SIMULATION OF FLUID FLOW AND MASS DIFFUSION IN IRRADIATOR TUBE

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Abstract: *This paper presents a numerical study of fluid flow and mass transfer in an irradiator tube. Optical fibers and wires are drawn through a coating die to apply protective coating of synthetic materials, and then passed through a glass tube where UV light from the surrounding irradiators causes curing of the coating materials. During this curing process, fumes are generated which needs to be washed out of the tube before it diffuses to the glass wall and causes tube smoking, a problem faced in the industries. Calculations are done to study the effect of laminar and turbulent flow, flow rate and tube diameter. Numerical simulation for the purging air flow and mass transfer of the generated chemical species is done using a computational model and results are presented. The irradiator tube flow with a lip at exit, as normally used by the industry is first simulated. The mass concentration profiles show that the concentration of generated species near the glass tube wall is high, which explains tube smoking. Simulations are repeated without the lip, and the mass concentration near the tube wall is found to be much less, which suggests elimination of tube smoking problem. Computations are also done for larger tube diameter and without the lip, which gives lowest mass concentration near the glass wall. Experiments are carried out to verify the simulated results. Experimental results show that irradiator tube smoking occurs for lip condition, but by removing the lip the tube smoking problem can be eliminated, which is desirable.*

INTRODUCTION

Generation of fume during curing of the coating material of optical fibers and wires is a common problem faced by the industries. Various wires and optical fibers for telecommunication have to apply some synthetic coating of polymers for cushioning and protection of the fibers and wires. In this modern technological world, huge amount of data is being transferred through optical fibers. As optical fibers are basically made of glass of very small diameter through which telecommunication data passes at tremendous speed in the form of photons or light, so the quality of the protective coating materials is very important. The wires or fibers are drawn through coating dies for applying the coating material, and then they are passed through transparent glass tubes surrounded by UV irradiators. The UV light from the irradiators causes curing of the coating materials while generating fumes of some chemical species. Air or Nitrogen gas flows through these transparent irradiator glass tubes to purge or flush out the fumes. But some of these generated species travel through mass diffusion across the tube, from the fiber or wire at the center to the tube glass wall. At the wall, due to the heat generated by the UV radiation, these species are pyrolyzed (burnt) and the glass tube wall loses its transparency. This is known as tube smoking. Due to this tube smoking, sufficient UV light from the irradiators can not pass through the glass tube, and the curing of the coating material of the optical fiber or wire becomes incomplete. Consequently, the continuous drawing process has to be stopped frequently for changing the irradiator tubes. This in turn reduces production and increases cost, which is undesirable.

The size of the irradiator glass tube used, laminar or turbulent flow of gases through the tube for purging of the generated species, inlet and exit condition of the gases in the tube, all have different effects on the mass diffusion of the species across the tube to cause tube smoking. Hence, an in-depth knowledge of the properties is required to eliminate the tube smoking problem. In industrial product development, designers are aided by experiments, but as a

Nomenclature

C_A	molar concentration of species A	t_c	convective time
C_1, C_2, C_μ	coefficients in turbulence model	t_d	diffusive time
D_{AB}	binary mass diffusion coefficient	u_i	mean velocity
d_{ij}	mean deformation rate tensor	v^*	friction velocity
k	turbulent kinetic energy	V	average velocity in the tube
L	length of the irradiator tube	x	axial coordinate
$\dot{N}_A$	generation of species *A* due to chemical reaction	ε	dissipation rate of turbulence kinetic energy
P	mean pressure	ε_m	turbulent mass diffusivity
Q	flow rate of purging air	ν	kinematic viscosity
r	radial coordinate	ν^T	turbulent or eddy viscosity
R	radius of the irradiator tube	ρ	constant mass density
Re	Reynolds number	σ^k	turbulent Prandtl number corresponding to *k*
R_{ij}	Reynolds stress tensor	σ^ε	turbulent Prandtl number corresponding to ε
S_c^T	turbulent Schmidt number	τ_o	shear stress at the wall

