International Journal of
Composite Materials and Matrices

ISSN: 2582-435X
Volume 10, Issue 1, 2024
DOI (Journal): 10.37628/IJCMM

https://journals.stmjournals.com/ijcmm/

Review IJCMM

Performance Characterization of Couette Flow Membrane Module Through Computational Fluid Dynamics

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Abstract

Membrane-based separation has been in rigorous applications in health services since the last few decennia. Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs) is a promising membrane module. The first reported DSEMFPs was a Couette flow type module in 1985. It was used for collecting plasma from donors. This module consists of two concentric cylinders. The outer one is fixed while the inner one is rotating, having a membrane on the outer surface of it. High rotational velocities generate Taylor vortices. These Taylor vortices and small annular spaces easily create high shear on the membrane surface to efficiently control concentration polarization (CP), subsequent fouling and maintain the minimum decline of permeate flux. The exhaustive analysis of this DSEMFP required for large-scale applications. The absence of this instigates further detailed study of it. In particular, shear stress distribution on the membrane surface with varying transmembrane pressure and rotational velocity is vital. Moreover, for a clear understanding of the default interior, turbulent kinetic energy, turbulent kinetic energy dissipation rate, velocity vector, strain rate and vortices are also studied. All the analyses suggest the positive effect of the high rotational speed of the inner cylinder for maximum permeate output.

Keywords: Concentration polarization, Fouling, Membrane, Couette flow, Taylor vortices

INTRODUCTION

Dynamic Shear Enhanced Membrane Filtration Pilots (DSEMFPs) efficiently control the two non-idealities of membrane-based separation, CP and subsequent fouling over cross-flow membrane modules owing to its feed flow-rate independent high shear generation facility. Moreover, DSEMFPs are the most suitable for high-fouling feed solutions [1, 2]. These properties make the DSEMFPs most acceptable in membrane-based separation industries. The Couette flow membrane module was the starting module under the DSEMFPs family. This module consists of two concentric cylinders. Within the fixed outer cylinder inner cylinder is rotating. The membrane is attached to the surface of the inner cylinder. During rotation, Taylor vortices were generated. The combination of smaller annular space and Taylor vortices restrict the decline of permeate flux by creating high shear on the membrane surface and efficiently reducing the CP and successive fouling. In the year 1985, the first successful commercialization of the Couette flow membrane module was done [3, 4]. This module is used to separate plasma from the human blood. In medical treatment, this module has created a revolution. Therefore, Large-scale application of this required further detailed analysis. The literature review draws a clear picture of the lack of study.

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Received Date: April 29, 2024
Accepted Date: May14, 2024
Published Date: Aug 13, 2024

Citation: Keka Rana, Debasish Sarkar. Performance Characterization of Couette flow membrane module through Computational Fluid Dynamics. International Journal of Composite Materials and Matrices. 2024; 10(1): 1–5p.

Therefore, a detailed study of this module is highly essential.

In this work, the complete hydrodynamic study of Couette flow attempted. Initially, through the grid independence test optimum mesh volume is selected. Therefore, various properties, turbulent kinetic energy, turbulent dissipation rate, wall shear stress, vorticity, strain rate etc. are investigated with varying transmembrane pressure (TMP), and membrane rotational speed. The average strain rate on the membrane surface is also studied with varying membrane rotational speed. All the analysis justifies the positive effect of rotational speed on the membrane shear stress control.

HYDRODYNAMIC SIMULATION

Optimum Grid Generation& Basic Assumption

Computational Fluid Dynamics (CFD) simulation was done by GAMBIT-FLUENT coupled solver. The finite volume method with three-dimensional double precision is chosen here to achieve accuracy in results [5, 6]. Moreover, optimum grid generation is also a prime requisite for any CFD simulation. Generally, finer grids are always acceptable at the cost of high computational time. Therefore, to optimize the grid generation, finer grids are selected for large gradient zones, whereas, coarser grids are selected for the uniform regions [7]. The grid independence test is depicted in the following Figure 1.

