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# NUMERICAL SIMULATION OF GLASS FIBER COOLING IN HIGH-SPEED OPTICAL FIBER PRODUCTION SYSTEM

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## ABSTRACT

*In optical fiber production, it is necessary to cool down glass fiber from furnace before liquid coating. This study focuses on the numerical investigation of glass fiber cooling process with helium supply. The results confirm the cooling effectiveness of helium supply compared to the case of no helium usage at higher fiber draw speed. The increase in helium supply enhances the fiber cooling by reducing the air entrainment. Helium cooling effect is found to be discrete when increasing fiber draw speed or helium supply rate, while it also depends on helium supply direction. There exists a certain threshold of helium supply rate for the saturation of fiber cooling effectiveness, as the fiber cooling ceases to improve after this threshold.*

**Key words:** Optical fiber, glass fiber, fiber cooling, numerical simulation.

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## 1. INTRODUCTION

As the silica-based optical fibers are widely used for many industrial applications in telecommunications and other technical areas, they are usually made of silica glass fiber as a medium for superior optical signal transmission and double layer coatings of polymer resins for providing fiber strength and surface protection [1,2]. The typical mass manufacturing systems of optical fibers are essentially an automated in-line process of high precision. This process consists of drawing of very thin glass fiber from melted silica preform in draw furnace, cooling of drawn glass fiber in a dedicated fiber cooling units, and liquid double layer coating of polymer resins on bare glass fiber surface followed by UV curing, as depicted in Figure 1 [3].

Predictably the mass productivity of optical fiber manufacturing greatly depends on fiber draw speed and, thus, the fiberoptics industry keep trying to increase the fiber draw speed. In 1970s when the present type of in-line optical fiber production system was first established, fiber draw speed was only several hundred mpm (meters per minute) [4]. At low fiber draw speed, glass fiber cooling relied on air cooling without any dedicated cooling unit [5]. However, fiber draw speed is currently exceeding 2000 mpm and the air cooling is not sufficient for the glass fiber from draw furnace cooled down enough to a certain required temperature before the glass fiber enters coating applicator. If glass fiber goes into coating process with high temperature, it is known that coating liquid could be deteriorated [5] or it would be the reason of coating flow instability [6], which may adversely affect the fiber coating quality.

Thus, the fiber cooling necessitates a dedicated cooling unit between draw furnace and coating applicator and there exist several computational research efforts on analyzing fiber cooling process [7-9]. Convective cooling flow was modeled and examined in annular passages with moving fiber of constant speed by Vaskopulos et al. [7], while Tschümperlé and Nicolardot [8] carried out numerical simulations for fiber cooling tube. Also, Kim et al. [9] found that the effects of air entrainment into helium injected cooling unit could be significant in lowering fiber temperature.

In the present study of optical fiber manufacturing, the glass fiber cooling process has been numerically modeled and simulated in order to investigate the effects of various system and process parameters such as fiber draw speed, cooling gas flowrate, and supply direction of cooling gas on fiber cooling effectiveness using convective and radiative thermal model of high-speed glass fiber cooling unit.

