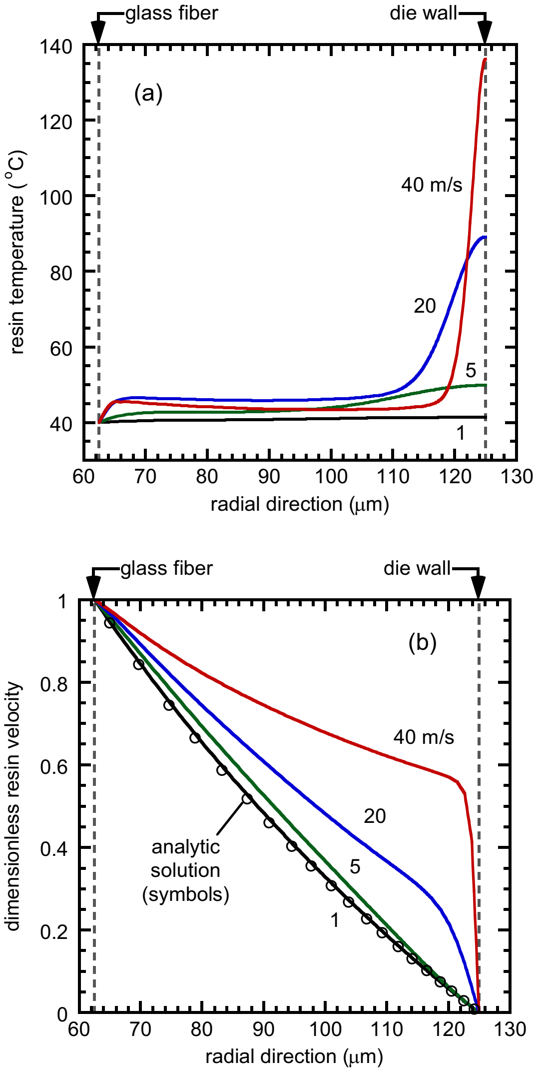

Fig. 3 Effects of fiber drawing speed on resin temperature (a) and velocity (b) profiles at the exit of capillary coating die with no pressurization (P_{in} = 0)

coating die inlet.

At first, the effects of increasing fiber drawing speed are examined for the case of no pressurization. Therefore, the resin flow is basically Couette type driven by sliding surface of glass fiber, if there were no viscous heating in the flow. However, viscous heating effects are expected to be significant at higher fiber drawing speed. Figs. 3(a) and (b) represent the resin flow velocity and temperature profiles in radial direction from glass fiber surface to coating die wall at the exit of capillary coating die from the present numerical computations. Note that the velocity profiles are expressed in dimensionless forms which are normalized by the corresponding fiber drawing speed. In Fig. 3(b), the symbols represent the analytic solution of coating die flow velocity of Couette type, which can be expressed as

$$u/V_f = \ln(r/R_d)/\ln(R_f/R_d) \qquad (2)$$

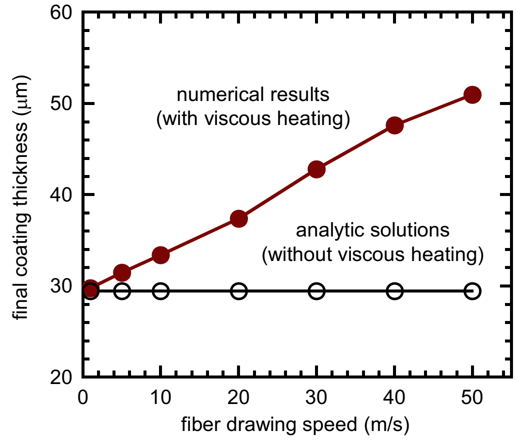

Fig. 4 Effects of fiber drawing speed on final coating thickness with no pressurization (P_{in} = 0).

and it is based on the assumption of a fully-developed flow in the unpressurized coating die with constant resin viscosity [4]. If the fiber drawing speed is extremely low such as 1 m/s, viscous heating is insignificant and the resin temperature at the die exit is quite constant, while the velocity distribution agrees very well with the analytic solution as expected. However, as the fiber drawing speed increases, temperature increase in the resin flow become very noticeable and the deviation of velocity profiles from the analytic solution is significant.

From the radial variation of resin temperature, it is found that the viscous heating effects show up mostly near the stationary die wall, not near the fast moving glass fiber. The zone affected significantly by viscous heating becomes more concentrated toward the coating die wall with the increasing fiber drawing speed. Maximum resin temperature occurs at the adiabatic coating die wall and temperature increase from the inlet value at the die wall is approximately 100°C for the fiber drawing speed of 40 m/s. This concentration of viscous heating leads to the severe drop of viscosity and, subsequently, very large velocity gradient near the die wall. If the fiber drawing speed is very high such as 40 m/s or 2400 m/min, viscous heating zone is quite thin and the resin flows much like slipping over the die wall.

