Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (21): 3640-3644, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.3640.3644

Computational Fluid Dynamics Modeling of High Viscous Feed Fluid in Rotating Corrugated Membrane Channel: Shear Stress Effect

A.L. Ahmad, Z.H. Ban and B.S. Ooi
School of Chemical Engineering, Engineering Campus, Seri Ampangan,
Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, 14300, Malaysia

Abstract: Shear stress on the membrane surface has been proven very important in reducing concentration polarization and cake layer formation in membrane processes. This paper investigates the effect of rotation of membrane channels with high viscous feed solution on the membrane shear stress using Computational Fluid Dynamics (CFD). This study focus on two small membrane channels separated with corrugated spacer. The inner membrane was 39 mm and outer membrane was 41.5 mm from the axis of rotation. The feed solution viscosity used for the simulation was 0.0025 Pa•s and the inlet feed velocity was 2 m sec^{-1}. The membrane shear stress is found out to be increasing with rotation speed. The shear stress on the outer membrane is also higher than inner membrane. There are three forces acting on the fluid flow in the membrane channels, namely pressure force, centrifugal force and tangential force. The rotation of the corrugated membrane channels can be applied to the spiral wound membrane module so that the membrane shear stress can be increased.

Key words: Shear stress, rotating, high viscous fluid, CFD, membrane

INTRODUCTION

Membrane application has widely been used in many industries. Furthermore, many more researches on membrane is still on going to extend the membrane application in various field (Abd El-Salam, 2006; Barakat, 2008; Ahmad and Chan, 2009). However, the main problem facing by most of the membrane application, which is the membrane fouling, caused by Concentration Polarization (CP) and cake layer formation is still under research progress to solve the problem (Sakinah *et al*., 2007; Zularisam *et al*., 2010). High shear stress on the membrane surface is proven can reduce CP formation (Bouzerar *et al*., 2003). The high membrane shear stress is able to increase the back transport of rejected solute on the membrane surface (Bian *et al*., 2000) and prevented formation of CP and cake layer on the membrane (Bouzerar *et al*., 2000; Akoum *et al*., 2005).

High membrane shear stress has been successfully achieved by the introduction of dynamic membrane. The dynamic membrane uses mechanical energy to move the membrane to create high shear stress on the membrane surface (Jaffrin, 2008) and reduce CP even for high viscous feed solution (Bhattacharjee and Bhattacharya, 2006). The feed flow velocity and membrane surface shear stress can be decoupled with the dynamic membrane system (Beier and Jonsson, 2006). The high membrane shear stress can extend the pressure limited regime and enable the increase of pressure that can increase the permeate flux (Ding *et al*., 2003). The permeate flux in dynamic membrane system can also be related with the membrane shear rate (Petala and Zouboulis, 2006). Thus, dynamic membrane can attain higher permeate flux than conventional crossflow (Akoum *et al*., 2004) and turbular (Al-Akoum *et al*., 2002) membrane system at the same transmembrane system.

The shear stress on the membrane surface can be easily estimated and modeled using Computational Fluid Dynamics (CFD) technique. In this study, CFD software (Fluent v6) is used to study the effect rotation of the membrane channels on the membrane shear stress for high viscous fluid solution.

MATERIALS AND METHODS

FLUENT v6 was used for modeling and simulation in current work. In present simulation, a fluid with viscosity of 0.0025 Pa•s was used to study the flow characteristics. This fluid viscosity is chosen based on the experiment performed by Da Costa *et al*. (1991), where the Dextran solution which has the fluid viscosity of 0.0025 Pa•s was used. The feed flow inlet velocity was set as 2 m sec^{-1} for all simulation. The permeate flux in the membrane channels is assumed to be very small compared

Corresponding Author: A.L. Ahmad, School of Chemical Engineering, Engineering Campus, Seri Ampangan, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, 14300, Malaysia

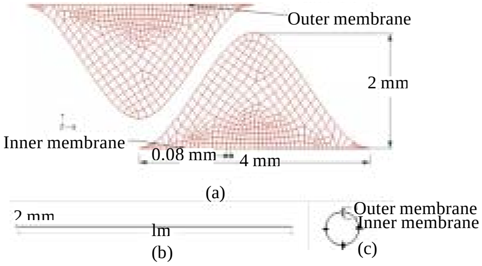

Fig. 1: Mesh and motion track of the small channel in the spacer (a) front view (b) side view (c) motion track

to the feed flow velocity and thus the hydrodynamics in the channels is not affected by the permeation through the membrane. This has enabled the membrane to be treated as impermeable wall. The simulations were performed using unsteady state laminar flow at ambient pressure. Dynamic mesh function was used to define the dynamic motion of the mesh where the motions were defined using User Defined Function (UDF). The UDF was written in ‘C’ programming language using predefined macro in the FLUENT solver. Macro ‘Define_CG_Motion’ for dynamic mesh was used in the UDF. The discretization of the governing equations was performed using a segregated incompressible flow solver in which each governing equation is solved separately. The velocity and pressure parameters would be linked and solved by SIMPLE algorithm. In order to achieve higher order of accuracy, second order upwind discretization schemes was selected to compute the momentum.

