Prediction of Mass Transfer in Axial Flow through a Hollow Fiber Module by Using of Numerical Simulation

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1. Introduction

Polymeric-based membranes are used for a wide range of membrane filtration processes including gas/vapor separation, reverse osmosis, dairy industry and medical application such as hemodialysis of kidney patients [1]. A hollow-fiber membrane dialyzer contains a bundle of approximately 5000 to 12000 hollow fibers depending on the dialyzer size that each fiber has almost 200 micron inner diameter and 40 micron thickness. The main role of the fiber walls of the hollow fibers is membrane separation. Uremic toxins and extra water mass transfer from blood to dialysate are very important and this phenomena is the combination of diffusion and convection of materials. In many cases, mass transfer rates are limited by fiber concentration boundary layers that depends on the blood flow through the fibers.

In this research, in order to study the boundary layer effects, it is necessary to predict the velocity and concentration fields in the single fiber module. To receive this goal, it must be studied the fluid flow parameters to predict the pressure and concentration gradient. The current work incorporates the advantages of computational fluid dynamics with using of CFX solver within a single fiber module to solve the steady flow problems.

2. Methods

To obtain the real flow, the Navier-Stokes formula and discretizing the domain into finite control volumes with using a mesh have chosen as an approach. The governing equations including mass and momentum [2] are integrated over each control volume according to following formulation.

$$\frac{d}{dt}\iiint_{\vartheta(t)} \rho d\vartheta + \iint_{S(t)} \rho(V - V') = 0$$

$$\frac{d}{dt}\iiint_{\vartheta(t)} \rho V.d\vartheta + \iint_{S(t)} \rho V(V - V').ds = \iint_{S(t)} \sigma \hat{n} dS \qquad (1)$$

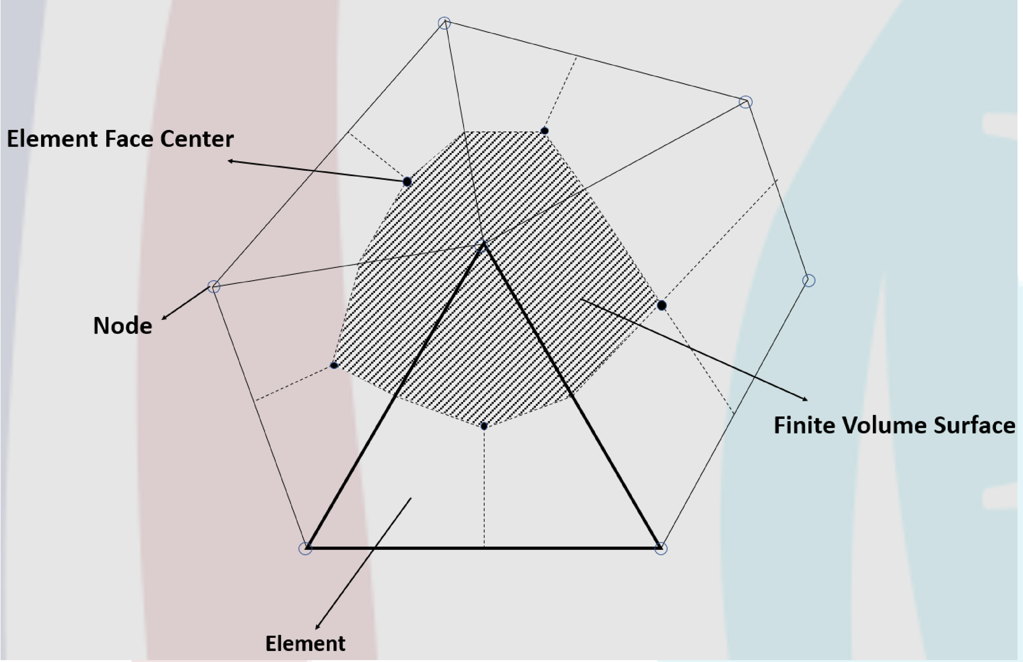
In the above equations [2], $d\upsilon$ is the cell volume, $V=ui+vj$ is the airstream velocity vector, $n=(n_x)i+(n_y)j$ is a unit vector normal to the cell face, $dS=(dS_x)i+(dS_y)j$ is an outward normal vector to the cell face with a total magnitude of $dS=((ds_x)^2+(ds_y)^2)^{1/2}$, where $ds_x=\Delta y$ and $dS_y=-\Delta x$. The cell surface forces appear in the right hand side of Eq. (1b). The total stress tensor σ includes the hydrostatic pressure p and the stress tensor terms τ as follows:

$$\sigma_{ij} = -P\delta_{ij} + \tau_{ij} \qquad (2)$$

Where the stress tensor τ is given by

$$\tau_{ij} = \mu_a\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad (3)$$

To introduce our FV formulation, we need to describe the volumes, elements and their connections. Figure 1 shows a few neighboring triangular and quadrilateral elements located in a part of the solution domain and a typical mesh with unit depth, on which one surface of the control volume is represented by the shaded area. It is clear that each node is surrounded by a set of surfaces that define the control volume. All the solution variables and fluid properties are stored at the element nodes. The solid lines indicate elements, the dashed lines illustrate their medians, and the solid circles represent the element face centers or element vertices.