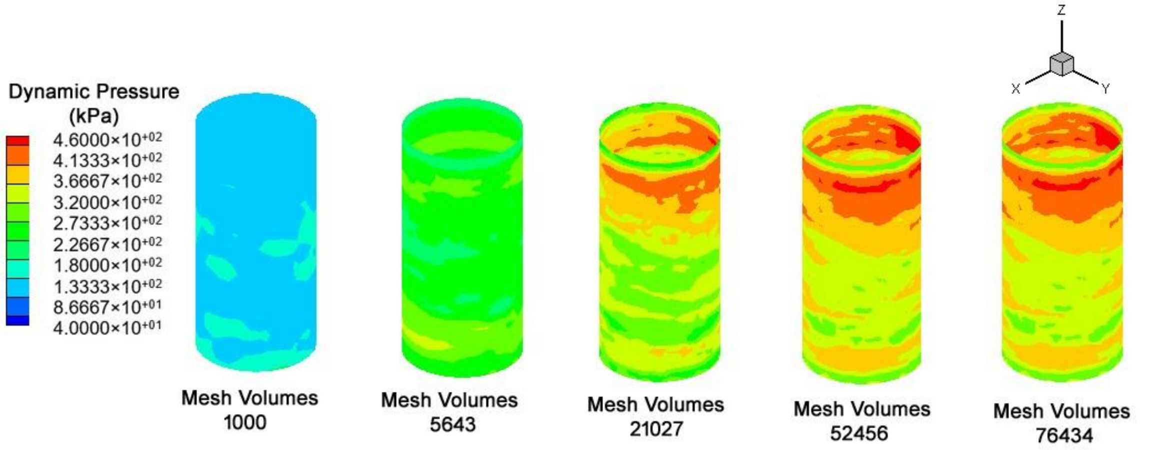


Figure 1. Dynamic pressure variation on membrane surface with varying mesh volumes.

Dynamic pressure distribution on the membrane surface with varying mesh volumes is depicted here. Increasing mesh volume represents the dynamic pressure distribution significantly. The last two mesh volumes don’t create any remarkable difference on the membrane surface. Therefore, to optimize the mesh volume while considering computational time, the second last mesh volume (=52456) was selected for further study. Figure 2 shows the mesh volume of the Couette flow module. For analysis the following assumptions are considered here:

i. Steady flow
ii. Incompressible, Newtonian fluid.
iii. No-slip boundary conditions at solid boundaries.
iv. Pressure inlet boundary condition is selected.

Selection of Model & Solver

FLUENT was used here to solve the mesh volume generated by GAMBIT. The turbulence model was used for simulation. Efficient simulation of vortices wakes, and high Reynolds number boundary layer simulation was done by model [8]. The second order SIMPLEC scheme was selected [7–9].

RESULTS AND DISCUSSIONS

Hydrodynamic simulation becomes the best way to complete an understanding of the inner phenomena of the module. The following properties, (i) turbulent kinetic energy, (ii) turbulent KE dissipation rate, (iii) vorticity, (iv) wall shear stress and (v) strain rate is selected here for analysis.