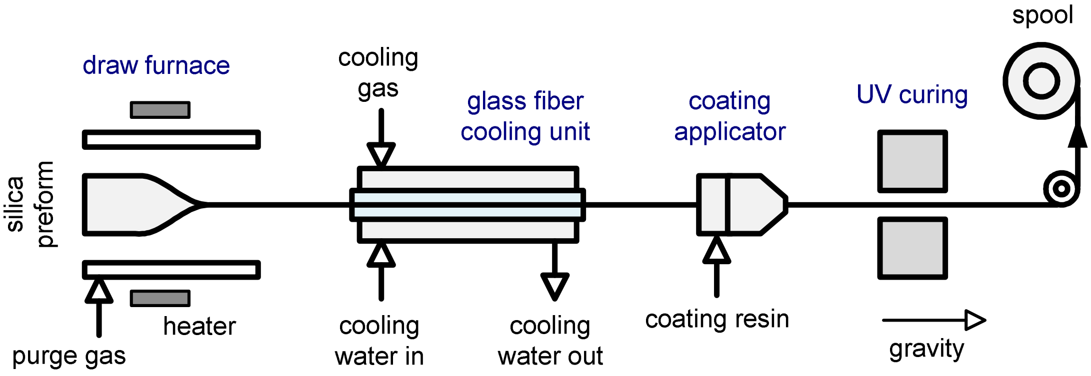

**Figure 1** Mass manufacturing process of silica-based optical fibers

## 2. NUMERICAL MODEL OF GLASS FIBER COOLING

The actual shape of cooling unit is quite complex but it is simplified into a geometric model of cooling unit in the form of long circular tube for the present computational study of fiber cooling process, as illustrated in Figure 2. The glass fiber drawn from furnace is cooled down while it passes through this cooling unit with cooling gas supply. In order to increase cooling effectiveness and shorten the cooling unit, it is customary to use helium as a cooling gas, even though helium is quite expensive. Note that the use of helium gas is essential in many sub-processes in optical fiber manufacturing system including glass fiber draw furnace [10]. Therefore, it is a great interest for fiberoptics industry to reduce helium usage without compromising the precision and productivity of optical fiber manufacturing process.

In this geometric model of fiber cooling unit, the inner diameter of cooling unit is 10 mm, while its length is 1.5 m. The diameter of glass fiber is set to be the industry standard 125 μm. Glass fiber enters and leaves the cooling unit through small holes of 4 mm diameter at the center. Note that small short tubes of 4 mm inner diameter and 10 mm length are attached to the entrance and exit holes of glass fiber, which is found to reduce the air entrainment from outer environment. Helium gas can be supplied into cooling unit through the annular shaped entrance either installed around fiber inlet or exit. Therefore, helium gas enters cooling unit either in fiber direction or opposing direction. The inner and outer diameters of this cooling gas entrance are 7 and 10 mm, respectively.

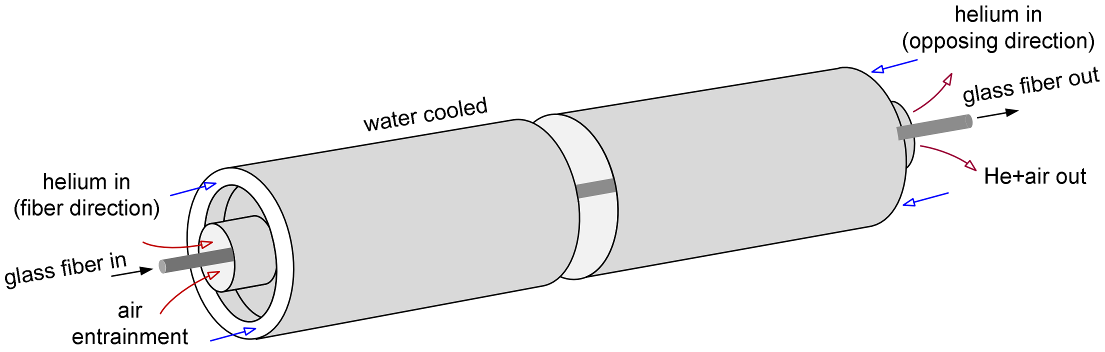

**Figure 2** Schematic diagram of glass fiber cooling unit with helium gas supply.

Convective and radiative heat transport of cooling gas in the glass fiber cooling unit is numerically simulated along with advection of moving glass fiber in the two-dimensional axisymmetric domain. Since the dimensions of glass fiber and cooling tube are small, the cooling gas is assumed to be laminar steady flow and the following forms of governing equations for mass, momentum, and energy conservation principles are employed in the numerical computations.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{V})}{\partial t} + (\nabla \cdot \rho \mathbf{V})\mathbf{V} = -\nabla p + \nabla \cdot \boldsymbol{\tau} \tag{2}$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [\mathbf{V}(\rho E + p)] = \nabla \cdot [k \nabla T - \sum_j h_j \mathbf{J}_j + \boldsymbol{\tau} \cdot \mathbf{V}] + S_r \tag{3}$$

Since the air enters with glass fiber into cooling unit, the following species transport equation is also considered for the mass concentrations ($Y_i$) of helium and air species in the gas mixture.

$$\frac{\partial (\rho Y_i)}{\partial t} + (\nabla \cdot \rho \mathbf{V}) Y_i = -\nabla \cdot \mathbf{J}_i \tag{4}$$

In Equations (3) and (4), $\mathbf{J}_i$ represents the diffusion flux of gas species $i$ which includes mass diffusion due to concentration gradients and thermal diffusion due to temperature gradient as follows.

$$\mathbf{J}_i = -\rho D_{mi} \nabla Y_i - D_{ti} \frac{\nabla T}{T} \tag{5}$$

Transport properties of helium and air mixture are evaluated by simple ideal gas mixing law [11]. As temperature variation is expected to be large in gas flow, temperature dependence of those transport properties is also considered in the gas property computations. The surface to surface (S2S) thermal radiation is considered between cooling tube and glass fiber surfaces. The surface emissivity is given to be 0.885 [12]. However, the effect of gas radiation is neglected, since the cooling gas consists of mostly monatomic and diatomic gases.

