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Hydrodynamic Study Through Computational Fluid Dynamics of Radial Flow Membrane Module

Keka Rana[1*], Debasish Sarkar[2]

Abstract

Historically Crossflow Membrane modules came first in the membrane-based separation (MBS) process. Its high shear generation overcomes two non-idealities concentration polarization and subsequent fouling. Primarily, high shear generation and large surface area create a positive domain for large applications. Thereafter, feed flow rate-dependent shear generation creates a hindrance. This obstruction is overcome with Dynamic Shear Enhanced Membrane Filtration Pilot (DSEMFPs). Low surface area is a vital drawback of DSEMFPs. This radial flow membrane module with its special design develops a large surface area. Moreover, its central inlet and nine peripheral outlets reduce the large pressure drop efficiently. With all the positive properties it efficiently removes the protein from waste water. Moreover, it can work satisfactorily on plenty of wastewater treatment processes. Therefore, a detailed hydrodynamic study of the radial flow module is the primary requirement. The absence of it makes a prominent path for further investigation. Considering the importance of shear, shear stress distribution on the membrane surface is studied here. Moreover, exact velocity vector distribution in the default interior is also vital to understanding the inner hydrodynamic relationship. Additionally, vortices, turbulent kinetic energy, turbulent KE dissipation rate, and dynamic pressure on the membrane surface are also reported in this study for a complete understanding of the exact condition of the membrane surface. All these results justify the positive impact of the Radial flow system in wastewater treatment.

Keywords: Cross flow module, Radial flow, Concentration polarization, Fouling, Waste water treatment, Membrane-based separation (MBS).

INTRODUCTION

Membrane-based separation (MBS) process is nowadays very familiar in separation industries [1]. Its plenty of advantages are covered owing to two non-idealities, concentration polarization and subsequent fouling. Although the large surface area of cross-flow membrane modules may increase the permeate flux but failed to overcome these two non-idealities, which ultimately creates a negative effect on the permeate flux generation [2]. Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs) easily overcome the problem of concentration polarization and subsequent fouling [3]. The minimum surface area of DSEMFPs compared to cross-flow modules draws a limitation for it. Therefore, this current radial flow module with its specific design successfully achieves this surface area requirement. Moreover, the internal disk within the module and one central inlet with nine peripheral outlets easily control the large pressure drop,

***Author for Correspondence**
Keka Rana
E-mail: kekarana28@gmail.com

[1]Assistant Professor, Department of Chemical Engineering, Haldia Institute of Technology, Haldia, India
[2]Associate Professor, Department of Chemical Engineering, University of Calcutta, Kolkata, India

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consequently concentration polarization and successive fouling [2]. These positive characteristics make a prominent path for large-scale applications of this present module in various wastewater treatment, separation processes and many more. Nevertheless, before starting those specific applications, plenty of research on this module is highly required. Through the literature survey, the inadequacy of analysis on the said module becomes prominent.

Therefore, in this work, a detailed hydrodynamic study is covered. Computational Fluid Dynamics (CFD) is a very promising method for hydrodynamic analysis. Initially, a mesh volume was prepared on the radial flow module with all the design specifications. After that, various parameters for instance, dynamic pressure, velocity vector, turbulent kinetic energy, turbulent KE dissipation rate, vorticity, and wall shear stress are analysed here. All these studies were maintained by varying transmembrane pressure (TMP). These studies create a clear understanding of the inner atmosphere of the module with the detailed condition of the membrane surface. All these are very helpful in furthering the use of radial flow modules for large-scale applications in various wastewater treatment, separation processes and many more.

Hydrodynamic Simulation
Computational Fluid Dynamics (CFD):

