Effect of permeation velocity on flow behavior and pressure drop in feed channels of membranes

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***Abstract* — The computational fluid dynamics (CFD) simulations are carried out for the membrane feed channel. The results are obtained with two different conditions defined at the membrane surface: (i) impermeable wall and (ii) permeable surface with specified velocity. From simulations, the cases in which both boundary conditions yield similar results are indicated.**

***Keywords* — spacers; pressure drop; membrane**

INTRODUCTION

Membrane separation techniques are increasingly applied in chemical, textile, petrochemical, food, paper, tanning industry and in treatment of municipal water. Depending on the size of the pores of the membrane, classes of separation processes are reverse osmosis, nanofiltration, ultrafiltration and microfiltration. For these separation processes, the spiral-wound membrane element is most widely used because it has a high membrane surface area to volume ratio, it is easy to replace, it can be manufactured from a wide variety of materials, and is sold by several manufacturers. Spiral wound devices are made from flat membrane leaves that are wound around a perforated central tube. Pressurized module housing holds the membrane leaves in place to prevent unwinding. Usually three or more modules are connected in series in housing. In spiral wound modules spacers are commonly used which are sandwiched between two membrane leaves. These spacers not only define the feed channel height and increase the mass transfer rate but inevitably increase the pressure loss. Detailed CFD studies [1-6] exist in literature to understand flow and mass transfer characteristics in membrane feed channels. A common assumption however used in these studies is impermeable boundary condition for the membrane surface due to low permeate flow rates in membrane modules. Some studies [7-8] consider the flow through membrane surface with varying and fixed velocity. The comparison in terms of pressure drop and flow patterns were not discussed at different permeation velocities. In this work we therefore find the effect of product flow rate on the flow structure and pressure drop in the membrane feed channel.

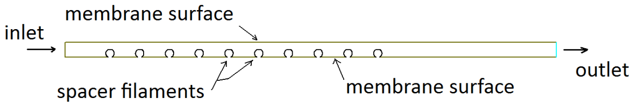

Figure 1. Schematic of membrane channel

COMPUTATIONAL DOMAIN AND GOVERNING EQUATIONS

The computational domain consists of a flat channel with multiple filaments as shown in Fig. 1. The channel height *h* is set to 1 mm whereas inter-filament spacing is 2 mm. Velocity is specified at the entrance and sufficient exit length is provided after the last filament to prevent the interference of the recirculation region with the channel exit. The permeation velocity v_p is varied at the membrane surface to study its effect on the fluid flow and pressure loss.

The governing equations are continuity and momentum equation for 2D flow as given in Equations (1) – (3).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y} = 0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad (3)$$

These equations are solved using a CFD code (Fluent 6.3.26). The flow fields are obtained using QUICK scheme and SIMPLEC algorithm. Fluid is assumed to be incompressible, and of constant viscosity.