SIMULATION DOMAIN

The front view and side view computational domain is shown in Fig. 1. The simulated domain was 1 meter in length, 2 mm in height and 4 mm in wide. The mesh size generated on the membrane surface is 8×10^{-5} m between each node. The distance of the Inner Membrane (IM) with the axis of rotation is 39 mm and the Outer Membrane (OM) is 41.5 mm. The x and y direction was the rotation direction and z direction was the direction of fluid flow from inlet to outlet. The motion track of the small channel is shown in Fig. 1.

RESULT AND DISCUSSION

The hydrodynamics in the membrane channels was solved by fluent using laminar Navier-Stoke equations. Rotation speeds from 0 to 200 rad sec^{-1} are simulated to study the effect of rotation on the membrane surface shear stress when the higher fluid viscosity which is almost six times higher than water is used. Time step of 0.0001 sec was used for all simulations. All the results shown in Fig. 2 were taken after the average shear rate was not changing with time.

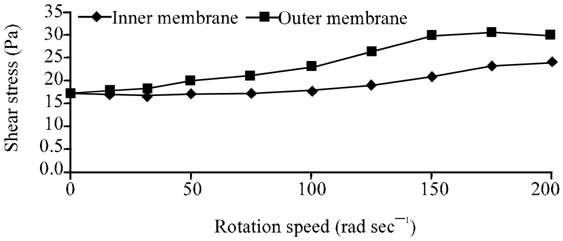

Fig. 2: Graph of average shear stress against rotation speed

The area weighted average surface shear stress was computed from IM and OM. Fig. 2 shows the average surface shear stress versus the rotation speed of the membrane channels. The rotation of the membrane channels affects the fluid flow in inner and outer membrane channels differently. The shear stress on the OM started to increase as the membrane channels is rotated but it only started to increase at rotation speed beyond 100 rad sec^{-1} on IM. However, the shear stress on OM did not increase at the rotation speed was beyond 150 rad sec^{-1} while the shear stress on OM is still increases with the rotation speed.

Membrane fouling and concentration polarization phenomenon was expected to be reduced by the increase of shear stress on membrane surface. Bergen *et al.* (2003) had studied the enhancement of spiral wound membrane by operating in dynamic operation in a centrifugal membrane separation system. Their experiments results showed that the membrane fouling was reduced when the membrane module was operated under centrifugal mode. Besides, they also found that the permeate flux obtained in dynamic condition was higher than static condition. Furthermore, the dynamic condition successfully reduced flux decline too. Their results had agreed with the finding in this work that the rotation of spiral wound membrane module can increase the membrane shear stress and thus reduce membrane fouling. In addition, Brou *et al.* (2002) had investigated the performance of rotating disk membrane filtration using similar feed solution with viscosity of 0.00262 Pa•s. They found out that the permeate flux increased with the rotation speed of the disk. The trend of permeate flux increase had further confirmed the increase of membrane shear stress with the rotation speed.

Three main forces were affecting the fluid flow in the rotating membrane channels, namely centrifugal force, tangential force and pressure force as shown in Fig. 3a.