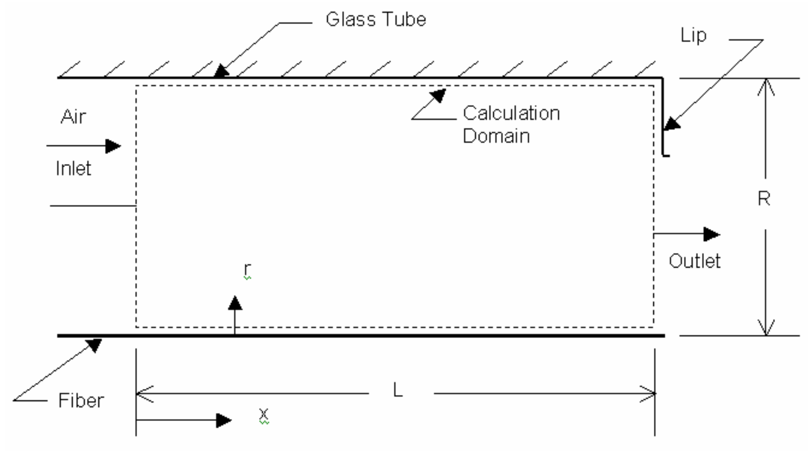

Figure 1: Geometry of an irradiator tube.

supplement to them, economical design and operation can be greatly facilitated by the availability of prior properties of the flowfield through some computational model. Due to proprietary or confidential nature of the problem, much literature is not available on this topic for reviewing.

The objective of the present study is to obtain numerical predictions for the laminar and turbulent flow and mass diffusion in the irradiator tube for various flow rates and tube diameters, and to analyze the effect of the exit condition, to minimize tube smoking and improve performance. Though sophisticated turbulence models have been developed, yet the k – ε model is still widely used in the industry due to its simplicity and as it has already been accommodated into many commercially available computer codes. Hence, in the present study the k – ε model[1] is used for turbulence calculations.

PROBLEM STATEMENT

The flow of gas through a typical irradiator tube is shown in Fig. 1. The optical fiber or wire being drawn is shown at the centerline. In a vertical draw tower, a thin controlled layer of synthetic coating is applied to the wire or fiber while passing through a coating die, just before entering this tube. The transparent glass tube has a radius R and a length L. The UV light of specific intensity from the irradiators around the transparent tube is used to cure the coating material as it passes through the tube. During this curing process fumes of some chemical species are given out from the coating material. Purging air or nitrogen gas enters the tube at inlet and tries to flush these species through the outlet. Honeycomb flow straightners are used at inlet to straighten the gas flow and reduce vibration of the fiber or wire, to maintain a uniform thin layer of coating on the fiber. For holding the vertical irradiator glass tubes in the draw tower, extended metallic annular strip or lips are used, which might affect the flow of purging gas. Some of these species generated during the curing process of the coating material, travel across the tube by mass diffusion to the glass wall. Due to the heat of UV light from the irradiators, the species at the glass tube wall are burnt and sticks to the wall, and the glass tube loses its transparency, which becomes worse with time. This is called Tube Smoking. After a few hours, the transparency of the irradiator glass tubes becomes so low that the UV light coming from the irradiators through the glass tubes are not sufficient to complete the curing process of the coating material, and the optical fiber or wire being drawn has to be discarded. As a result, the drawing process has to be stopped frequently for changing the irradiator glass tubes, which means loss of production capability and increase in production cost. To solve this problem, irradiator tubes are to be designed which does not cause tube smoking even after extended hours of use and allows continuous draw of optical fiber or wire in the draw tower, assuring product quality.

SIMPLIFIED MODELING AND ANALYSIS

For understanding the irradiator tube smoking, as preliminary or first round analysis of the problem, the convective time required to purge or flush the generated species out of the tube and the diffusive time required for mass diffusion of the species to the tube wall are calculated.

