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Short Communication

Dramatic improvement of membrane performance for microalgae harvesting with a simple bubble-generator plate

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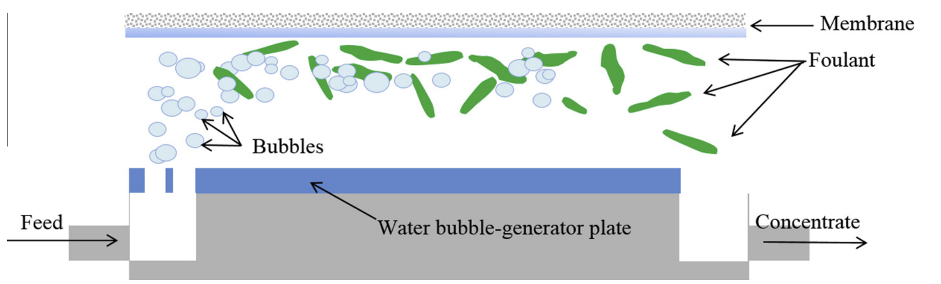
HIGHLIGHTS

- We develop a simple bubble-generator plate to mitigate membrane fouling.
- CFD tool simulates hydrodynamic changes by the plate on the membrane surface.
- The plate effect was improved with asymmetrically-structured membrane in a synergetic way.

GRAPHICAL ABSTRACT



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ABSTRACT

To overcome fouling issue in membrane-based algae harvesting and thus make an otherwise promising harvesting option more competitive, a bubble-generator plate was developed. According to computational fluid dynamics analysis, the plate generated substantial hydrodynamic power in terms of high pressure, velocity, and shear stress. When installed in a membrane filtration system with membranes of different surface and structural characteristics (one prepared by the phase inversion method, and a commercial one) the bubble-generator was indeed effective in reducing fouling. Without the plate, the much cheaper homemade membrane had the similar performance as the commercial one. Use of the bubble-generator considerably improved the performance of both membranes, and revealed a valuable synergy with the asymmetrical structure of the homemade membrane. This result clearly showed that the ever-problematic fouling could be mitigated in a rather easy manner, and in so doing, that membrane technology could indeed become a practical option for algae harvesting.

1. Introduction

Fouling is one of the most detrimental issues in any membrane-based technology. Harvesting of microalgae is not an exception; rather, due to the high cell density of the feed water it is even more problematic (Hwang et al., 2013). More aggressive means may be needed to ensure effective prevention or slowing of fouling. Thus, a great deal of effort has been made to mitigate this seemingly unavoidable natural phenomenon with limited success. Some approaches have included operational, systematic, physical, and chemical, or combinations of two or more of these. For example, a membrane system can be operated below critical flux defined as maximum flux, which leads to substantially reduced fouling formation. The flux is determined by relationships among operation parameters such as flux, cross-flow velocity, and transmembrane pressure (TMP) (Field et al., 1995; Sheikholeslami, 1999). This operational approach, however, is unable to solve completely the problem in that it still tends to produce flux higher than the critical flux; and worse, still leads to the problem of too long operation below the critical flux (Rickman et al., 2012). As a systematic approach, a turbulence-generating device was employed with

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meaningful improvement of membrane performance (Finnigan and Howell, 1990; Millward et al., 1995). Physical and chemical cleaning (e.g., backwashing and oxidation) is a conventional and straightforward route. Its aim is not to prevent the fouling but to remove the fouling already on membrane surface and in its pores. This method, though effective, has other problems: consumption of extra energy and chemicals, and occasional interruption of operation (Chen et al., 2012). Another direction is to fabricate entirely new membrane materials with anti-fouling functionality. In this case, there is continuous effort being made to resolve current issues of high cost and instability (Van der Bruggen, 2009). Its applicability to algae harvesting is even more questionable.

In the present study, a new way of tackling the fouling issue was developed, one with distinct effectiveness and yet low burdens of fabrication and maintenance, i.e., installation of a simple bubble-generator plate.

Fouling mitigation via bubble generation has been studied in many fields such as membrane bioreactor and even in microalgae harvesting (Abeynayaka and Visvanathan, 2011; Bilad et al., 2012). All these systems, however, needed separate compressed air injectors for bubble generation, causing additional and high energy consumption. This study employed a thin orifice-typed plate, through which micro-sized bubbles are generated; all this takes place just by fluid flow, without the aid of an additional, power-consuming device, thereby leading to only limited consumption of extra energy. The bubbles produced, scoured the membrane surface very effectively so as to disrupt a fouling layer, yet left the membrane undamaged.