In performing thermo-fluid simulations, commercial CFD software, ANSYS FLUENT, has been employed in solving above mentioned governing equations, where the computational domain is resolved into the structured computational mesh system. Through a series of mesh sensitivity tests, total number of 28,000 cells is found to be enough in this numerical study. Note that more meshes are placed near the surface of fast moving glass fiber and cooling unit inlet/exit in order to account for large velocity and temperature gradients.

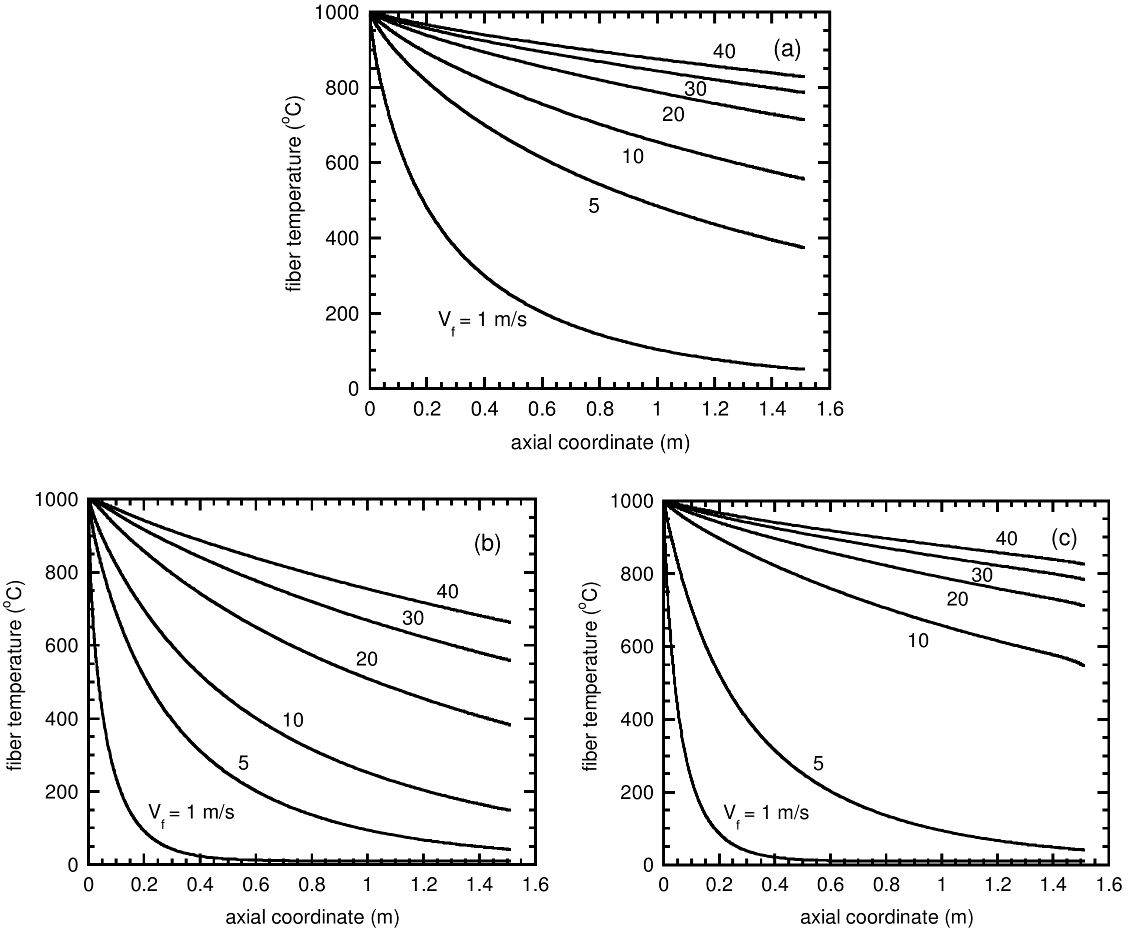

**Figure 3** Effects of fiber draw speed on axial variation of glass fiber temperature: (a) no helium supply; (b) helium supply of 5 LPM in fiber direction; (c) helium supply of 5 LPM in opposing direction.