Nitrogen or air at a flow rate Q enters the irradiator tube at inlet, to flush the species generated from the coating materials of the fiber or wire during the curing process, out of the tube before it diffuses to the tube wall. The convective time t_c required for this is calculated as,

$$t_c = L/V \tag{1}$$

where L is the length of the irradiator tube and V is the average velocity in the tube found as,

$$V = Q/.A \tag{2}$$

Here, A is the cross-sectional area of the tube.

The diffusive time t_d required by the generated species to travel through mass diffusion from the center of the irradiator tube to the glass wall for laminar or turbulent flow is calculated as,

$$t_d = \frac{R^2}{D_{AB}} \quad \text{(laminar)} \tag{3}$$

$$t_d = \frac{R^2}{D_{AB} + \varepsilon_m} \approx \frac{R^2}{\varepsilon_m} \quad \text{(turbulent)} \tag{4}$$

where, R is the radius of the tube, D_{AB} is the binary mass diffusion coefficient or mass diffusivity, and ε_m is the turbulent or eddy mass diffusivity. The turbulent mass diffusivity can be written as,

$$\varepsilon_m = \frac{\nu^T}{S_C^T} \tag{5}$$

Here, ν^T is the turbulent or eddy viscosity and S_c^T is the turbulent Schmidt number.

An irradiator glass tube of diameter 0.022 m and length 1.2 m is first considered. The flow of gas through

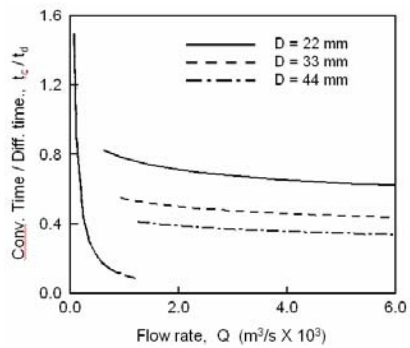

Figure 2: Comparison of convective / diffusive time profiles for laminar and turbulent flow.

the tube for Reynolds number $R_e \geq 2300$ is assumed turbulent. As the properties of the materials being used at the industries are proprietary or confidential and can not be published, so the binary mass diffusion coefficient for preliminary analysis is considered as $D_{AB} = 0.28\times10^{-4}$ m^2/s, corresponding to ammonia and air. The convective and diffusive time for various flow rates having laminar flow are calculated using Eqs. (1) and (3) above, and their ratio t_c/t_d plotted in Fig.2 for different flow rates. For calculating the Reynolds number,

$$R_e = VD/\nu \tag{6}$$

the kinematic viscosity was assumed as $\nu = 15.86\times10^{-6}$ m^2/s.

Shear stress at the wall for turbulent flow through pipes can be calculated as[2],

$$\tau_o = \frac{1}{8}\lambda\rho V^2 \tag{7}$$

For frictional resistance of smooth pipes, Blasius gave[2],

$$\lambda = 0.3164 R_e^{-0.25} \tag{8}$$

Hence, the friction velocity v^* becomes,

$$v^* = \sqrt{\frac{\tau_o}{\rho}} = \sqrt{\frac{\lambda}{8}}\, V \tag{9}$$

For estimating the eddy viscosity, it is found from Schlichting[2],

$$\frac{\nu^T}{v^* R} = 0.08 \tag{10}$$

From the data of Groenhof[3] and Notter and Sleicher[4] the turbulent Schmidt number is taken as,

$$S_c^T = 0.8 \tag{11}$$

The convective and diffusive time for various flow rates having turbulent flow are calculated using Eqs. (1), (2) and (4)–(11), and their ratio t_c/t_d plotted in Fig.2 for different flow rates.

The above calculations are also repeated for larger tube diameters 0.033 m and 0.044 m, but having same tube length of 1.2 m, at different flow rates and the results plotted in Fig. 2.