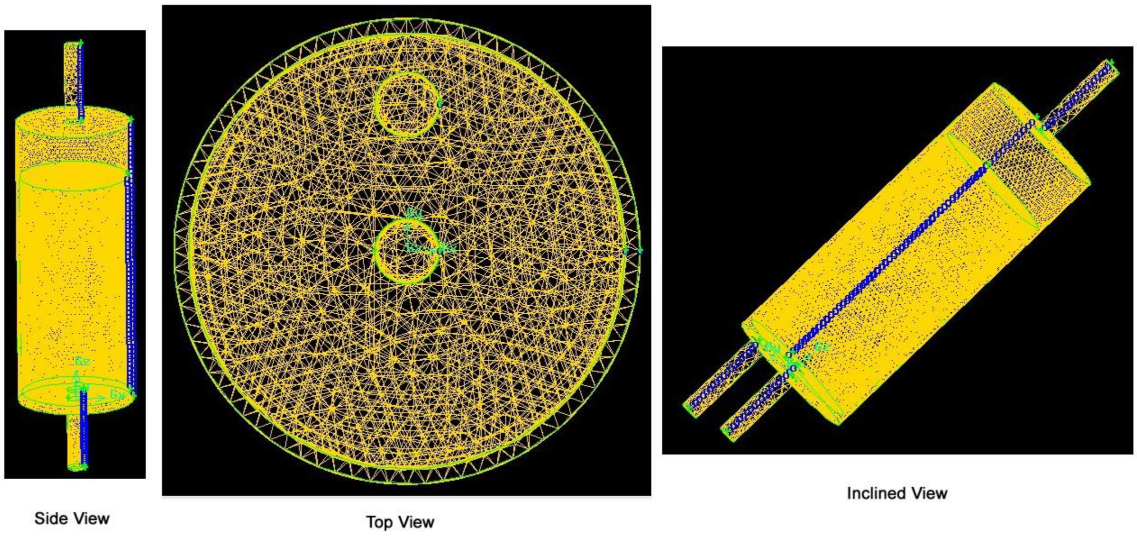

Side View
Top View
Inclined View

Figure 2. Mesh volumes of the Couette flow membrane module.

Variation of Turbulent Kinetic Energy

Turbulent kinetic energy is a vital property to estimate the turbulence's nature. The variation of turbulent kinetic energy on the membrane surface was analyzed by varying TMP (= 98 kPa, 196.1 kPa, 392.3 kPa, 588.4kPa), with fixed rotational speed (=104.72 rad s-1) (Figure 3). No such remarkable changes prove the insignificant role of TMP on turbulent kinetic energy variation. Other hydrodynamic variables were also examined by varying TMP. All the analysis follows the previous trend. Afterwards, in Figure 4, variation of turbulent kinetic energy with varying rotational speed (= 31.416 rad s^{-1}, 62.8318 rad s^{-1}, 83.78 rad s^{-1}, 104.72 rad s^{-1}) at fixed TMP = 588.4 kPa is represented. The significant variation of turbulent kinetic energy for rotational speed is visible here. Moreover, higher rotational speed generates higher turbulent kinetic energy on the membrane surface.

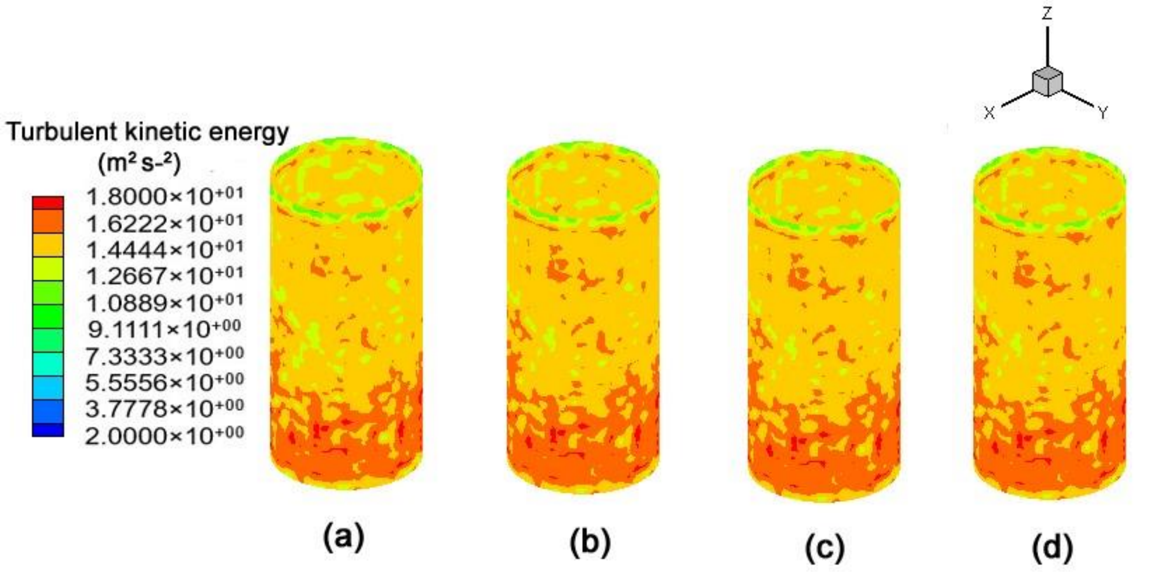


Figure 3. Variation of turbulent kinetic energy on membrane surface of Couette flow module varying TMP (Fixed rotational speed = 104.72 rad s^{-1}) (a) 98kPa, (b) 196.1 kPa, (c) 392.3 kPa, (d) 588.4 kPa.