## 3. RESULTS AND DISCUSSION

In this computational study of glass fiber cooling process, the effects of fiber draw speed and helium supply rate are investigated on fiber cooling effectiveness. Glass fiber freshly drawn from softened silica preform is assumed to enter the cooling unit at temperature of 1000°C. The cooling unit is usually cooled by circulation of cooling water and, thus, the inner surface temperature of cooling tube is set to be 10°C. The incoming helium supply and possible air entrainment are also at temperature of 10°C. As depicted in Figure 2, helium gas could be supplied either in fiber direction near fiber inlet or opposing direction against fiber movement near fiber exit.

### 3.1. Effects of Fiber Draw Speed on Fiber Cooling

In order to assess the fiber cooling effectiveness in using helium gas, the cooling process has been first simulated without any helium supply and compared with the cases with helium supply. In this case of no helium supply, the cooling unit is expected to be filled with air only from air entrainment at the fiber inlet. Figure 3(a) contains the axial variation of fiber temperature from inlet to exit for fiber draw speed from 1 to 40 m/s (or 60 to 2400 mpm) when there is no helium supply, as this shows the difficulty of natural fiber cooling with air at higher fiber draw speed. Thus, glass fiber cooling system of present high speed optical fiber production system requires the helium supply. In Figure 3(b), the use of 5 LPM helium supply in fiber direction is applied for identical range of fiber draw speed, showing that the fiber cooling is significantly improved at each fiber draw speed tested.

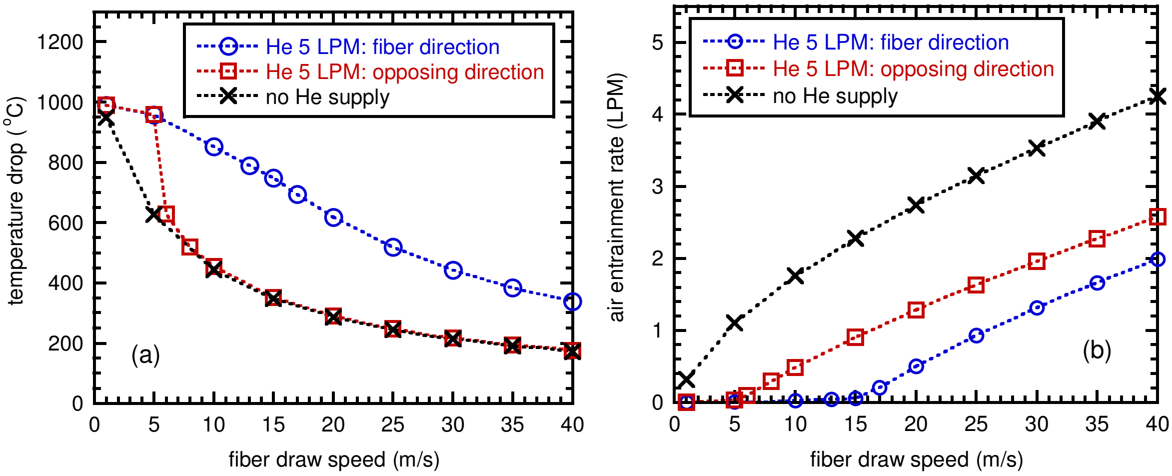

**Figure 4** Effects of fiber draw speed on (a) total fiber temperature drop in cooling unit and (b) air entrainment rate at the fiber inlet of cooling unit.

In contrast, the cases with helium supply into cooling unit in opposing direction reveals more complicated effects in Figure 3(c). At lower fiber draw speed such as 1 and 5 m/s, the cooling effectiveness is nearly identical to cases of helium supply in fiber direction. However, helium supply of 5 LPM in opposing direction does not provide comparable cooling rate of helium supply in fiber direction at higher fiber draw speed over 10 m/s and, in fact, the improvement of fiber cooling is quite negligible when compared to cases without helium supply. Figure 4(a) summarizes the cooling effectiveness for those three cases with 5 LPM helium supply in different directions and with no helium supply as the fiber temperature change or drop from fiber inlet to exit. This clearly shows that the helium supply enhances the convective cooling of glass fiber at higher fiber draw speed.