In Fig.2, the horizontal axis shows the variation of flow rate, and the vertical axis shows the variation of the convective to diffusive time ratio, t_c/t_d for three different irradiator tube diameters. For laminar flow, the curves for all three diameters merge into a single one, and decreases rapidly with the increase of flow rate, until reaches transition to turbulent flow. When the flow becomes turbulent, the convective to diffusive time ratio, t_c/t_d suddenly jumps. A low value of t_c/t_d means the convection time required for the fume to travel along the tube length and flush out is smaller than the diffusion time required for traveling across the flow by mass diffusion to the tube wall. Hence, a low value of t_c/t_d is desirable to eliminate the tube smoking problem. For turbulent flow, the eddy mass diffusivity ε_m is much larger compared to the binary mass diffusion coefficient D_{AB}, and as can be seen from Eq. (4) the diffusive time required t_d becomes much smaller. Though the convective time required t_c also decreases with increase of velocity, but not at the same rate as t_d, hence the ratio t_c/t_d increases as the flow transition from laminar to turbulent. The flow rate of purging gas corresponding to laminar flow might not be sufficient to remove all the fumes generated, and so in most cases the flow has to be turbulent.

For turbulent flow through a particular tube diameter, as the flow rate increases the velocity also increases, and from Eq. (1) convective time t_c reduces. But with the increase of velocity, turbulent or eddy mass diffusivity ε_m also increases to some extent, which causes a decrease of diffusive time t_d, from Eq. (4). Consequently, for turbulent flow through a particular tube diameter, with the increase of flow rate the ratio t_c/t_d does not decrease appreciably. This means by increasing the flow rate alone, might not remove the tube smoking problem. On the other hand, excessive increase of flow rate might cause fiber vibration, which again will cause non-uniformity in the coating thickness and fiber defect.

For a particular turbulent flow rate, when the tube diameter increases, the velocity and eddy mass diffusivity reduces. From Eqs. (1) and (4), convective and diffusive time t_c and t_d will both increase, but t_d will increase more than t_c. As a result, the convective / diffusive time ratio t_c/t_d will decrease appreciably. For example, at a flow rate Q = 4 cfm = 1.888×10^{-3} m^3/s, for tube diameters D = 22mm, 33mm and 44mm, the t_c/t_d ratios are 0.719, 0.504 and 0.392, respectively. This means that increasing the tube diameter from 22mm to 44mm will help in eliminating the tube smoking problem.

DETAILED COMPUTATIONAL SIMULATION

In order to have a better understanding of the tube smoking problem, the fluid flow and the mass diffusion in the irradiator tube is simulated using a CFD tool.

Basic Equations and Numerical Details: The equations governing the mean turbulent motion of an incompressible fluid using the k – ε model closure of Launder and Spalding[1] are given as,

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{12}$$

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} R_{ij} \tag{13}$$

$$u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu^T}{\sigma^k}\right)\frac{\partial k}{\partial x_j}\right] - R_{ij}\frac{\partial u_i}{\partial x_j} - \varepsilon \tag{14}$$

$$u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu^T}{\sigma^\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C_1 \frac{\varepsilon}{k} R_{ij}\frac{\partial u_i}{\partial x_j} - C_2 \frac{\varepsilon^2}{k} \tag{15}$$

