Finned spacer panel system for fouling control in *Chlorella vulgaris* harvesting

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Abstract. Membrane filtration has been proved as a viable harvesting candidate to harvest microalgae for biofuels application. Though largely limited by membrane fouling that lowers overall process efficiency. The novel finned spacer is proposed to reduce fouling control in *Chlorella vulgaris* harvesting. The assessment of this work is focusing on these aspects: evaluation performance of finned spacer in directing air bubbles toward the membrane surface, study the effect of fin’s gap on membrane fouling control performance, the impact of aeration rate on membrane fouling control and operation under fins switching mode. Effectiveness of finned spacer has been obviously proved by its function to direct and encourage air bubbles toward the membrane surface thus improve their contacts and their foulant scouring impact. The projection of air bubbles is more effective at the narrowest fins gap applied of about 2cm gap. The increasing aeration rate proportionally increases flux of 90 L/(m².h) at 1.5 L/min aeration. Switching mode was applied to increase module packing density without reducing specific membrane performance. It was found effective at periods of below 5 min. Overall results are very encouraging and promising to obtain significant improvement in fouling control for *C. vulgaris* filtration. Further study on fundamental aspects as well as parameters optimization can still be done to increase the finned spacer efficiency.

1. Introduction

The approaches to explore viable alternative renewable energy have been increased due to high concern about negative impacts of fossil fuels to environment. Microalgae biomass is found as one of potential option for energy sources [1]. It can be converted into fuel such as biohydrogen, biodiesel, methane etc [2,3]. Microalgae has favorable attributes, such as fast growing, containing high amount of lipid that makes convincing as a source of biofuels feedstocks [4]. Nonetheless, the challenge associated to energy-intensive harvesting process, about 90% of total production cost [2,5] must be overcome to boost its potential.

Membrane filtration is a favorable option for harvesting microalgae because it offers several advantages: low energy foot-print, high biomass recovery, easy to be operated and scale-up, minimum
use of chemicals, etc [6]. Application of pressure driven membrane technology is, however, strongly limited by membrane fouling. The mechanism of fouling in microalgae harvesting can be classified into pore blocking, adsorption, cake layer formation, and gel layer formation [7]–[10]. Fouling diminishes membrane flux, complicates operation, shortens life span thus deflates productivity [7,11].

Air bubble scouring has become a standard cleaning method for porous pressure driven membrane process [12]. Air bubbles reduce the rate of foulant deposition and help to scour-off the deposited foulant. In the traditional membrane panel configuration, plate-and-frame panels are arranged vertically with certain gaps to allocate a channel flow through which air bubble and liquid feed stream are flown to clean the membrane surface [13]. The two-phase flow of air in the feed liquid promotes turbulence and increases shear-rate that beneficial for foulant removal [14]. The key issue of the traditional aeration system is the poor contact of air bubble to the membrane surfaces that leads to inefficient scouring. In vertical panel, air bubbles tend to move in the central space between adjacent panels, which then minimize its contact to membrane surface. Definitely, it reduces foulant scouring impact.

Horizontal membrane panel improves the effectiveness of air bubbles scouring [15]. Despite its effectiveness, horizontal panel is difficult to be scaled-up and even if it is viable, it leads to very low module packing density for facilitating the aeration. In more recent study Eliseus et. al., 2017, attempt to solve this situation by tilting the membrane panel. However, this approach is limited to amounting membrane sheet in one side of the panel, substantially lowering module packing density. Remedial action of such limitation via panel switching as proposed recently [6], can increase the energy food print and complexity of operation because the movement of bulk-mass. Such operation is difficult considering the necessity to switch an array of panels and liquid contained inside the system.

Conventional vertical panels module system is highly limited by poor contacts of air bubbles to the membrane surface that minimize their effectiveness in scouring-off membrane fouling. Recently developed unconventional modules via horizontal or tilted panels, despite showing remarkable improvements, have practical limitations [6,15]. Horizontal panel is difficult to scale-up and would leads to a very low module packing density [15]. Tilted panel only allows membrane sheet to be mounted in one-side of the panel thus reducing module packing density. Operating the tilted panel dynamically by involving periodic panels switching can avoid the aforementioned limitation [16]. However, dynamic system is often vulnerable from technical problems, especially in the panels switching case where a large number of panels have to be alternatingly tilted in opposite directions.