However, helium supply in opposing direction is effective only at lower fiber draw speed but not effective at higher fiber draw speed, exhibiting discrete change of temperature drop between 5 and 6 m/s of fiber draw speed. This can be explained by looking into the amount of air entrained with glass fiber at the cooling unit inlet such as in Figure 4(b). Without any helium supply, the air entrainment rate at the inlet is great and it increases constantly with fiber draw speed. In cases of helium supply, the discrete change of air entrainment rate can be observed with increase of fiber draw speed, though differently by helium supply direction. When the helium is supplied in opposing direction, it can be seen that fiber draw speed at this discrete change coincides with 5 to 6 m/s of sudden change in fiber temperature drop discussed in Figure 4(a). When the helium is supplied in fiber draw direction, air entrainment is suppressed up to 15 m/s of fiber draw speed and the fiber cooling is much more effective than the case of helium supply in opposing direction.

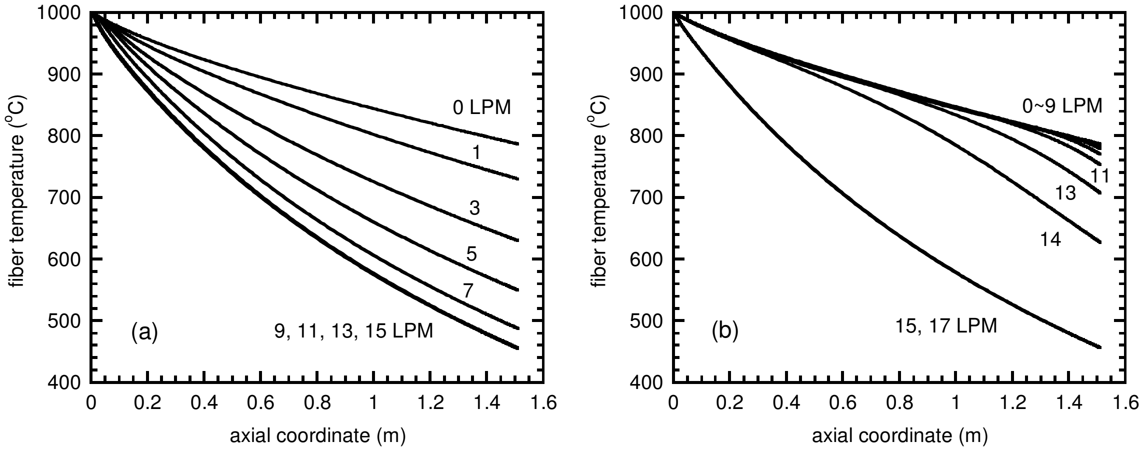

**Figure 5** Effects of helium supply rate on axial variation of glass fiber temperature at fiber draw speed of 30 m/s: (a) helium supply in fiber direction; (c) helium supply in opposing direction.

## 3.2. Effects of Helium Supply Rate on Fiber Cooling

At this time, the effects of helium supply amount into cooling unit on the fiber cooling effectiveness are investigated, while fiber draw speed is fixed at 30 m/s or 1800 mpm, which speed represents the process condition in current optical fiber production. The helium supply rate is varied from 0 (no helium supply) to 15 LPM in both supply directions. The computational results of axial fiber temperature variation are shown for the cases of helium supply in fiber and opposing directions in Figures 5(a) and (b), respectively. At this high speed fiber drawing process, the increase in helium supply improves the fiber cooling noticeably in Figure 5(a) but up to the rate of 7 LPM, when helium is supplied in fiber direction. After this amount of helium, further increase in helium supply does not improve the fiber cooling effectiveness any more, as can be seen in helium supply cases of 9, 11, 13, and 15 LPM.

Figure 5(b) now shows the effects of helium supply in opposing direction on fiber cooling. Here, the helium supply up to 9 LPM does not provide any significant cooling enhancement from the case of no helium supply. In order to have helium cooling effect, more than 9 LPM of helium supply is required. The effects of helium supply rate on fiber cooling are compiled into Figure 6(a) as total fiber temperature drop, as these results can be compared and discussed with air entrainment rate for both directions of helium supply in Figure 6(b). In those figures, the computational results without inclusion of surface-to-surface radiation are also listed to show the effects of radiative cooling. There is some significant difference in fiber temperature especially when convective cooling is relatively weak. However, the inclusion of radiation does not affect the amount of air entrainment noticeably, as shown in Figure 6(b).