3. Results

In this section, we would like to study the impact of fluid flow parameters in mass transfer. In this regard, we simulate flow in a hollow fiber with considering inlet pressure at 5 psig (34473pa). Figure 2(a) is shown the geometry of single hollow fiber that has been considered in this research. As it was mentioned in the first section, the mass transfer mechanism involves the combination of diffusion and convection phenomenon. According to the Ref. [4], convection is the transportation of solution from semipermeable membrane along a pressure gradient. Also, the diffusion is to transport of solution from membrane surfaces along the concentration gradient. As can be seen in the figure 2(b), the pressure contour profile in cross sectional area on hollow fiber module are presented. The pressure loss is clearly observed along the fiber. According to the dialysate motion in opposite direction of main fluid in hollow fiber and linear pressure drop for dialysate, As a result of local variation of trans-membrane pressure and blood pressure loss through the hollow fiber pathway, back-filtration might occur. Back-filtration problem is very critical during dialysis session as it induces contamination into the blood. So, the convection phenomenon is remarkable at the beginning of hollow fiber. figure (c) also shows the velocity profile in the different cross sectional areas (beginning section, middle and the end) of hollow fiber module. This velocity profile is for wall to middle section and shows that the velocity is constant in the different sections. But while the dialysate flow near the inlet and outlet ports is non-uniform in nature [4]. So there is a non-uniform velocity gradient on the sides and along the fiber. It is concluded that the mass transfer in the hollow fibers is vividly various at different locations.