In this study, we propose a novel finned spacer system as attached to the conventional vertical panels for membrane fouling control in microalgae filtration. The finned spacers help to direct and encourage the bubbles to the surface of the membrane. Unlike in the tilted panel, where the whole panel is tilted to block the upward trajectory of air bubbles, in the proposed system, finned spacer is positioned in between membrane vertical panels to encourage the air bubbles towards the membrane surface. As in the switching panel, the fins can be switched to accommodate aeration of both panels by intermittent fins switching. This idea is reliable as more practical due to the moving part of fins instead of the whole membrane panel. This study focuses on fouling control on the membrane filtration system during the process of harvesting microalgae. Membrane used for the project is lab-made microfiltration polyvinylidene fluoride (PVDF). This membrane materials are commonly used for Chlorella Vulgaris filtration as reported in literatures [17].

Few assumptions can be made; cleaning of the membrane achieved full flux recovery indicating no irreversible foulant. The concentration and condition of the microalgae feed are assumed to be constant throughout the experiment.

2. Material and methods
2.1 Chlorella vulgaris feed and analysis
The Chlorella vulgaris broth was provided by Center for Biomass and Biofuel Research (CBBR) Universiti Teknologi Petronas (UTP) -Malaysia. The broth was used as received without pre-treatment. It was cultivated on extract of compost as nutrient source and collected once a batch-wise cultivation
reaches the stationary phase, corresponding to biomass concentration of 1.1 g/L. This concentration is considerably higher than the concentration used in earlier study (<0.5 g/L) [6].

2.2 Membrane characteristics and panel assembly

The tests were performed using phase inverted polyvinylidene fluoride (PVDF) membrane. The membrane sheet was prepared via immersion precipitation using PVDF (Arkema, MW of 300 PDa), dimethylacetamide (DMAC, Sigma-Aldrich) and demineralized water as the polymer, the solvent and the non-solvent, respectively. Dope solution was prepared by dissolving 15 wt% of PVDF into DMAC. The mixture was thoroughly dissolved and degassed before casting. The dope solution was casted using a doctor blade with a wet thickness of 0.22 mm at room temperature and humidity atop a non-woven support to avoid membrane shrinkage (ref 1) (Novatexx 2471, Freudenberg-Filter, Germany). After casting, the cast film was immediately immersed in a bath containing DI water. The membrane was stored wet until usage. To be practically applicable for filtration, the membrane sheet was assembled into a panel with an effective area of 140 cm² (one-sided surface of 10 x 14 cm). It was attached and sealed (Epoxy + 100% RTV silicon) on the membrane frame panel.

The clean water flux was measured after the prepared membrane was assembled into a filtration panel in a submerged filtration system. The flux ($J$) were calculated by using Eqs. 1.

$$J = \frac{V}{At} \quad \text{(L m}^{-2} \text{h}^{-1})$$

where $V$ is volume of permeate (L), $A =$ membrane area (m²), $t =$ filtration time (h).

The properties of the membrane were characterized in earlier study [6], microstructure images of the membrane were obtained using scanning electron microscope which later processed by using ImageJ (NIH software) to estimate surface porosity, surface pore size and surface pore density following the procedures reported elsewhere [18]. The pore size and size distribution were also measured using capillary flow porosimeter. Goniometer, micrometer and dry wet method were used for measuring contact angle, sheet thickness and porosity, respectively. The thickness (mm), maximum pore size (µm), mean pore (µm), contact angle (°), clean water flux (L m² h⁻¹), surface pore size (µm), surface pore density (pores µm⁻²), and lastly surface porosity (%) of the membrane were 0.18±0.1, 0.19±0.01, 0.16±0.01, 75±5, 1960±110, 0.1±0.01, 19±2 and 11±2, respectively.

2.3 Spacer specification

The finned spacer was self-fabricated using acrylic material which consists of fins and housing to mount the membrane panel. Number of fins, fins gap, length, width and thickness are as detail 6, 2, 12, 5, 0.1 cm respectively. Whilst housing height and width are 18 and 5.5 cm. Air distributor was installed underneath with distance 6 cm from the lowest.

2.4 Experimental Set-up and Procedure

Illustration of the experimental set up is shown in Figure 1. The pump was connected to the permeate pipe and the aeration was provided by the air pump. The membrane panel was fully submerged into the feed tank. The pressure of the pump was set at -0.1 bar for all tests. The set-up for tilted panel system is similar to our previous report [6].
Figure 1. The apparatus set-up

The permeate was collected semi-batch wise for under operation cycle of 9.5 min filtration and 0.5 min relaxation. After permeate volume was measured, the permeate was returned back into the filtration tank to maintain feed liquid level.