Here, the flow is assumed to be steady. Equations (12) – (15) are the statements of conservation of mass, balance of linear momentum, conservation of turbulence fluctuation energy, and transport equation for turbulence dissipation rate. In these equations ρ is the mass density, u_i is the mean velocity, ν is the kinematic viscosity, ν^T is the turbulent or eddy viscosity, P is the mean pressure, ε is the dissipation rate, k is the fluctuation kinetic energy, σ^k and σ^ε are the turbulent Prandtl numbers corresponding to k and ε. In all these equations regular tensor notation with Latin subscripts is employed. The Reynolds stress tensor is given as,

$$R_{ij} = \frac{2}{3}k\delta_{ij} - 2\nu^T d_{ij} \tag{16}$$

The mean deformation rate tensor is,

$$d_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{17}$$

and the eddy viscosity is given as,

$$\nu^T = C_\mu \frac{k^2}{\varepsilon} \tag{18}$$

where C_μ is a constant. The turbulence model constants are assigned the following values[1]

$$C_\mu = 0.09,\ C_1 = 1.44,\ C_2 = 1.92,\ \sigma_k = 1.0,\ \sigma_\varepsilon = 1.3 \tag{19}$$

The conservation of chemical species or transport equation for species concentration, for the steady mean turbulent flow can be written as,

$$u_j \frac{\partial C_A}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(D_{AB} + \varepsilon_m\right)\frac{\partial C_A}{\partial x_j}\right] + \dot{N}_A \tag{20}$$

Here, C_A is the molar concentration of species A, D_{AB} is the binary mass diffusion coefficient, ε_m is the turbulent or eddy mass diffusivity as given by Eq. (5), and $\dot{N}_A$ is the generation of species A due to chemical reaction.

The computational domain for the irradiator tube flow is shown in Fig.1. A jet of air with a flow rate, Q = 4 cfm = 1.888×10^{-3} m^3/s enters the tube through the annular space close to the wall at inlet. The optical fiber or wire with the coating material is drawn through the centerline. The function of the air is to purge or flush the species generated from the fiber coating material during curing before it diffuses to the glass wall. The irradiator glass tube has a length L = 1.2 m, and two radius of R = 0.022 m and 0.044 m, are considered for comparison. At the outlet, an annular metallic strip or Lip for holding the tube with a radial thickness of 0.003 m is also considered to study its effect on the flow and mass diffusion.

A staggered mesh finite volume method is used to discretize the differential equations written as Eqs. (12) – (20). The computational domain is divided into a 110 X 34 non-uniform grid with finer spacing in the regions of large spatial gradients. The above differential equations are integrated over their appropriate staggered control volumes and discretized using a hybrid differencing scheme[5]. No slip boundary conditions along with wall functions are applied at solid walls. The turbulence kinetic energy k and the dissipation rate ε at inlet are calculated as

$$k_{in} = \lambda_1 u_{in}^2 \ ; \ \varepsilon_{in} = \frac{k_{in}^{3/2}}{\lambda_2 R} \tag{21}$$

where u_{in} is the axial velocity of air at inlet, λ_1 and λ_2 are two constants having the values of 0.03 and 0.02, respectively. As the properties of the materials being used at the industries are proprietary or confidential and can not be published, so the binary mass diffusion coefficient is considered as $D_{AB} = 0.28\times10^{-4}$ m^2/s, corresponding to ammonia and air. The turbulent Schmidt number is taken as, S_c^T = 0.8. At the outlet boundary zero gradient conditions are applied. The discretized equations with boundary condition modifications are solved using the SIMPLE[6] and TDMA algorithm. Here, semi-implicit line-by-line relaxation method is employed to obtain converged solutions iteratively. Under relaxation factors are also used to promote computational stability.

RESULTS AND DISCUSSION

The turbulent flow of the purging air and the mass transfer of the species generated during curing of the coating materials in the irradiator tube, as shown in Fig. 1, are analyzed numerically using the above computational code and the results are presented below. The model was previously used to simulate the turbulent flow in a combustor for the experimental condition of Brum and Samuelsen[7], and the results were published in Chowdhury and Noman[8]. The simulated results were in good agreement with the experimental data, which shows that the present numerical model has the capability of predicting complex turbulent flows with reasonable accuracy.