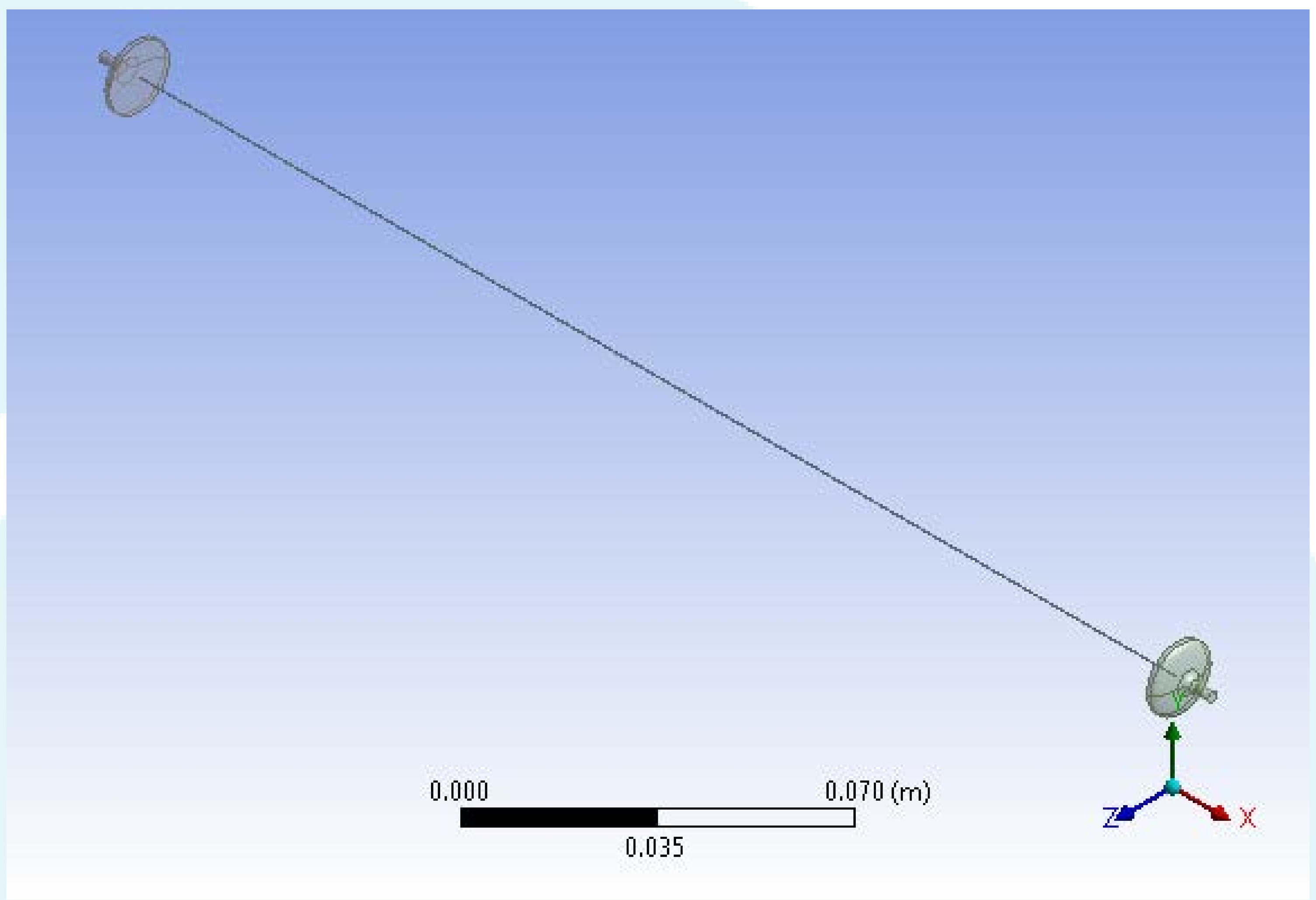


Fig. 2(a) Isometric view of single fiber module including a hollow fiber, inlet cap and outlet cap