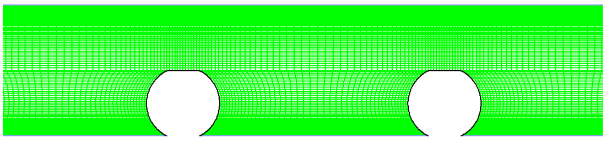

Figure 2. Computational grid

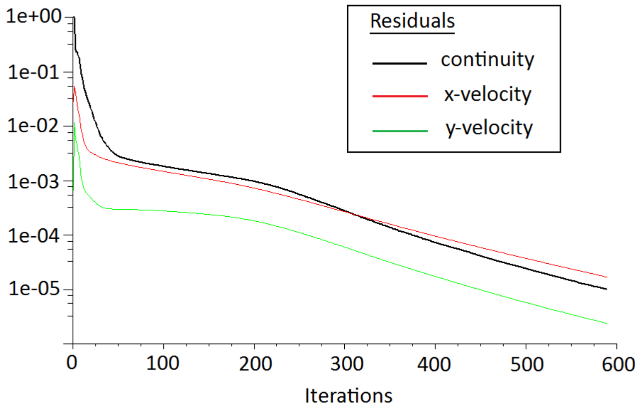

Figure 3. Residuals versus iterations

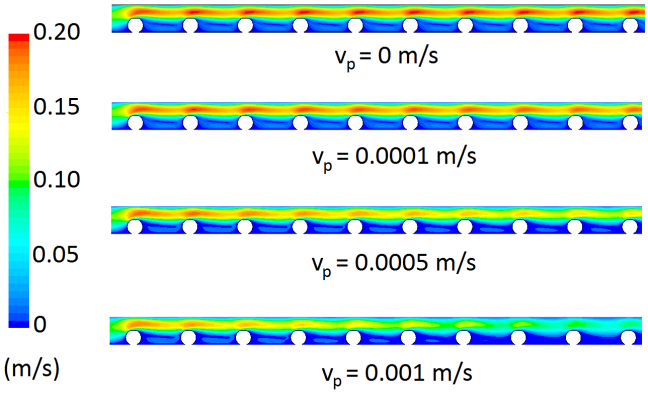

Figure 4. Velocity contours at various permeation rates

RESULTS AND DISCUSSIONS

The computational domain is divided into around 60,000 cells using a grid. The grid is small enough to make results independent of the grid size as in Fig. 2. The difference in pressure drop is found less than 1.35 % between 60,000 and 110,000 cells. The criteria for convergence are 10^{-4} for residuals of continuity and velocity components. The solutions usually converged within 700 iterations for the cases solved in this paper as can be seen in Fig. 3. The velocity profiles in the membrane channel are shown in Fig. 4 at various permeation rates v_p. The contours (in Fig. 4) illustrate that velocity becomes higher in the top portion of the channel when fluid flows above the filaments. In the bottom region fluid velocity is seen lower. When impermeable wall is assumed for the membrane the velocity is relatively higher in the top region when compared to be permeable boundary condition. The comparison of velocity contours at different permeation velocities v_p indicate that at higher v_p of 0.0005 and 0.001 m/s, the local feed velocity (in top region) at the first few filaments is higher. The flow velocity continuously decreases as fluid moves in the main flow direction. The flow pattern with higher permeation rates still has some qualitative similarity with the flow pattern observed using impermeable surface assumption.

The pressure drops are also determined in this work for quantitative comparison. The plot between pressure and permeate velocity in Fig. 5 shows that almost linear relation exist between the two parameters. When v_p is 10^{-5} m/s negligible difference (≈ 0.6 %) exist between the pressure drop value obtained with wall boundary condition with one obtained with permeation condition. This shows that for membrane processes with low product fluxes like reverse osmosis, the difference in pressure gradients in membrane channel is not significant and impermeable boundary condition for the membrane is sufficient. At higher permeate velocities v_p like 10^{-4} and then 2 x 10^{-4} m/s the difference is approximately 5 and 10 %. When v_p further increases the pressure drop difference reaches up to 80 % indicating that impermeable wall is an incorrect assumption in such situations. The pressure drop value from CFD modeling is compared with experimental results available in literature [7]. The friction factor is calculated from pressure drop Δp, inlet velocity u_0, density ρ, channel length l and height h using equation (4) and evaluated against experimental friction factor.

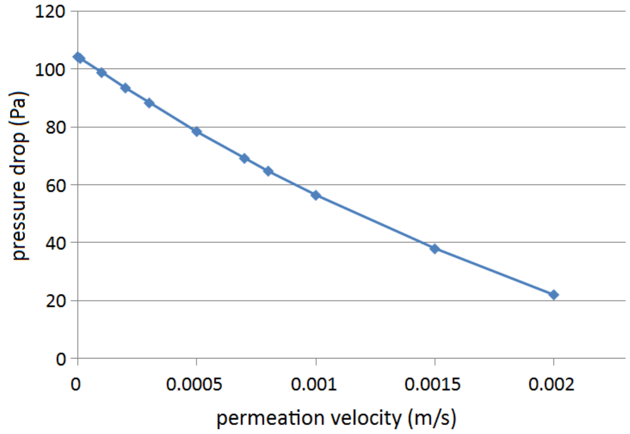

Figure 5. Pressure drop in feed channel

$$f = \frac{\Delta p h}{l \rho u_0^2} \tag{4}$$

The difference of friction factor calculated from two methods is less than 25 %. This difference indicates satisfactory agreement and shows reliability of the CFD results in this paper.

CONCLUSIONS

The paper assesses the validity of impermeable wall boundary condition assumption commonly used for membrane surface for computational modeling in membrane channels. The velocity contours in feed channel at different permeation flow rates show qualitative similarity. This means that treating membrane as impermeable for modeling purpose is a suitable approximation in particular at low permeations. The difference in pressure drop values found from wall and permeable boundary condition is less than 1 % when permeation velocity is 10^{-5} m/s which is usually the case for many of membrane processes. For higher permeation rates the assumption is noticed to be incorrect as difference increased up to 80 %.

ACKNOWLEDGEMENTS

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