Variation of Turbulent Kinetic Energy Dissipation Rate

Prediction of turbulence is very tough work. To increase the accuracy of results turbulent kinetic energy dissipation rate also plays an important role. Therefore, variation of turbulent KE dissipation rate also studied here varying rotational speed (Figure 5). The same trend is shown here also like in Figure 4. Increasing rotational speed has a positive effect on dissipation rate.

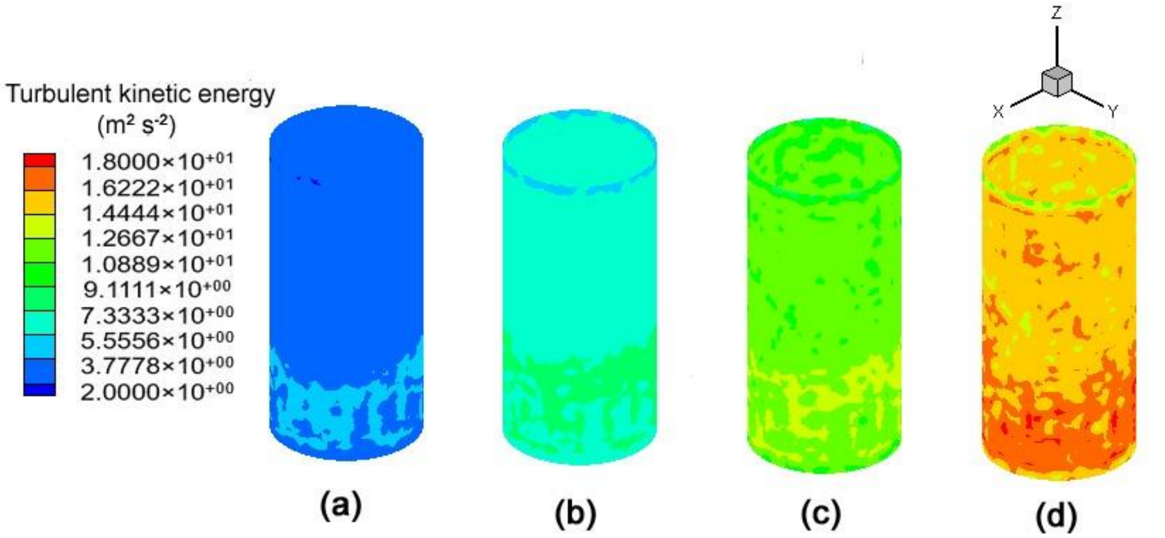


Figure 4. Variation of turbulent kinetic energy on membrane surface of Couette flow module varying rotational speed (Fixed TMP = 588.4 kPa) (a) 31.416 rad s^{-1}, (b) 62.8318 rad s^{-1}, (c) 83.78 rad s^{-1}, (d)104.72 rad s^{-1}.