Model Description

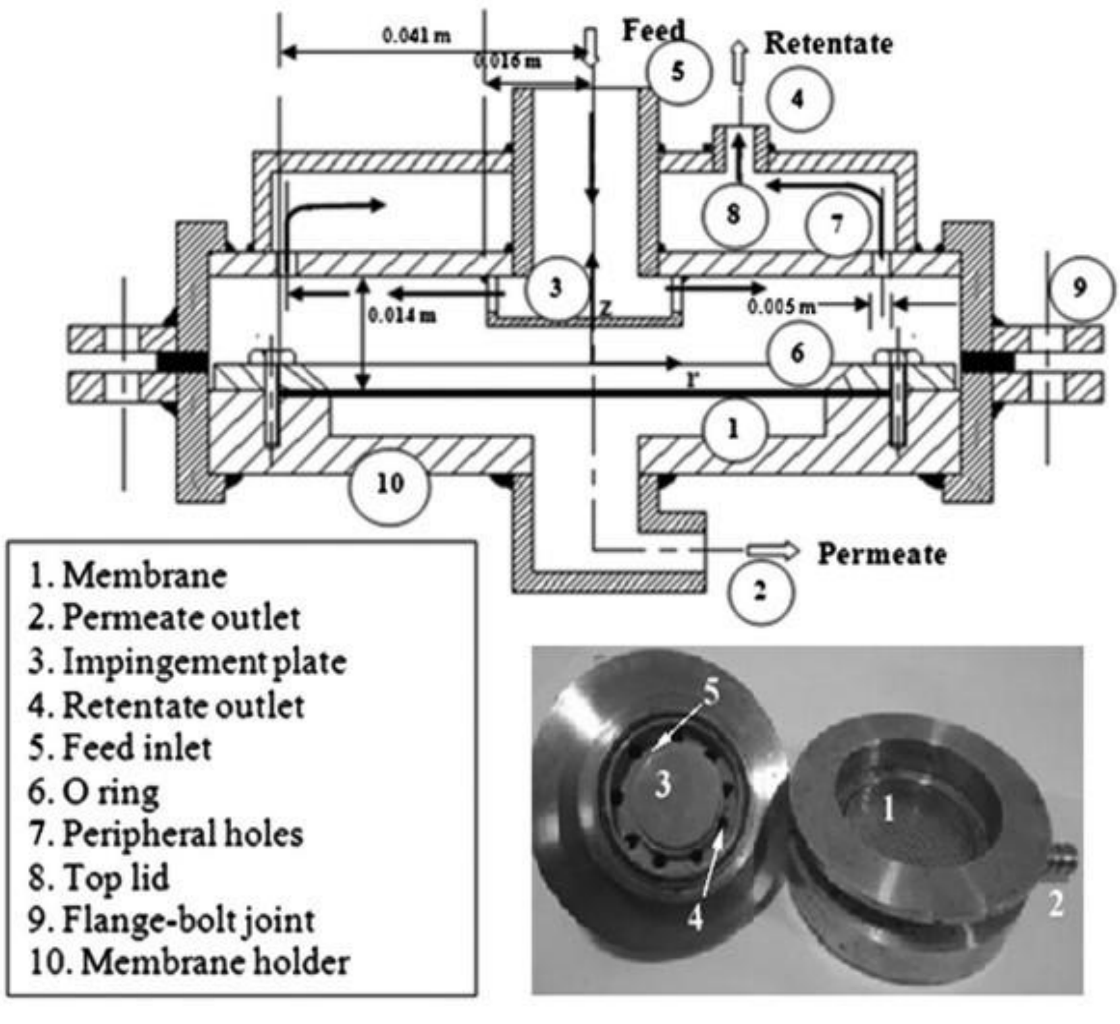

Fig. 1: Sectional view of the radial flow membrane (RFM) module (insert showing the photograph of the modules internals [2].

Fig. 1 shows the schematic of the module. There are nine peripheral outlets with one central inlet. Each peripheral holes have a 0.005m diameter. There is a 0.014m gap between the membrane surface and the top of the casing. Feed is entering the module from the top. The membrane is attached at the base of the system. A circular impingement plate of 0.016m radius is placed between the membrane and inlet line, to withstand the inlet feed pressure with uniform distribution of the feed throughout the module for proper utilization of the membrane surface area. It also saves the membrane from the high-feed jet impact. Permeate is collected from the bottom of the module, whereas the retentate comes out from the top portion of it.

Grid Generation and assumptions:

GAMBIT-FLUENT coupled solver is used to simulate the module. The mesh volume was generated through FLUENT software. Optimum mesh volume generation is the primary requirement for any CFD simulation. Less change in surface area promotes coarser mesh however finer one is for non-uniform areas [4]. After a proper grid independence test our desired optimum mesh volumes (= 75678432) for the present module are chosen.

To simplify the simulation, analysis was based on some assumptions,

i) Flow is incompressible.
ii) Fluid is Newtonian.
iii) Steady flow with no-slip boundary conditions at solid boundaries.
iv) Pressure is selected as an inlet boundary condition.