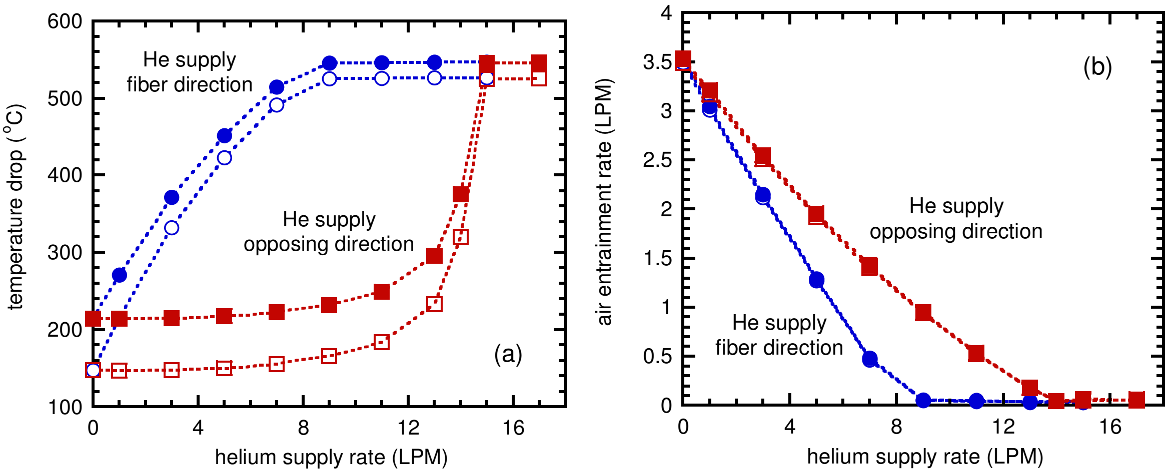

**Figure 6** Effects of helium supply rate in fiber and opposing directions on (a) total fiber temperature drop in cooling unit and (b) air entrainment rate at fiber draw speed of 30 m/s. Filled symbols represent the computational results with radiation effects, while open symbols are from computations without radiation.

In case of helium supply in fiber direction, the introduction of helium into cooling unit makes rather gradual and linear change in fiber temperature drop at first when the helium supply rate increases from 0 LPM. However, the cooling effectiveness becomes rather saturated once helium supply rate reaches approximately 9 LPM. Further increase of helium supply does not give any significant increase in fiber cooling effectiveness. This saturation of helium supply effect on fiber cooling can be compared with change of air entrainment rate shown in Figure 6(b). The introduction and increase of helium supply helps to reduce the air flow entrained into cooling unit and, thus, increase helium content in cooling gas and convective transport on glass fiber surface. However, when helium supply rate reaches approximately 9 LPM, the air entrainment is reduced to its minimum and, thus, fiber cooling is not enhanced further after this amount of helium supply.

When helium is introduced in opposing direction, it is quite different how the fiber cooling is affected by increase of helium supply. Starting from 0 LPM, increase of helium supply rate delivers little change in fiber cooling up to approximately 9 LPM. It is implied that helium introduced does not increase helium content in cooling gas for significant portion of cooling unit, as most of helium leaves the cooling unit through fiber exit with glass fiber, not spreading deep into the cooling unit. As the helium supply rate increases by passing over 10 LPM, the cooling effect by helium finally shows up and it is quite discrete by showing sudden jump in fiber temperature drop around 13 LPM of helium supply. Here also, additional improvement of fiber cooling effectiveness ceases over certain rate of helium supply, which is approximately 14 LPM. Once again, this threshold matches the helium supply rate for reducing the air entrainment to minimum but this threshold is significantly higher than corresponding value for helium supply in fiber direction.

## 4. CONCLUSIONS

In this computational study of optical fiber manufacturing, glass fiber cooling process in fiber cooling unit with helium supply is numerical modeled and simulated in order to appreciate how fiber draw speed, helium supply rate, and helium supply direction affect the fiber cooling effectiveness. The important findings in this investigation can be summarized into the followings:

1. The introduction of helium into fiber cooling unit enhances fiber cooling by reducing the amount of air entrainment which enters the unit with fast moving glass fiber. The air entrainment increases with fiber draw speed, which in turn requires higher helium supply rate to reduce the air entrainment to its minimum and achieve sufficient fiber cooling.
2. At higher draw speed of present optical fiber manufacturing system, a certain threshold of helium supply rate exists for saturation of cooling effectiveness. The helium supply in fiber direction is found to be significantly more effective than the helium supply in opposing direction. Depending on helium supply direction, the increase in helium supply rate differently affect the fiber cooling effectiveness.

## ACKNOWLEDGMENTS

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