The computational model is first used to analyze the fluid flow and mass transfer of Fig. 1, having a metallic lip for holding the glass tube in vertical position in the draw tower, which is normally done in the industry. The tube diameter (D = 2R) is taken as 0.022 m, the length (L) as 1.2 m, and the lip is extended 0.003 m inside the tube. The annular jet of air at inlet is assumed to enter through the flow straightners with a uniform inlet axial velocity and a flow rate, Q = 4 cfm = 1.888×10^{-3} m^3/s. The corresponding Reynolds number in the tube is Re = 6890, which means the flow is turbulent.

The molar mass concentration of the species, C_A generated during curing of the fiber coating material at the tube centerline is computed and presented in Fig. 3. In this figure, the radial distribution of the mass concentration at three different axial locations, x/L = 0.1, 0.5, and 0.9 are shown. Here, x is the axial distance from the inlet of the tube and R is the tube radius. It is found that, at x/L = 0.1, close to the inlet the mass concentration, C_A near the tube wall is very low. At x/L = 0.5 and 0.9, the mass concentration near the tube center increases significantly compared to that at x/L = 0.1. The mass concentration from the tube center to the wall decreases sharply, but it is still quite large near the wall at larger x/L. As the species generated during curing of the coating materials are being flushed downstream, their concentration would increase along the centerline. But high values of concentration near the wall indicates that a large amount of species travel by mass diffusion across the flow to the tube wall before they are being flushed out. Due to the heat of the UV lamps, some of the species attached to the wall near x/L = 0.9, where the concentration is high enough will pyrolyze (burn) and produce some dark gummy substance which stick to the wall. These sticky substances change the characteristics of the flow near the wall. With time the concentration of these burnt sticky substance near the downstream end of the tube increases and they extend upstream. After a few hours of operation, the entire glass tube becomes dark, and the transparency becomes so low that sufficient UV light from the irradiators can not enter for curing the coating material any more. As mentioned above, this problem is known as tube smoking. The fiber or wire drawing process has to be stopped for changing the tube, which means a loss of production and increase of manufacturing cost, and is undesirable.

For finding a possible solution to the tube smoking problem, the computational model is then used to analyze the flow of Fig. 1, but without the lip. As above, the tube

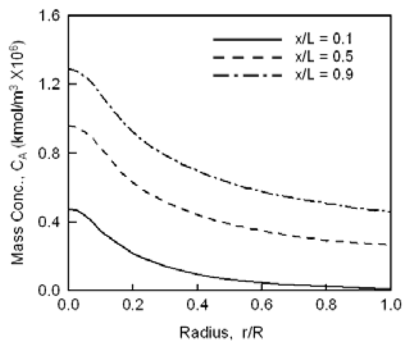

Figure 3: Comparison of mass concentration profiles for 22mm diameter tube and with Lip condition.

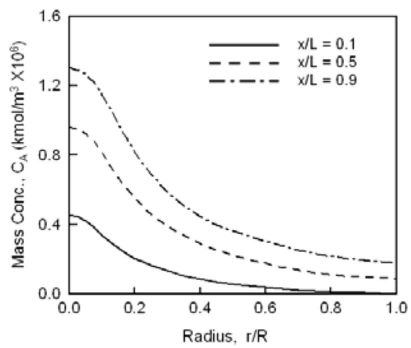

Figure 4: Comparison of mass concentration profiles for 22mm diameter tube and No Lip condition.

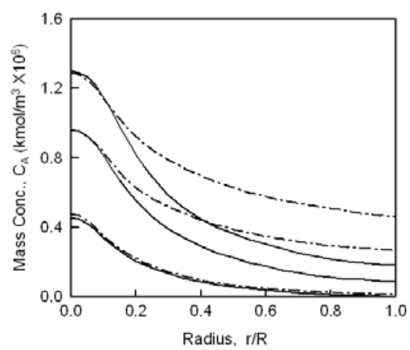

Figure 5: Comparison of mass concentration profiles (22mm dia tube): solid line for No Lip and dashed line for Lip condition.