Solver

FLUENT solver is used to solve the meshed volume prepared by GAMBIT. Continuity and momentum balance equations are solved in the module. Three-dimensional double precision, finite volume method is used here [5-6]. A pressure-based solver with implicit formulation was used here. Generally, incompressible flow becomes more comfortable in a pressure-based solver. On the other hand, the Green Gauss node-based gradient evaluation technique was used. This shows better accuracy over the cell-based evaluation technique for high Reynolds number flow [7]. A better convergence rate is instigated to go with the simple first-order upwind scheme [8]. Complex geometries are handled efficiently by the k-ε model [9]. The realizable k-ε model is superior compared to the previous in respect to accuracy [9]. SIMPLEC scheme has better pressure-velocity coupling properties over the SIMPLE [10], as a result, this is selected under solver with the standard relaxation factor.

Results and Discussions

The proper understanding of the inner default interior is the prime requisite for further large-scale applications. Therefore, the velocity vector of the default interior is studied here. Moreover, membrane surface behavior is analyzed with various hydrodynamic properties for instance turbulent kinetic energy, turbulent KE dissipation rate, vorticity, dynamic pressure, and wall shear stress. Transmembrane pressure is varied for the analysis. Values of TMP were collected from the available experimental results [2]. The highest and lowest TMP values were chosen here for comparative analysis.

Variation of Velocity Vector in the Default Interior

In the above figure (Fig. 2), velocity vector distribution is depicted with varying transmembrane pressure (TMP), one lowest (a) 196.2 kPa and another one highest value (b) 392.4 kPa. Non-monotonic velocity vector distribution throughout the default interior is shown here. The existence of nine peripheral outlets is also very prominently visible in the above-mentioned figure. A circular velocity vector distribution around all the nine peripheral outlets is most clearly presented here.

Moreover, high velocity is achieved around each outlet for high TMP. At the inlet also similar result is visible for high TMP. Furthermore, the inlet has a lower velocity magnitude than the outlets. These phenomena justify the actual flow behavior of the module's internal fluid. Additionally, at higher TMP, high-velocity magnitude is shown clearly throughout the whole default interior of the module compared to the lower TMP. This draws the positive effect of TMP on the velocity magnitude. Therefore, this velocity vector distribution makes a proper understanding of the internal fluid activities within the module.

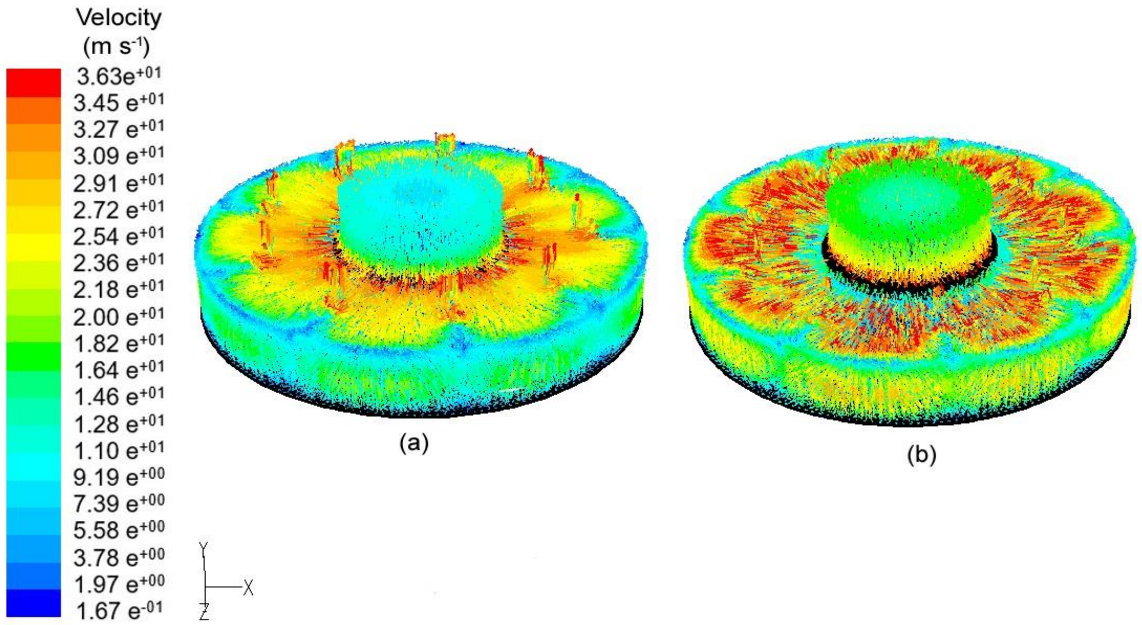

Fig. 2: Velocity vector distribution in the default interior of the radial flow module at varying TMP (a) 196.2 kPa, (b) 392.4 kPa.