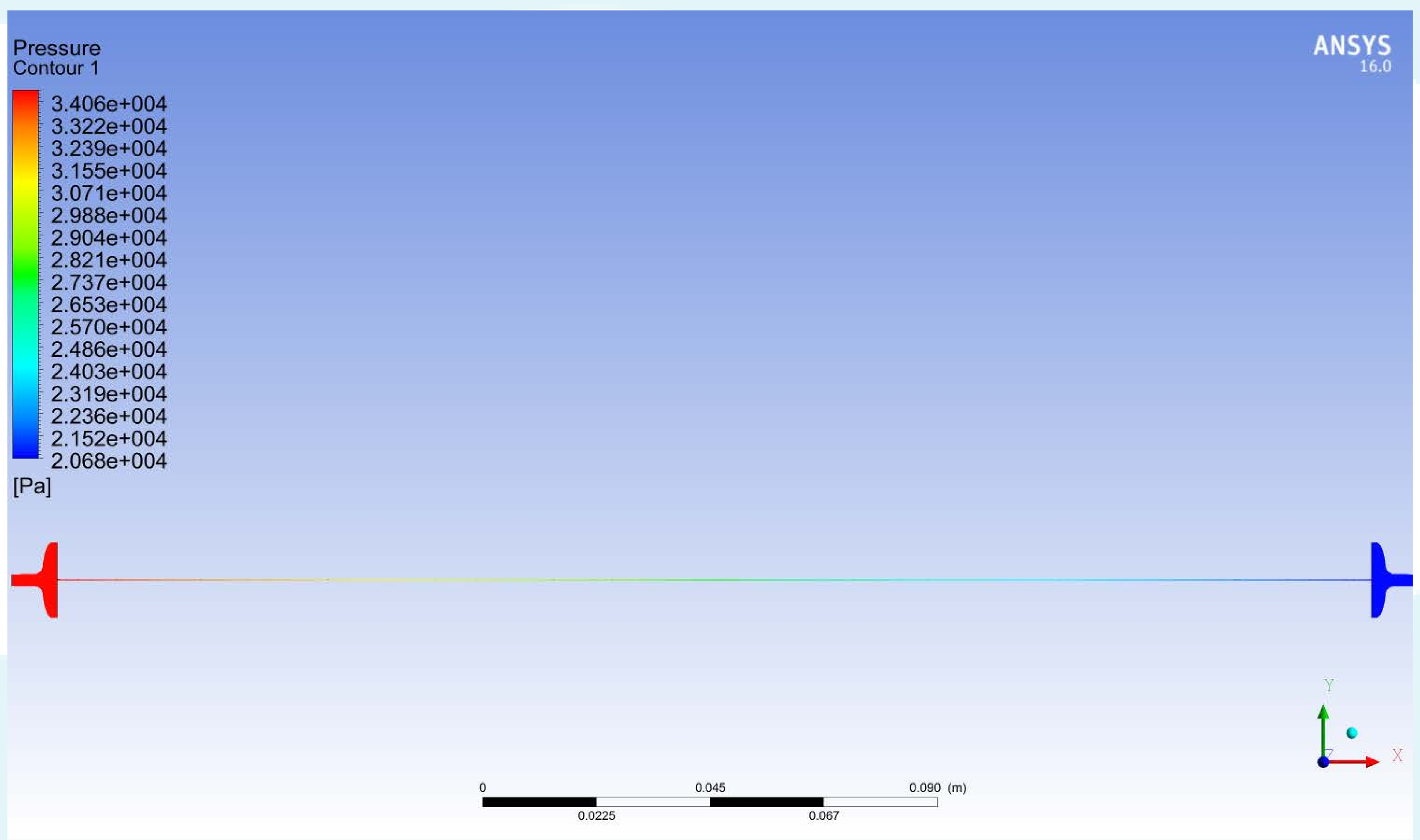


Fig. 2(b) Pressure contour on hollow fiber module

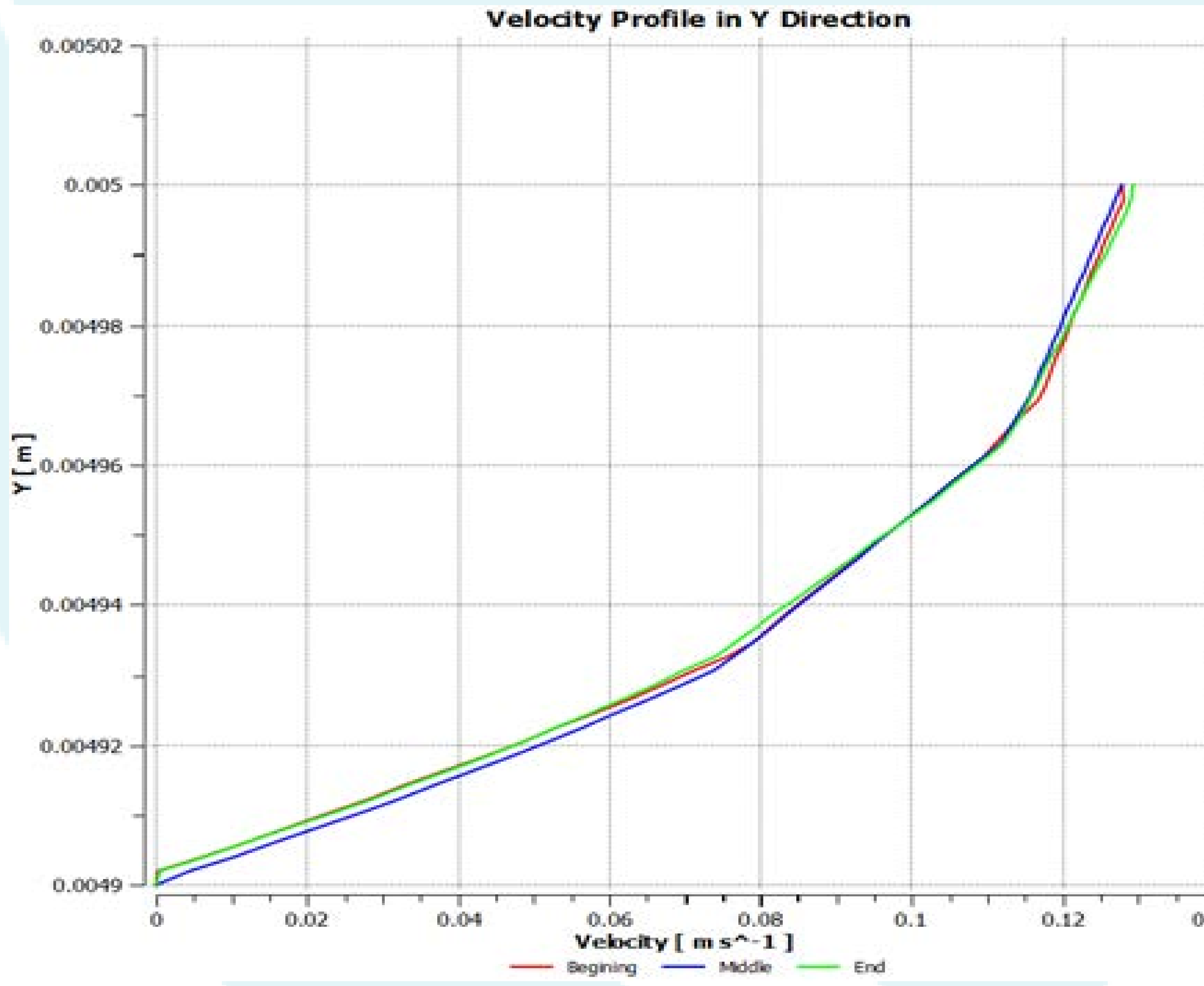


Fig. 2(c) Velocity Profile in the section of Beginning, Middle and the end of fiber

4. Conclusion

We used a numerical method to simulate the fluid flow in a hollow fiber module. It was performed by the using of finite-volume discretization methods. We investigated the effect of flow parameters including pressure and velocity gradients along the fiber module. We concluded that the mass transfer is affected by the pressure and concentration gradients along the fiber.

5. References

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