Fouling can be detected from the flux profile over time. When under constant pressure, flux decreases over time due to foulant’s accumulation. The queasy steady state flux values were taken as average valve of the last 30 minutes of filtration. Biomass rejection was calculated using Eqs 2. The biomass concentration was measured gravimetrically.

\[
R (\%) = \left(1 - \frac{C_p}{C_f}\right) \times 100
\]  

where, \( C_p \) and \( C_f \) is permeate and feed parameters. All filtrations achieved complete rejection of the biomass.

2.5 Filtration tests

In the first objective, the performance of traditional system (vertical panel) and a system with finned spacer was compared. In addition, a study on tilting panel system was also performed to compare its performance to the current system. The tilted panel system was tested (at tilting angle of 0°, 5°, 10°, 15°, 20°). The finned spacer system was tested at different fins gap (of 2, 4 and 6 cm). The effect of aeration rate on the finned spacer system was tested at fins gap of 2 cm and aeration rates of (0, 0.25, 0.3, 0.75, 1, 1.5 and 2 L/min). The study on the effect of switching period was performed at periods of (2, 5 and 10 min).

The background study of tilted panel was running at 9/0.5 cycle (10 minutes), with 0.5 minutes relaxation with 1 L/min or aeration rare and pressure of 0.1 bar. Permeate collected were measured and recorded for analysis. Average of the flux for last 30 minutes were consider as queasy steady state flux. The angles evaluated start with 0° indicate the panel in vertical position and the filtration test repeated by increasing the angle at 5°, 10°, 15°, 20°. After each filtration test, the membrane cleaned using 1% sodium hypochlorite (Cloroc®) in DI water for the membrane recovery.

The test followed with the finned spacer direct the bubbles to the membrane surface and repeat with direct the bubbles away from the membrane surface. The results are compared with the background test earlier.

3. Results and discussions

3.1 Effect of aeration projection and tilting angle

The effect of air bubble projection toward filtration flux is shown in Figure 2A and 2B. The occurrence of membrane fouling is indicated by a decline trend of flux overtime (Figure 2A). At the last 30 minutes of the filtration, the flux achieves somewhat a steady state value. Under the steady state condition, the system achieves equilibrium condition where drag force driving the foulant into the membrane is balanced by the back transport away from the membrane surface [19]. The steady state fluxes (Figure 2B) show that membrane fouling can significantly (26%) be reduced by employing aeration with the
help of finned spacer. Air bubbles improves the hydrodynamic near the membrane surface and promotes local mixings. The fouling observed in early stage of filtration is mainly due to adsorption of foulant materials and pore blocking [20].

Further tests on the effect of aeration rate on membrane fouling control in finned-spacer system have been conducted. As expected, aeration can improve the steady-state flux of the membrane (Figure 2B). It is evaluated by comparing the flux value of projected and not projected. It obviously shows that the aerated panel has higher flux (77 L/m².h) compared to the non-projected one (60 L/m².h). The membrane cleaning is facilitated by air bubbles that induces shear-rate to scour-off foulant from the membrane surface. This finding confirms the effectiveness of air bubble for membrane fouling control and its application as one of the standard methods for membrane fouling control in large-scale membrane unit, and finned spacer to improve the efficacy of air bubbles for membrane fouling control.

The presence of the finned spacer helps to significantly improve the steady-state flux of the membrane for about 20%. Finned spacer directs the flow trajectory of air bubbles toward membrane surface. The travelling bubbles near the membrane surface have intense contacts and thus enhance their foulant scouring efficacy. Without finned spacer, the bubbles pathway is unpredictable and mostly travel away from the membrane surface. Flux of the finned spacer (Figure 2B) proved that finned system can gives high flux as the flux of tilted panel at 20° (Figure 2D) compared with the flux at 5°. Finned spacer is effectively improving contact surface between bubbles and membrane surface. As shown in Figure 2C air bubbles directed to the membrane panel (left side) as they follow the fins direction. Advantages using this system are the panel is not required to be switched to clean both sides of the membrane, smaller footprint required for the finned spacer system and it is easier to switch the finned direction compared to switch heavier panel in the submerged system.

![Figure 2. Effect of air bubble projection on steady-state membrane flux (A) and the tests were performed under aeration rate of 1L/min with filtration cycle of 9.5/0.5 min (B) Effect of air bubbles at aerated and unaerated condition. (C) The condition of bubbles in the filtration medium. (D) Effect of tilting angle to the membrane flux](image)
3.2 Effect of aeration rate
The effect of aeration rate toward membrane performance is shown in Figure 4. It shows that increasing aeration rate proportionally increases membrane flux till reaching a critical value as also reported elsewhere [21]. The highest flux can be reached at an aeration of 1.5 L/min aeration. It exhibits 55% advantages over the unaerated one (90 vs 58 L/m²·h). We identify 1.5 L/min as the minimum test value beyond which no increment of flux is obtained. It represents the maximum achievable flux.