Variation of Dynamic Pressure on Membrane Surface:

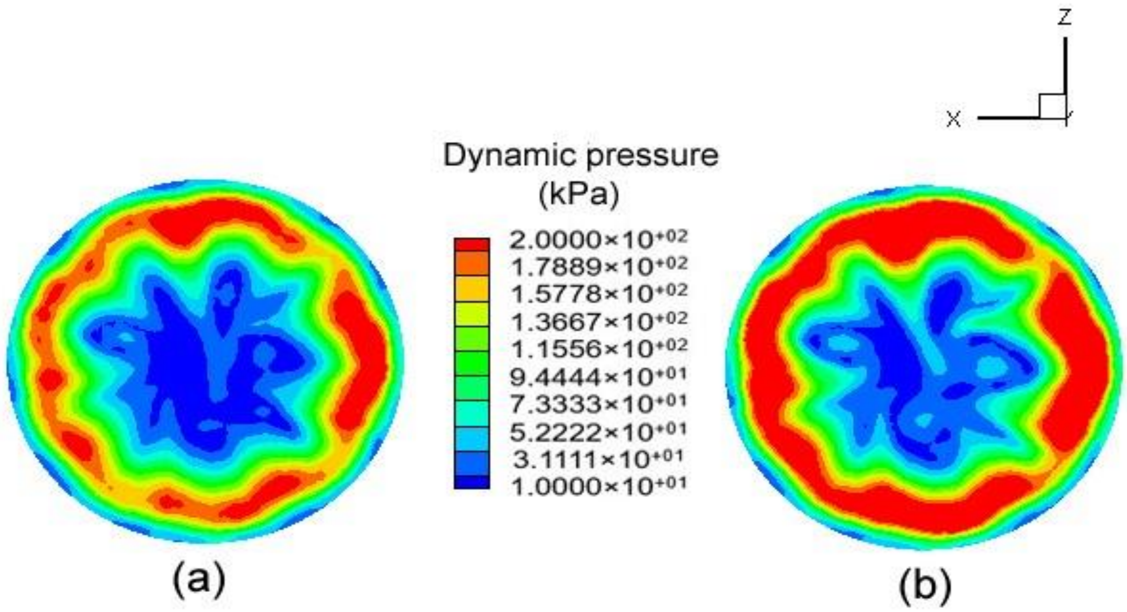

Fig. 3: Contour of dynamic pressure on the membrane surface of the radial flow module at varying TMP (a) 196.2 kPa, (b) 392.4 kPa.

Undoubtedly, the velocity vector throughout the default interior enriches the knowledge about the inner atmosphere of the module. Nevertheless, a detailed analysis is required to make a distinct idea about the membrane surface phenomena. Owing to that, various hydrodynamic study on the membrane surface was also analyzed. Among them, the major hydrodynamic properties are dynamic pressure, turbulent kinetic energy, KE dissipation rate, vorticity, and shear stress. Dynamic pressure is a vital parameter for fluid in motion. Therefore, its variation on the membrane surface is also a major requisite for a proper idea of the membrane surface phenomena. Pressure promotes easily more solute to scoop up from the membrane surface and restricts the flux decline. Consequently, more pressure means more solute scoop up. In Fig. 3, the contour of dynamic pressure varying TMP (a) 196.2 kPa and (b) 392.4 kPa is plotted. It depicts the increasing trend of dynamic pressure from the center to the outer surface. Moreover, the effect of nine outlets is also visible on the membrane surface prominently.