Precise control of final resin coating thickness on the glass fiber might be the one of prime interests in process design of the optical fiber coatings. The volume flow rate of resin (Q) can be determined at the die exit by performing the integration of numerical results and final resin coating thickness (h) is evaluated by the following relation.

$$h = R_f\left(\left(1 + Q/\pi R_f^2 V_f\right)^{1/2} - 1\right) \qquad (3)$$

If the resin viscosity is constant and resin velocity profile is given as (2), final coating thickness can be easily found and its result is independent of fiber drawing speed or resin viscosity. For given dimensions of coating die and glass fiber, final

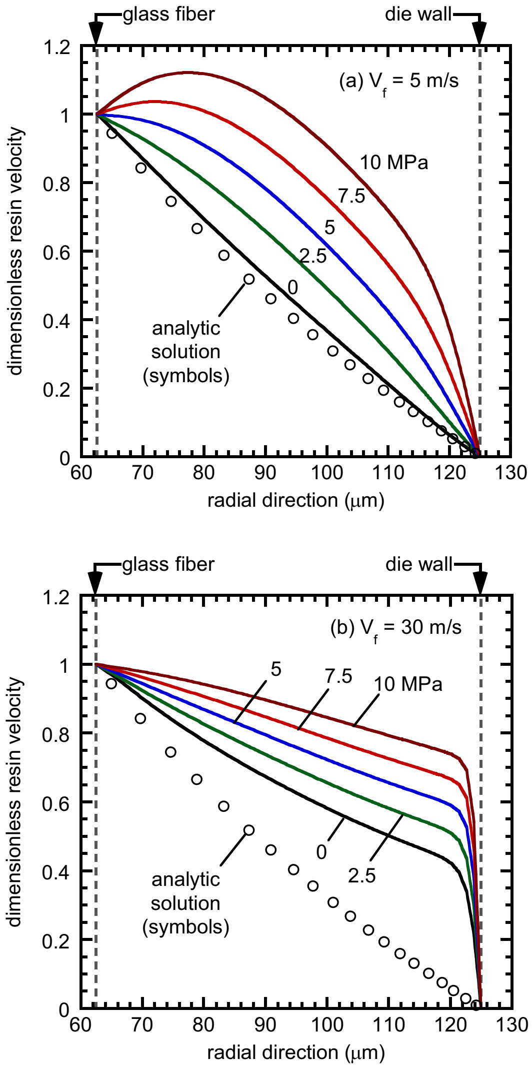

Fig. 5 Effects of pressurization on resin velocity profiles at the exit of capillary coating die for fiber drawing speeds of 5 and 30 m/s

coating thickness is calculated to be 29.4 μm and it is compared with final coating thickness from the numerical simulations that include the viscous heating and the temperature dependent resin viscosity. Fig. 4 shows the increasing final coating thickness because of more intense viscous heating with increment of fiber drawing speed, which can be expected from the fuller velocity profiles at higher fiber drawing speed in Fig. 3(b). Reduction of coating die radius might be required to maintain the same coating thickness at higher fiber drawing speed.

At this time, coating die pressurization of resin flow at the coating die inlet is introduced in the flow simulations. Figs. 5(a) and (b) show the change of radial velocity profiles at five different levels of pressurization up to 10 MPa/mm for two fiber drawing speeds of 5 and 30 m/s, respectively. At a relatively lower fiber drawing speed of 5 m/s, flow velocity profiles exhibit the predictable combination of Couette and Poiseuille flows. In contrast, for the case of higher drawing speed at 30 m/s,

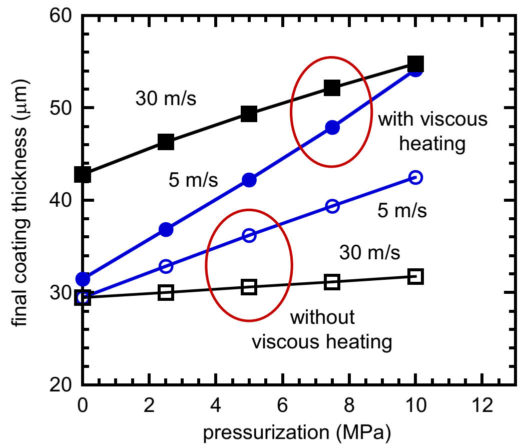

Fig. 6 Effects of pressurization on maximum resin temperature (a) and final coating thickness (b) for fiber drawing speeds of 5 and 30 m/s

the pressurization effect is shown less pronounced due to higher viscous force by moving glass fiber, but the flow velocity gradient near the coating die wall becomes steeper showing the increased intensity of viscous heating at higher level of the pressurization.

In Fig. 6, the effects of die pressurization on final coating thickness are shown for the cases of the low and high fiber drawing speeds with and without the inclusion of viscous heating in the simulations. As discussed earlier, pressurization of coating die increases final coating thickness less effectively at higher fiber coating speed. Another finding would be that die pressurization boosts the viscous heating, and increase of final coating thickness due to pressurization is amplified to some extent when the viscous heating is present in the resin flows.

IV. Conclusions

As the fiber drawing speed continually increases in optical fiber manufacturing to achieve higher volume production, viscous heating effects should be considered in the resin coating process of glass fibers at high fiber drawing speed. In this article, two-dimensional axisymmetric laminar flows of coating resin in the capillary coating die of optical fiber coating applicator are numerically simulated in order to appreciate the effects of viscous heating and subsequent temperature increase in coating resin. Temperature dependent resin viscosity is also included in the flow simulations.

Resin flows are driven by fast moving glass fiber and the pressurization at the coating die inlet. As the fiber drawing speed increases, there exists the severe viscous heating confined very near the coating die wall. This significantly affects the radial velocity distributions and increases the final coating thickness. Increasing level of die pressurization also augments viscous heating and temperature rise in resin flows. Therefore, precise control of final coating thickness on the glass fiber requires the thorough understanding of the effects by the viscous heating in capillary coating die flows.

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