Computational fluid dynamics analysis of mini membrane module flow behavior

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Abstract. A newly developed green ultrafiltration membrane has been successfully made by utilizing natural antibiofoulant impregnated cellulose acetate mixed matrix membranes. The extract impregnated into cellulose acetate polymer to form mixed matrix membranes with higher and foodgrade antibiofouling properties. In order to evaluate mixed matrix membrane mass transport, a specialized mini membrane modules has been developed. This study utilizing computational fluid dynamics (CFD) simulation to evaluate fluid distribution in rectangular, quadrilateral and circular narrow channels. Three different superficial velocities which are normally found in spiral wound membrane modules were evaluated, i.e. 0.11, 0.16 and 0.2 m/s. Trans-membrane pressure normally used in ultrafiltration processes were evaluated, i.e. 50, 100, and 150 kPa. Based on CFD analysis, circular channel provides a more uniform and distributed velocity stream compare to the others. The circular shape also provide advantage on managing superficial feed flow inside the membrane channel, compared with rectangular and quadrilateral shapes channel. The mini membrane modules potentially reduces laboratory scale research cost, while maintaining the similar operating variables of larger scale.

1. Introduction

Physical separation of food substances using microfiltration and ultrafiltration membranes could be improved by using a mixed matrix membranes [1]. In order to determine mixed matrix membrane mass transport, a laboratory-scale mini membrane modules (mMm) has been developed. The customized module has circular shape, unlike the typical membrane test cells [2]. For monitoring biofouling development in spiral wound membrane channel, a rectangular shape monitoring device has been developed. The flat sheet monitor (FSM) made of stainless steel and covered lid from PMMA has external dimensions of 0.32 m x 1.03 m x 0.07 m. A smaller version, named membrane fouling simulator (MFS) has external dimensions of 0.07 m x 0.30 m x 0.04 m [3]. On the contrary, a long-channel membrane test cell (LCMTC) was developed by mimicking the real length of a spiral wound element to study flow fields in the channel [4]. In order to study the effect of high-pressure, a sapphire window was used in a flat sheet membrane module allowing the module endured pressure up to 8,300 kPa [5].

While most contemporary studies used rectangular membrane channel test, a more preceding study use a circular membrane channel to study mass transport over reverse osmosis membrane [6].
The study intrigued new questions whether circular channel is more appropriate to study mass transport over the flat membrane or provides a better flow fields in the membrane channels. Computational fluid dynamics analysis could provide rapid and accurate answers to the questions [7]. This paper reported CFD study of flow fields comparison in flat sheet membrane channels.

2. Materials and Method

2.1. Process parameters and fluid properties

Mixed matrix membranes used in the study is a microfiltration membrane, it is therefore the process parameters also follows microfiltration conditions. The transmembrane pressure (TMP) varied into 3 different pressure, i.e. 50 kPa, 100 kPa and 150 kPa. Although mass transport over the membrane is not involved in this computational study, the pressure is simulated due to its effect into the flow behaviour in the channels. Three superficial veloties or cross flow velocity (CFV) were selected as initial condition in the channel inlet, i.e. 0.11 m/s, 0.16 m/s and 0.2 m/s.

As shown in Figure 1, three membrane channel shapes were selected, i.e. square, rectangular and circular channels. The square channel dimension was 90 mm x 90 mm corresponds with 8,100 mm² effective membrane area. The rectangular channel dimension was 30 mm x 90 mm corresponds with 2,700 mm² effective membrane area. Finally, the circular channel diameter was 90 mm, corresponds with 6,358 mm² effective membrane area.

![Figure 1. Selected membrane narrow channels: square, rectangular and circular shapes](image)

Two types of liquids were simulated, i.e. water and olive oil as a more viscous liquid. The properties of liquids were set at room temperature [8,9], with olive oil density set at 916 kg/m³ and viscosity at 0.084 kg/ms.

2.2. Computational study

The cross-section representation of membrane narrow channel is shown in Figure 2.

![Figure 2. Cross-section view of membrane channel](image)

The channel height was 2 mm, allowing the feed fluid flow over the membrane surface. There was no turbulence promoter involved in the fluid flow, assuming that the flow freely distributed over the membrane surface. The computational study was evaluated at different channel height i.e. 0.5 mm (closed to membrane surface), 1 mm (middle channel) and 1.5 mm (closed to cover lid). The feed inlet and retentate outlet diameter were 8 mm. The x-axis represented channel length or diameter of 90 mm.

The governing equations was described elsewhere [10], while cartesian coordinate system was selected. Discretization and flow simulation was conducted using ANSYS Academic Fluent software ver. 18.1.
2.3. Module development
Beyond the CFD simulation study, selected membrane channel which provided the best flow distribution, was then manufactured. The design and material properties were selected depended on the process condition.