Variation of Turbulent Kinetic Energy on Membrane Surface

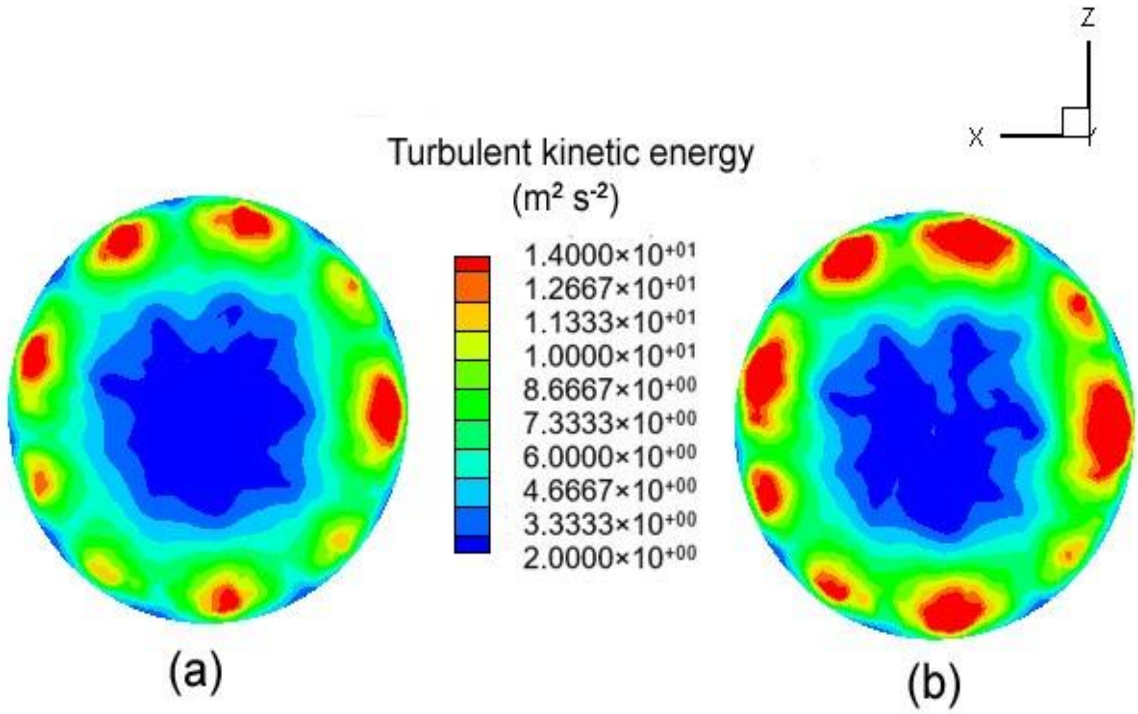

Fig. 4: Contour of turbulent kinetic energy on the membrane surface of the radial flow module at varying TMP (a) 196.2 kPa, (b) 392.4 kPa.

In continuation, several studies were also maintained. For, high Reynolds number turbulence behavior is a vital one. The generation of turbulence also has a great effect on solute dislodgement from the membrane surface. Therefore, turbulent kinetic energy is a very important property in analyzing the kinetic energy associated with fluid particles. In Fig. 4 the turbulent kinetic energy variation with TMP on the membrane surface is represented. Owing to the specific design the circulation of fluid is also examined in the above figure. The nine peripheral outlets are more vividly shown here. Maximum value achieved at the peripheral outlets, because of the presence of high kinetic energy associated with the fluid particles. The contour plot of turbulent kinetic energy follows a similar trend of dynamic pressure. The result validates the positive effect of TMP on the turbulent kinetic energy variation.