2. Methods

2.1. Membrane preparation and characterization

Two polyvinylidene fluoride (PVDF) membranes were prepared and tested for the potential effects of surface and structural characteristics, on the anti-fouling behavior of water bubbles. Commercial PVDF membrane (C-PVDF) with 0.45-μm pore size was purchased from Merck Millipore (Immobilion, Merck Millipore, Germany). The other membrane, called porous PVDF membrane (P-PVDF), was fabricated in the laboratory using a phase inversion method according to Zuo et al. (2008). Briefly, various concentrations of PVDF (Alfa Aesar, Ward Hill, MA) and polyethylene glycol (PEG, MW = 6000, Sigma Aldrich, St. Louis, MO; see Table 1) were completely dissolved in 250 mL of N,N-dimethylacetamide (DMAc, Junsei, Japan) in a 3-neck round-bottom flask with vigorous mixing at 80 °C for 3 h. This mixture was spread on a polyethylene terephthalate support of nonwoven fabric, using a film casting knife (BYK-Gardner Gmbh, Geretsried, Germany) of 150-μm thickness. The cast membrane was immersed in deionized (DI) water (18.2 MΩ) at 25 °C, and allowed the active coating agents to be precipitated on its surface. The membrane was then washed out several times using DI water to remove the residual solvent and PEG addictive. The P-PVDF membranes were optimized based on both DI water and algae permeability. The C-PVDF and optimized P-PVDF membranes were characterized with scanning electron microscopy (SEM, Field-emission Scanning Electron Microscope S-4800, Hitachi, Japan) for surface and cross-section morphologies, contact angle analyzer (Pheonix 300 Plus, SEO Co., Ltd., Korea) for hydrophilicity, and Fourier transform infrared spectroscopy (FTIR, IFS66V/S & HYPERION 3000, Bruker Optiks, Germany) for chemical functional groups on the membrane surface.

Table 1
Compositions of mixture used for P-PVDF membrane preparation and permeability of two different feed water (DI water and microalgae solution).

Concentration (wt%)			Permeability (LMH[c]/bar)	
PEG[b]	PVDF[a]	DMAc	DI water	Microalgae
1. PEG optimization				
0	14	86	65 ± 4	29 ± 2
3	14	83	164 ± 17	45 ± 5
5	14	81	184 ± 21	50 ± 5
8	14	78	259 ± 53	49 ± 8
2. PVDF optimization				
5	10	85	111 ± 20	43 ± 4
5	14	81	184 ± 21	50 ± 5
5	20	75	102 ± 6	38 ± 4

[a] PVDF concentration was fixed followed Zuo et al. (2008).
[b] PEG concentration was fixed from optimized PEG results.
[c] LMH: L/m^{2}h.

2.2. Harvesting system with the bubble-generator plate

Microalgae biomass was harvested using a cross-flow membrane filtration system. The effective membrane area was 30 cm^2 and 1 L volume of microalgae (*Chlorella* sp. KR-1) solution was used for filtration test. Microalgae conditions were described in previous study (Hwang et al., 2013). System was operated at 1 m/s of cross-flow velocity and 2 bar of TMP. To make data analysis straightforward, initially a membrane was compacted by operating the filtration unit with DI water for 1 h at high TMP (3 bar). The membrane compaction, which typically occurs whenever a new membrane is used, is caused by pore structure change due to high TMP and it causes flux reduction (Dang et al., 2006). This is why compaction must be done first, to examine flux reduction caused purely by fouling.

A bubble-generator plate was designed, constructed, and installed within the membrane filtration unit and it was expected to generate micro-sized bubbles and substantially mitigate fouling (see Fig. S1 in Supplementary information). The plate, made of stainless steel, had 1 mm diameter pores, whose number was carefully determined so that their sum of total area was less than that of the pipe cross-sectional area (71 mm^2). Computational fluid dynamics (CFD) tool (Solidworks, Dassault Systemes, Vélizy-Villacoublay, France) was employed for simulating hydrodynamic phenomena on the membrane surface. The simulation conditions were set via experimental results obtained from filtration test at same operating condition. Water was used as fluid at 25 °C and PVDF membrane was placed over the plate with 115 μm gap. Fluid inlet were set as pressure-inlet type (3 bar) with uniform volume flow rate (4.5 L/m), while outlet pressure was 2 bar. The distribution and maximum values of cross-flow velocity, shear stress, and pressure, were obtained to visualize and reveal the effectiveness of the plate, especially over the entire membrane area.

Harvesting efficiency was calculated in terms of permeability and concentration factor (CF) using the same equations from a previous study (Hwang et al., 2013), and rejection (Rej) was calculated by the following equation:

$$\mathrm{Rej}\ (\%) = (1 - C_p/C_0) \times 100$$

where, C_p and C_0 are permeate and initial concentrations of microalgae.

Harvesting time was measured when 1 L of a feed solution was 10-times concentrated (i.e., CF: 10) which was a minimum volume level for system operation.