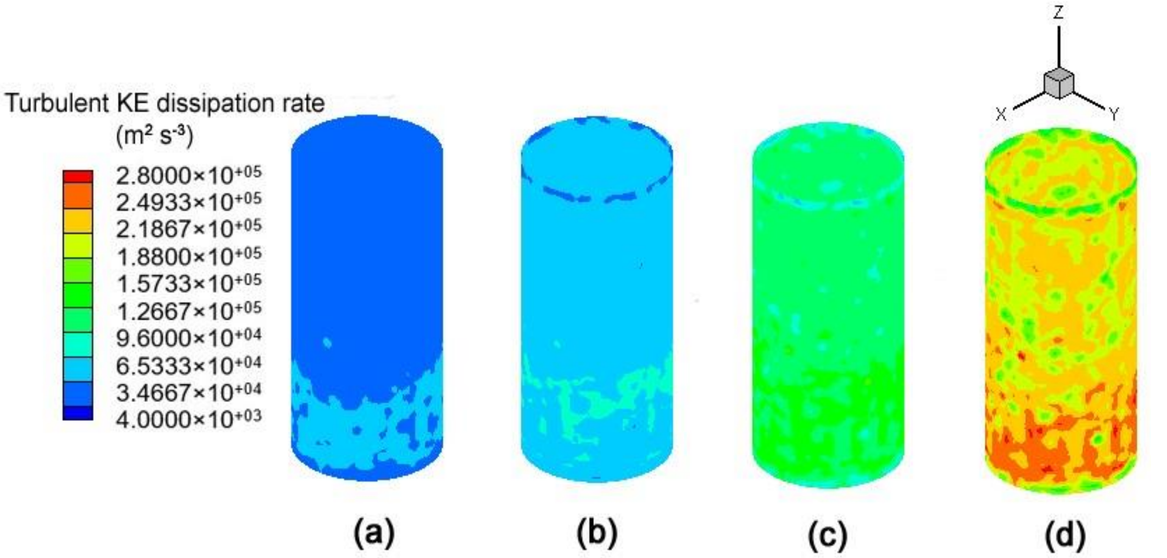
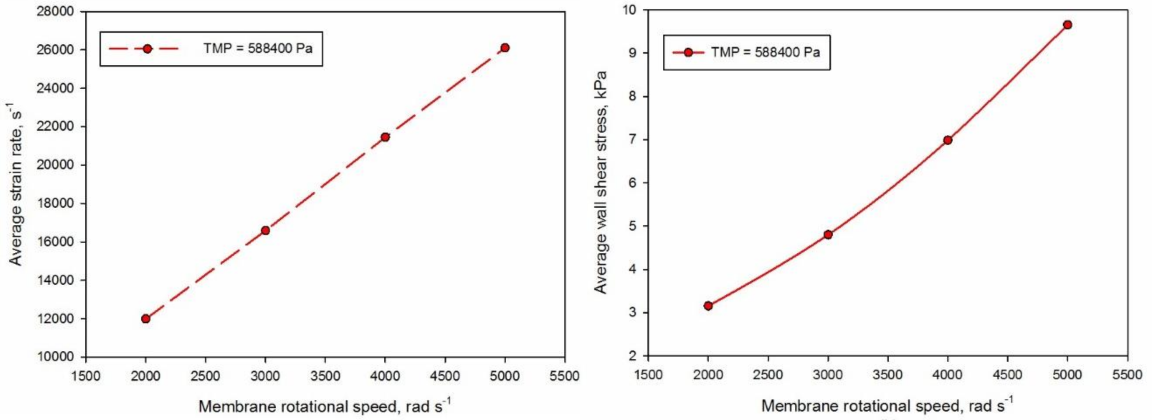


Figure 5. Variation of turbulent kinetic energy dissipation rate on membrane surface of Couette flow module varying rotational speed (Fixed TMP = 588.4 kPa) (a) 31.416 rad s^{-1}, (b) 62.8318 rad s^{-1}, (c) 83.78 rad s^{-1}, (d)104.72 rad s^{-1}.

Variation of Average Strain rate & Average wall shear stress

Strain rate is a major property of the analysis of the turbulence nature of any fluid flow module. Consequently, the average strain rate variation with rotational speed on the membrane surface is represented graphically in Figure 6 (a). These results follow the previous nature of the distribution. Wall shear stress also has a great impact on controlling CP and subsequent fouling. Therefore, the exact distribution of wall shear stress becomes a prime requisite under CFD simulation. Following that, wall shear stress was also studied (Figure 6 (b)). This result also shows an increasing trend but a slightly convex nature is shown here.



(a) (b)

Figure 6. Variation of (a) Average strain rate, (b) Average wall shear stress on membrane surface with varying rotational speed (Fixed TMP = 588.4 kPa) 31.416 rad s^{-1}, 62.8318 rad s^{-1}, 83.78 rad s^{-1}, 104.72 rad s^{-1}.

CONCLUSION

The hydrodynamic study through CFD simulation of the Couette flow membrane module is done in this work. The turbulent model is used here for analysis. Various hydrodynamic variables, turbulent kinetic energy, turbulent KE dissipation rate, wall shear stress, and strain rate are investigated at different parametric conditions. The results prominently show the insignificant role of TMP and significant effect of rotational speed. Furthermore, the distribution of variables on the contour plot over the membrane surface is not uniform. This nature of distribution helps to estimate the exact solute scooped up from the membrane surface.

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