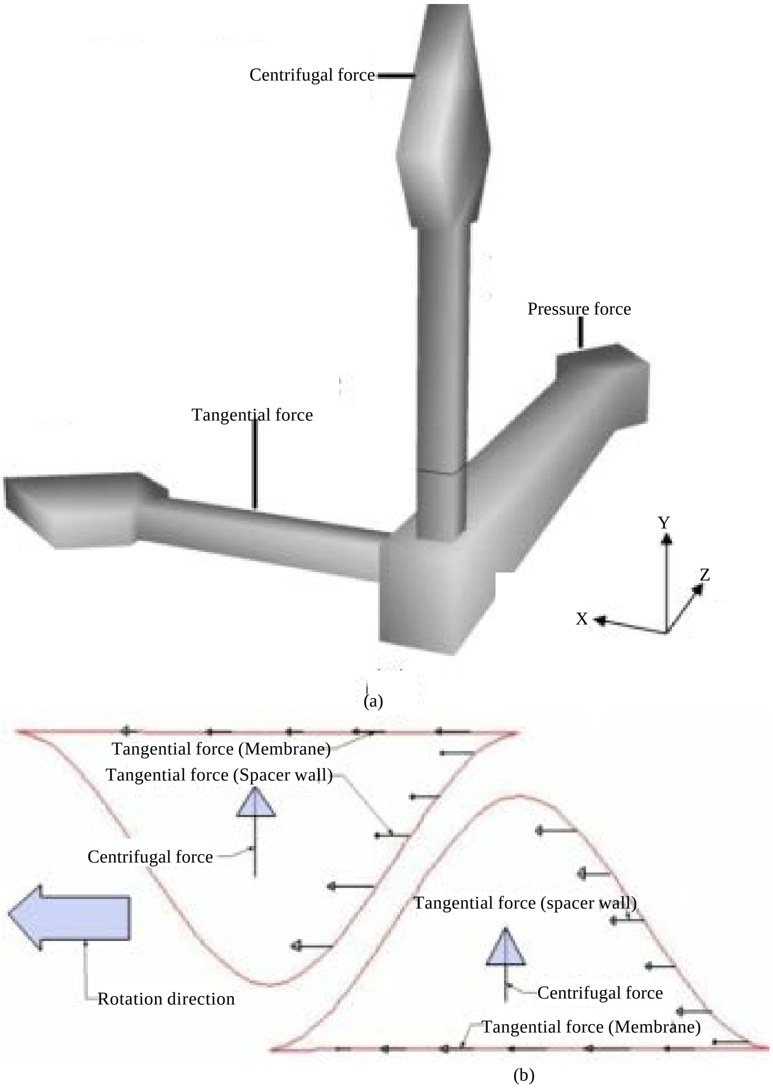

Fig. 3: Forces acting on the fluid flow in the outer and inner channel (a) three forces acting direction (b) forces acting in corrugated spacer filled channel

The rotation has created the centrifugal force; tangential force exists due to spacer wall and pressure force is supplied by the feed pump. The feed pump constantly pumped the feed fluid across the membrane channels at the specific flow rate and formed a strong pressure force that pushes the fluid to flow from the inlet towards the outlet direction. Thus, the pressure force is always in the direction from inlet to outlet direction. This is also the main force that determines the shear stress created on the membrane surfaces like conventional crossflow membrane filtration process.

The tangential force due to the corrugated spacer wall and centrifugal force was created due to the rotation of the membrane channels. Centrifugal force is always facing in the direction out from the axis of rotation. Thus, the centrifugal force had significantly shifted the high velocity region in the laminar Poiseuille flow to the outer side of the membrane channels. This is the reason the shear stress on the OM was always higher than the IM. When the centrifugal force shifted the high velocity region outwards, the effect on the OM and IM was different. The high velocity region was shifted near to the OM but away from the IM as shown in Fig. 3b. The shear stress on OM was greatly increased as high velocity gradient is created near OM. The shear stress on IM was not affected much from the centrifugal force as the high velocity region is shifted away from the IM. Thus, the shear stress on OM was increased even at low rotation speed but there was no effect for the IM.

Tangential force was created due to the corrugated spacer wall as the rotation started. The corrugated spacer wall exerted the force in the rotation direction as if a plate pushing the fluid. This was the critical force that increases the shear stress on the membrane surfaces. This force was able to increase the fluid flow velocity in the membrane channels and thus increase the velocity gradient near the membrane surfaces. Hence, the shear stress on the membrane was able to increase due to the existence of tangential force even for a fluid with viscosity almost six times higher than water. The effect of this force is significant beyond the rotation speed of 100 rad sec^{-1}. The shear stress on IM started to increase significantly only when rotation speed was beyond 100 rad sec^{-1} because it was not affected by centrifugal force. Tangential is the only force that able to increase the shear stress on IM. This tangential force also helps to further increase the shear stress on OM.

However, the shear stress on OM was not increased when the rotation speed beyond 150 rad sec^{-1}. This phenomenon happens because at rotation speed higher than 150 rad sec^{-1}, the fluid flow velocity was not increased by the tangential force as much as the increase of OM instantaneous velocity. Since the fluid viscosity was higher than water, higher force is required to move the fluid as it has higher internal resistance. Thus, when the membrane channels were rotating at high speed, the tangential force created by the spacer wall was not able to increase the fluid flow velocity significantly. Anyhow, the increase of instantaneous velocity of IM was still lower than the increase of fluid velocity in inner membrane channel and caused the shear stress on IM was still in the increasing manner even rotation speed was exceed 150 rad sec^{-1}. However, due to the centrifugal force that shifted the high velocity region outwards, the shear stress on the OM was still higher than IM when rotation speed was below 200 rad sec^{-1} although the shear stress did not increase with rotation speed.