The effectiveness of higher aeration rates in controlling membrane fouling happens thanks to the role of the air bubbles that scrub the membrane surface [22]. At higher aeration rate, the higher the number of air bubbles and the higher their impact and drag forces to scour-off the foulant [23]. This finding is in line with another report, Pradhan et. al., 2012, which suggests that the increment of air flowrate helps to reduces the foulant deposition in reducing the cake development on the membrane surface. The aeration reduces convective effect of permeate flow in dragging the foulant material in/onto the membrane pore [24] and thus reduces membrane fouling.

Increasing aeration rate only helps to increase the steady-state flux until a plateau flux (90 L/m²·h) is achieved (Figure 3). Increasing aeration rate beyond 1.5 L/min to 2 L/min offers a similar flux value. Such finding is also reported elsewhere [25]. Within the plateau flux zone, ample number of air bubbles present and aeration rate is sufficient enough in introducing sufficient shear-rates to prevent build-up reversible foulant. The remaining fouling, largely in the initial stage of filtration, is mainly irreversible adsorption and pore blocking. It is irremovable by air bubbles scouring.

![Figure 3. The effect of aeration rate on the steady-state flux. The dashed line shows the plateau flux value beyond which increasing aeration rate does not increase the flux](image)

3.3 Effect of fins gap
The effect of fins gap on flux toward is investigated by varying several gaps: 2, 4, 6 cm. The results are in Figure 4 show the steady state flux and picture of the membrane after filtration tests. It is found that larger fin gap leads to lower steady-state flux. Increasing the fins gap from 2 cm to 6 cm reduces the steady-state flux from 84 to 76 L/m²·h. When the gap between the fins is large, the probability of the membrane to contact with the membrane is reduced because after passing a fin, the air bubbles tend to move away from the membrane surface. It is due to the nature effect of air bubble trajectory on curved line of fins. Air bubbles near core have stronger centrifugal motion than near wall [26] which tend to away from membrane surface. Hence, the scouring effect on the membrane surface reduce. Small gap ensures the trajectory of air bubbles to move within the vicinity of the membrane surface to scour-off foulant (Figure 4B).

The effect of fins gap can be explained by its role in the system to direct the trajectory of movements. Finned spacer offers higher flux to the membrane by employing the fins to encourage trajectory of air bubbles movement towards the membrane surfaces. In this view, the higher number of fins can enhance
it functions in directing air bubbles. This condition then improve mass transfer rate [27]. The pressure drop between air bubbles and fins is found insignificant with trans membrane pressure [27–29].

![Figure 4](image.png)

**Figure 4.** Effect of fin gap on steady-state flux (A) on flux (B) on membrane fouling

### 3.4 Effect of switching period

The effect of switching period was investigated by applying intermittent aeration on one sided-membrane panel. The effect of switching period is shown in Figure 5. It shows that applying a short (2 min) intermittent aeration in the finned spacer system can maintain flux. At 90 L/m².h which suggest the ability to mount two panels sandwiching a finned spacer. A short switching period is required to avoid excessive build-up of foulant in absence of aeration [30–32]. Small of foulant when the panel is not projected by aeration can be removed when the panel projected.

![Figure 5](image.png)

**Figure 5.** Effect of fins switching period on steady-state flux

At large switching periods (> 5 min) the flux of the membrane decreases (Figure 5). The decrement occurs because the interval is too long as such a full recovery of flux could not be achieved due to irreversible nature of the foulant deposited on the membrane surface. According to Christensen et. al.,2016, an optimum switching period must be determined for every types of feed since the properties of the medium determined the relaxation time for the membrane [16].
4. Conclusion
This study proofs the effectiveness of finned space to improve efficacy of air bubbles for membrane fouling control for *Chlorella vulgaris* broth filtration. The fins effectively direct the air bubbles toward the membrane surface and thus improve their contacts and scouring effect of air bubbles to reach plateau flux of 90 L/m²·h. The projection of air bubbles is more effective at smaller fins gap, being most effective at 2 cm (the lowest applied in this study). Small gaps help to maintain the bubbles to be intact with membrane surface and avoid them from moving away from the desired trajectory. Aeration rate improve flux to reach plateau flux at 1.5 L/min producing ample the number of air bubbles to prevent accumulation of reversible foulant. Switching mode can be applied to increase module packing density without reducing specific membrane performance at switching periods of <5 mins. Overall results demonstrate the efficacy of finned spacer in promoting membrane fouling control for microalgae harvesting.

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