3. Results and Discussion
3.1. Comparison of membrane channel shapes
Figure 3 shows comparison velocity streamline between membrane channel shapes, in the following conditions: water, 150 kPa transmembrane pressure, 0.2 m/s water superficial velocity and flow field close to membrane surface.

As shown in Figure 3, rectangular and square channels promoted a non-uniform flow distribution over the membrane surface. In the edge of each channels, "dead zones" occurred, in which fluid flow was not reached the region. When the flow was not reached the dead zones, there was no liquid passed the membrane over the region, and the effective membrane area was decreased. The condition could promoted membrane flux decrease. The opposite condition occurred in circular channel, which uniform flow distribution was expected. The condition stimulated a more liquid transported into permeate side as the consequence of flux increase. While comparing the channel shape, it is obvious that circular membrane channel provide better mass transport compared to rectangular dan square channels [2].

3.2. Comparison of fluid properties
Figure 4 shows comparison velocity contour between different fluid properties, e.g. water and olive oil. While the transmembrane pressure set at 150 kPa and liquid superficial velocity set at 0.2 m/s, and flow field simulated closed to membrane surface.
Figure 4. Velocity contour at circular shape using water (left) and olive oil (right), with 150 kPa TMP and 0.2 m/s CFV

As shown in Figure 4, the velocity contour for both liquids were uniformly distributed over the membrane surface. However, while using a more diluted liquid, e.g. water, there was higher flow velocity close to feed inlet. Viscous liquid, e.g. olive oil, showed more uniform velocity even in the inlet and outlet of the channel [10].

3.3. Comparison of liquid superficial velocity
Figure 5 shows comparison velocity contour at different water superficial velocity of 0.11 m/s and 0.2 m/s at 150 kPa transmembrane pressure, closed to membrane surface.

Figure 5. Velocity contour at circular shape at CFV of 0.11 m/s (left) and 0.2 m/s (right), while TMP both of 150 kPa

As shown in Figure 5, the velocity contour for higher velocity promoted a more higher velocity over the membrane surface, and possible higher flux due to higher cross flow velocity. Higher CFV would allow better prevention of fouling on the membrane surface and promoted higher mass transport across the membrane. Maintaining single phase liquid flow velocity or multiphase flow were able to enhance fouling removal either particulate, organic or microbial fouling [11].

In this regards, higher cross flow velocity could also reduced concentration polarization over the membrane surface, which also stimulated higher mass transport across the microfiltration membrane. When fouling required membrane surface cleaning, concentration polarization could be reduced by released trans-membrane pressure for a while until concentration of bulk solution become uniformly distributed over the membrane surface.

3.4. Comparison of transmembrane pressure
Figure 6 shows comparison velocity contour at different transmembrane pressure of 50 kPa and 150 kPa, by using same water superficial velocity of 0.2 m/s, closed to membrane surface.
Figure 6. Velocity contour at circular shape at different TMP of 50 kPa (left) and 150 kPa (right); CFV of 0.2 m/s

As shown in Figure 6, the velocity contour for both 50 kPa and 150 kPa were very similar. The condition occurred might occurred due to insignificant different of TMP. It was expected that a more higher TMP could promotes a more higher mass transfer across the membrane.

3.5. Comparison of membrane channel height
Figure 7 shows comparison velocity contour at at different channel height i.e. 0.5 mm (closed to membrane surface), 1 mm (mid channel) and 1.5 mm (closed to cover lid), at same water superficial velocity of 0.2 m/s and 150 kPa transmembrane pressure.

Figure 7. Velocity contour at circular shape at different channel height i.e. 0.5 mm (left), 1 mm (middle) and 1.5 mm (right); by using CFV 0.2 m/s and TMP 150 kPa

As shown in Figure 7, the velocity contour at different channel height were slightly different. However, the distinction was only at inlet or outlet channel, when similar condition was observed over the major channel area. Obviously, the narrow channel of only 2 mm contributed to this uniformly velocity profile condition. Uniform supervicial velocity over the membrane surface also could promoted uniform mass transfer across the membranes [2].

3.6. Module manufacture
Schematic drawing of circular membrane module is shown in Figure 8. The mini membrane module has ring-shaped stainless steel plates with 160 mm outer diameter and 100 mm inner diameter. A couple of 10 mm thick circular PMMA plates with diameter 120 mm mounted between two halves of the ring-shaped stainless steel plates. A coupon of mixed matrix membranes placed within the circular plates with customized grooves thickness to place feed spacer and permeate spacer mimicking the
configuration of industrial scale spiral-wound membrane modules. The used of circular PMMA plates allows direct monitoring of membrane mass transfer without disturbing the process.

Figure 8. Schematic drawing of circular membrane module

4. Conclusions
CFD analysis provided comparison of flow field distribution at different membrane narrow channel shapes. Circular shape however, promoted better uniform flow distribution compared with square and rectangular channels. In order to enhance membrane flux, selected circular channel was manufactured to evaluate the performance of mixed matrix membranes.

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