CONCLUSION

The shear stress on the membrane surfaces for fluid with viscosity of 0.0025 Pa•s, which is almost six times more viscous than water, in the corrugated spacer filled membrane channels is able to be increased by rotating the membrane channels. The higher shear stress on membrane surface can reduce the concentration polarization and cake layer formation on the membrane surface and further enhance the membrane application. The shear stress is found out to be increase with rotation speed of the membrane channels. The hydrodynamics in the rotating membrane channels is governed by three forces, namely pressure force, centrifugal force and tangential force. Pressure force is the main force that determines the shear stress on the membrane surfaces. Centrifugal force is the force moved the fluid flow high velocity region away from the axis of rotation and caused the difference of shear stress on IM and OM. Tangential force is created by the corrugated spacer wall which is the critical force that plays the important role to increase the shear stress on the membrane surfaces in the rotating membrane channels.

ACKNOWLEDGMENTS

This work was funded by the Grant PRGS by Universiti Sains Malaysia. The authors would also like to thank USM fellowship for giving financial support to Mr. Z.H. Ban.

REFERENCES

Abd El-Salam, M.H., 2006. Separation of casein glycomacropeptide from whey: Methods of potential industrial application. Int. J. Dairy. Sci., 1: 93-99.

Ahmad, A.L. and C.Y. Chan, 2009. Sustainability of palm oil industries: An innovative treatment via membrane technology. J. Applied Sci., 9: 3074-3079.

Akoum, O., M.Y. Jaffrin and L.H. Ding, 2005. Concentration of total milk proteins by high shear ultrafiltration in a vibrating membrane module. J. Membrane Sci., 247: 211-220.

Akoum, O., M.Y. Jaffrin, L.H. Ding and M. Frappart, 2004. Treatment of dairy process waters using a vibrating filtration system and NF and RO membranes. J. Membrane Sci., 235: 111-122.

Al-Akoum, O., L.H. Ding and M.Y. Jaffrin, 2002. Microfiltration and ultrafiltration of UHT skim milk with a vibrating membrane module. Separation Purification Technol., 28: 219-234.

Barakat, M.A., 2008. Removal of Cu (II), Ni (II) and Cr (III) ions from wastewater using complexation-ultrafiltration technique. J. Environ. Sci. Technol., 1: 151-156.

Beier, S.P. and G. Jonsson, 2006. Dynamic microfiltration with a vibrating hollow fiber membrane module. Desalination, 199: 499-500.

Bergen, A., N. Djilali, T.M. Fyles, G.W. Vickers and P.M. Wild, 2003. An experimental assessment of centrifugal membrane separation using spiral wound RO membrane elements. Desalination, 154: 225-232.

Bhattacharjee, C. and P.K. Bhattacharya, 2006. Ultrafiltration of black liquor using rotating disk membrane module. Separation Purification Technol., 49: 281-290.

Bian, R., K. Yamamoto and Y. Watanabe, 2000. The effect of shear rate on controlling the concentration polarization and membrane fouling. Desalination, 131: 225-236.

Bouzerar, R., L. Ding and M.Y. Jaffrin, 2000. Local permeate flux-shear-pressure relationships in a rotating disk microfiltration module: Implications for global performance. J. Membrane Sci., 170: 127-141.

Bouzerar, R., P. Paullier and M.Y. Jaffrin, 2003. Concentration of mineral suspensions and industrial effluents using a rotating disk dynamic filtration module. Desalination, 158: 79-85.

Brou, A., M.Y. Jaffrin, L.H. Ding and J. Courtois, 2002. Microfiltration and ultrafiltration of polysaccharides produced by fermentation using a rotating disk dynamic filtration system. Biotechnol. Bioeng., 82: 429-437.

Da Costa, A.R., A.G. Fane, C.J.D. Fell and A.C.M. Franken, 1991. Optimal channel spacer design for ultrafiltration. J. Membrane Sci., 62: 275-291.

Ding, L.H., O. Akoum, A. Abraham and M.Y. Jaffrin, 2003. High shear skim milk ultrafiltration using rotating disk filtration systems. AIChE J., 49: 2433-2441.

Jaffrin, M.Y., 2008. Dynamic shear-enhanced membrane filtration: A review of rotating disks, rotating membranes and vibrating systems. J. Membrane Sci., 324: 7-25.

Petala, M.D. and A.I. Zouboulis, 2006. Vibratory shear enhanced processing membrane filtration applied for the removal of natural organic matter from surface waters. J. Membrane Sci., 269: 1-14.

Sakinah, A.M.M., A.F. Ismail, R. Md Illias and O. Hassan, 2007. Development of Enzymatic Membrane Reactor (EMR) for cyclodextrins production. J. Applied Sci., 7: 2028-2032.

Zularisam, A.W., A.F. Ismail and M. Sakinah, 2010. Application and challenges of membrane in surface water treatment. J. Applied Sci., 10: 380-390.