Variation of Turbulent KE Dissipation Rate on Membrane Surface

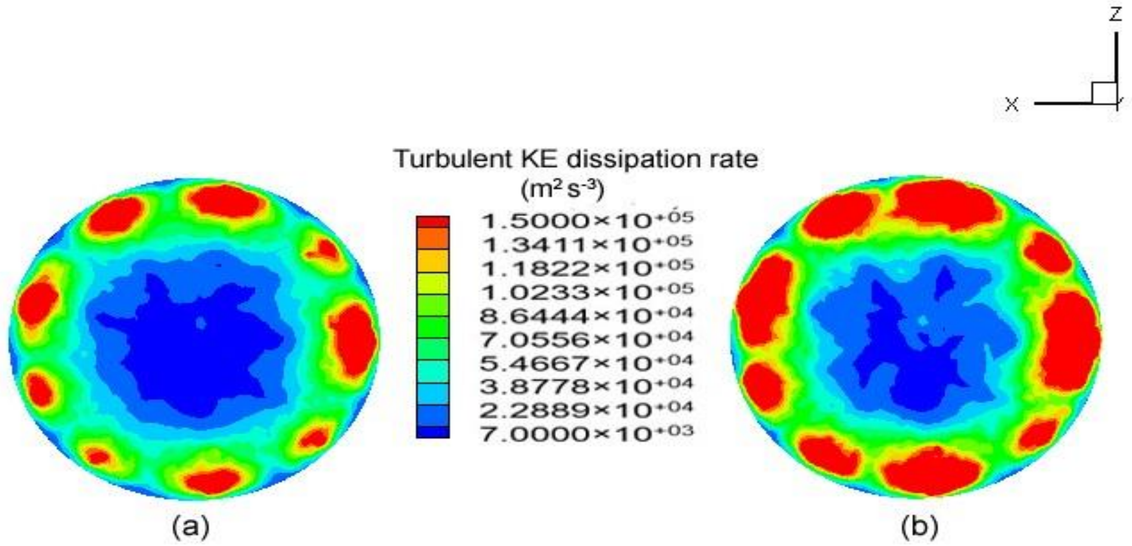

Fig. 5: Contour of turbulent KE dissipation rate on the membrane surface of the radial flow module at varying TMP (a) 196.2 kPa, (b) 392.4 kPa.

Turbulent kinetic energy and KE dissipation rate are very closely related. In turbulent KE dissipation, the mechanical energy eventually converts into heat through viscous forces and eddy production. Therefore, more kinetic energy means more dissipation rate and consequently more eddy generation. Accordingly, more eddy means more chance of solute separation from the membrane surface and minimization of fouling. Less fouling means more permeate throughput. In Fig. 5 the contour plot of turbulent KE dissipation rate with TMP (highest and lowest) is presented. Dissipation shows the same type of distribution pattern like turbulent kinetic energy on the membrane surface. Higher TMP generates a more turbulent KE dissipation rate compared the lower TMP. Therefore, the positive effect of TMP is also noticed here.

V*ariation* of Vorticity on Membrane Surface

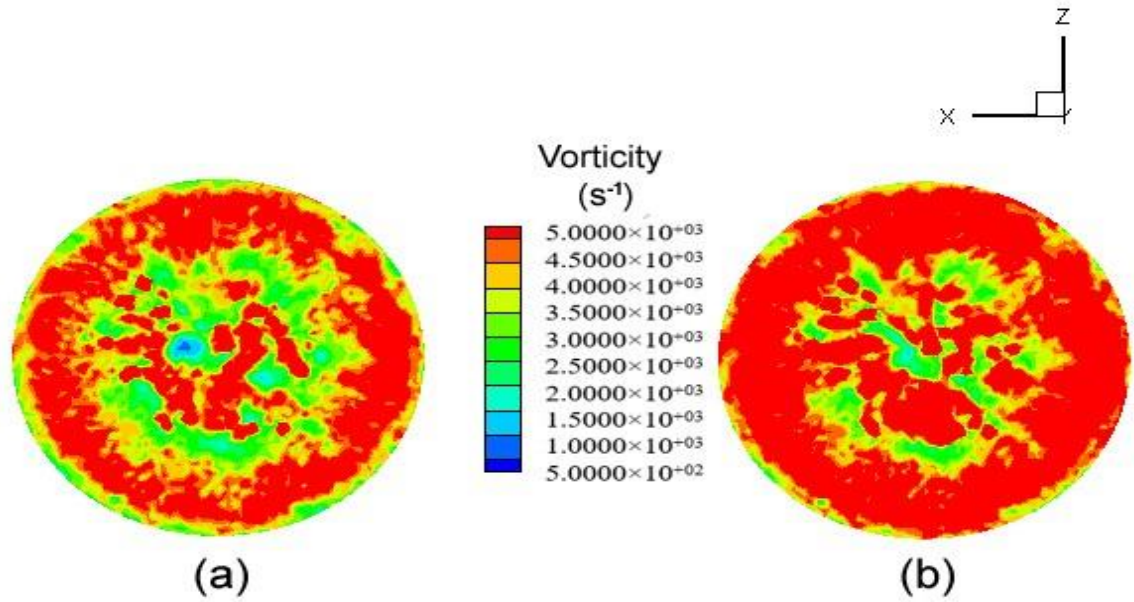

Fig. 6: Contour of vorticity on the membrane surface of the radial flow module at varying TMP (a) 196.2 kPa, (b) 392.4 kPa.