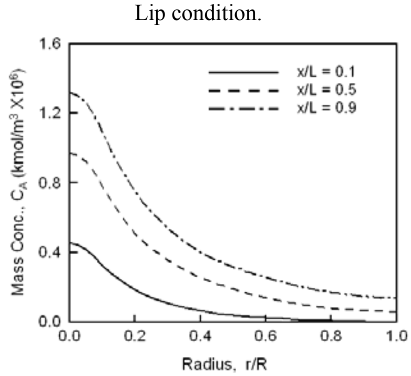

Figure 6: Comparison of mass concentration profiles for 44mm diameter tube and No Lip condition.

diameter (D) is taken as 0.022 m and the length (L) as 1.2 m. The flow rate of purging air, Q = 4 cfm (1.888×10^{-3} m^3/s), at a Reynolds number of Re = 6890. The molar mass concentration of the species generated during curing of the coating material inside the irradiator tube is again calculated at different axial locations and are shown in Fig. 4. It is found that, at x/L = 0.1, the mass concentration, C_A near the tube wall is almost zero. At x/L = 0.5 and 0.9, the mass concentration near the tube center increases significantly compared to that at x/L = 0.1, but near the wall it is still low. The mass concentration from the tube center to the wall decreases exponentially. This means that the species generated during curing of the coating materials are being flushed downstream before they can diffuse to the tube wall, which is desirable. Though the mass concentration near the wall at downstream (x/L = 0.9) is non-zero, it is quite low compared to Fig. 3, and might not be enough to cause tube smoking.

For comparing the above two cases, with and without lip, the radial distribution of mass concentration at different axial locations, x/L = 0.1, 0.5 and 0.9 are again plotted in Fig. 5. Here the solid lines correspond to no lip condition, while the dashed lines correspond to the usual condition of having lips. From the figure it is found that, the presence of the lip causes the mass concentration near the glass tube wall to rise considerably and start tube smoking. The presence of the lip causes an adverse pressure gradient in the irradiator tube and a recirculation close to the exit. The axial velocity of the purging air near the wall becomes small, which increases the convective time t_c as well as the ratio t_c/t_d. From Fig. 2, it can be seen that increase of ratio t_c/t_d means that the chances of the mass to diffuse to the wall before it is flushed out are higher.

From the preliminary calculations in Fig. 2, it is found that increasing the tube diameter at the same flow rate would reduce the convective/diffusive time ratio t_c/t_d, which means a reduction in chances that the mass will diffuse to the wall before it is purged out. So to further eliminate the tube smoking problem, using the above model computations are repeated for the flow of Fig. 1, but without the lip, and a larger irradiator tube diameter (D) of 0.044 m. The tube length (L) is taken as 1.2 m and the flow rate of purging air is maintained at Q = 4 cfm = 1.888×10^{-3} m^3/s, at a Reynolds number of Re = 3445. The molar mass concentration of the coating fume in the irradiator tube is calculated and presented in Fig. 6. The plot shows the mass concentration profiles in the radial direction at three axial locations. Similar to Fig. 4, as the flow proceeds downstream, the mass concentration near the centerline increases as the generated species are washed out. But the mass concentration decreases exponentially from centerline to the tube wall, even faster than that in Fig. 4. This means that the probability of the species being washed out of the irradiator tube before they can diffuse to the wall is even higher.

Figure 7 shows the mass concentration profiles at axial locations x/L = 0.1, 0.5 and 0.9, for the above two no lip conditions with same air flow rate, but having tube diameters (D) of 0.022 m and 0.044 m. The solid lines correspond to tube diameter of 0.022 m, while the dashed lines represent the larger tube diameter of 0.044 m. From the figure it is observed that, for D = 0.044 m the radial distribution of the mass concentration decreases faster than that for D = 0.022 m, similar to the findings of Fig. 2. Hence, to eliminate the tube smoking problem completely, 0.044 m diameter tubes without lip may be considered having the same flow rate of purging air.

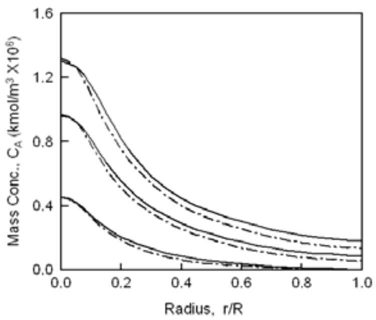

Figure 7: Comparison of mass concentration profiles (No Lip condition): solid line for 22mm dia tube and dashed line for 44 mm dia tube.

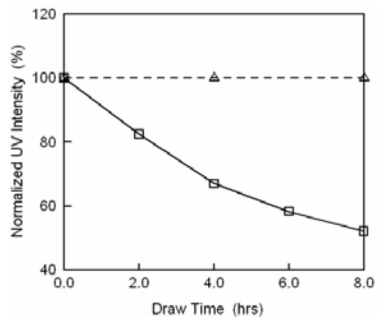

Figure 8: Normalized Intensity of UV light entering for fiber curing: solid line for Lip and dashed line for No Lip condition.

EXPERIMENTAL VERIFICATION

Experiments are done to verify the numerical findings. Optical fiber is drawn vertically in a draw tower through a coating die and a glass irradiator tube as shown in Fig. 1. The diameter of the tube is 0.022 m, length is 1.2 m, flow rate is 1.888×10^{-3} m^3/s and the usual lip for holding the tube is considered having a thickness of 0.003 m. The UV light from the irradiator caused curing of the coating material and generated fumes. The experiment is carried out for eight hours. The intensity of light passing through the irradiator glass tube at the end of every two hours is measured and normalized with the intensity of light passing through a clean glass tube. The results are plotted in Fig. 8. It is found that tube smoking occurred, and got worse with time. Consequently, the intensity of light passing through the glass tube dropped, and at the end of eight hours the normalized intensity became only about 52%. Hence, the fiber drawing process has to be stopped frequently for changing the glass tube. The experimental result supports the computational results in Fig. 3.

The above experiment is repeated for same tube diameter of 0.022 m, length of 1.2 m and purging air flow rate of 1.888×10^{-3} m^3/s, but without the lip. It is observed that there is no tube smoking, and the normalized intensity of the UV light from the irradiator passing through the glass tube for curing the optical fiber coating material is about 100%, even after eight hours of drawing in the draw tower. The computational results in Fig. 4, explain this experimental observation. Increasing the purging air flow rate to 6 cfm = 2.832×10^{-3} m^3/s increases fiber vibration, this causes fiber coating defect, and so is discarded.

CONCLUSION

Based on the computational results and experimental verification, the following conclusions may be drawn:

i. The present computational model is capable of predicting the fluid flow and mass transfer in the irradiator tube with reasonable accuracy.

ii. The convective time / diffusive time ratio, t_c/t_d for laminar flow of purging air in an irradiator tube decreases exponentially with increase in flow rate. Low values of t_c/t_d ratio means, the species generated during curing of the coating material are more likely to be washed out from the tube before they can diffuse to the glass wall and cause tube smoking.

iii. For turbulent flow, increasing air flow rate for the same tube diameter does not lower the t_c/t_d ratio appreciably.

iv. Presence of lip at the tube exit increases the mass diffusion across the irradiator tube, which increases the concentration of the generated species close to the glass wall and initiates tube smoking.

v. Removing the lip reduces mass diffusion across the tube, and lowers the concentration of the species close to the glass tube to such extent that prevents tube smoking.

vi. Increasing tube diameter for turbulent flow of air at constant flow rate causes large reduction in the t_c/t_d ratio, reduces the concentration of generated species close to the glass wall, and helps in the elimination of tube smoking problem.

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