Vortices are the effect of turbulence. More turbulence means more vortices. Subsequently, more vortices enable the solute to scoop up efficiently from the surface of the membrane. Therefore, to study the vorticity variation with TMP is a very vital one. Fig. 6 shows the distribution of vorticity on the membrane surface with varying TMP. Higher TMP shows high vorticity on the membrane surface. Vorticity increases from the center to the periphery of the membrane. The high vorticity-prone zone creates a ring-like structure on the membrane surface. This ring thickness increases for high TMP compared to the lower one. This signifies less chance of solute accumulation on the periphery than the center of the membrane and the constructive effect of TMP on vorticity.

Variation of Wall Shear Stress on Membrane Surface

Finally, wall shear stress is examined on the membrane surface varying TMP (Fig. 7). Shear is a very effective property to dislodge the solute particles from the membrane surface smoothly. Therefore, the exact distribution pattern of shear stress on the membrane surface is a prime requirement to fulfil a clear understanding of the hydrodynamics of the membrane surface. The distribution maintained at low and high TMP similar to the all-previous analysis. Since pressure and shear are related to each other the distribution pattern of shear stress on the membrane surface follows the same trend as the dynamic pressure. More shear on the periphery enables less solute accumulation, less fouling and more permeate throughput.

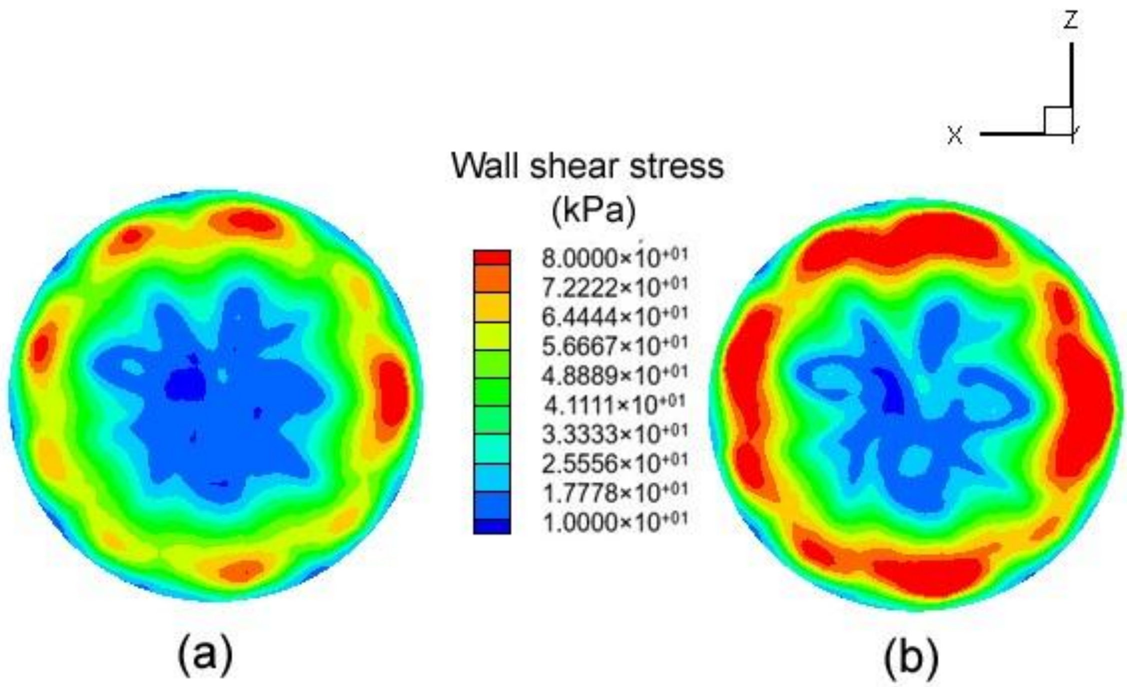

Fig. 7: Contour of wall shear stress on the membrane surface of the radial flow module at varying TMP (a) 196.2 kPa, (b) 392.4 kPa.

CONCLUSION

Hydrodynamic simulation is done in this project for radial flow membrane module varying TMP. The result shows a clear concept of the constructive effect of TMP on shear stress, velocity vector distribution, vorticity, turbulent kinetic energy, turbulent KE dissipation rate and dynamic pressure. Moreover, the results of all the analyses make a clear picture of the inner atmosphere of the module and the membrane surface. These effectively help a lot for further application of these modules in various applications, for instance, dye removal, valuable component (protein, drug) separation, and various wastewater treatment and separation industries.

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