Journal of Membrane Science 517 (2016) 30–38

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Using axial vibration membrane process to mitigate membrane fouling and reject extracellular organic matter in microalgae harvesting

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ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form
13 June 2016
Accepted 14 June 2016
Available online 16 June 2016

Keywords:
Vibration membrane
Membrane fouling
Microalgae
EOM
Rejection

ABSTRACT

Membrane fouling caused by algae cells and extracellular organic matter (EOM) is a major challenge in microalgae harvesting. In the present study, the axial vibration membrane (AVM) process can effectively reduce membrane fouling by increasing vibration frequency. An equation was obtained to explain why the vibration frequency has a more important impact on critical flux than the amplitude. During the continuous filtration, the flux decline rate was only 3.6% at the frequency of 10 Hz and amplitude of 1 cm. While at the frequency of 5 and 0 Hz the decline rates were 34% and 64.2%, respectively. At high frequency, AVM can not only prevent the deposition of algae cells on membrane, but also reduce the adsorption of EOM on membrane. Scanning electron microscope and fourier transform infrared spectroscopy analysis showed that AVM can effectively reduce EOM adsorbing on membrane at 10 Hz. AVM had better rejections of protein (28–39%) and polysaccharide (about 35%) at 10 Hz, compared with 0 and 5 Hz. Membranes had obvious rejection of low molecular weight EOM, regardless of at high or low frequency; however, compared to low frequency at high frequency AVM could reject more high molecular weight organics.

1. Introduction

Recently, fossil fuel depletion and food security have aroused people's concern, and the microalgae could be very good candidates for biofuel and food production, due to their advantages of higher biomass production, faster growth and the renewable, nontoxic properties [1–3]. Many researches have investigated the renewable fuel sources, extractions of high added value foods and pharmaceutical products through microalgae [4–7]. Biofuel, as an alternative to fossil fuels, can reduce global warming caused by fossil-fueled. High value-added compounds, such as protein, carbohydrates, lutein, vitamins and other valuable trace elements to be the source of functional food products, can be extracted from microalgae [4–7]. However, the lack of an efficient and economical technology to harvest microalgae is a major problem [7–9]. Membrane filtration is an appropriate technology to harvest microalgae, as it can completely remove microalgae cells by size exclusion [8,10–13]. However, membrane fouling caused by microalgae cells and extracellular organic matter (EOM) is a major problem [6,14,15]. During the filtration, algae cells and EOM can accumulate on the membrane surface, and some even enter the pores of the membrane, which decreases the membrane permeability and increases the resistance to filtration. Membrane fouling can result in a remarkable decline of flux, which lead to frequent membrane cleaning and reduce the filtration efficiency.

Many researches have shown that increasing the shear rate at the membrane surface could reduce the membrane fouling and improve flux [16–18]. There were also literatures reporting using Vibratory Shear Enhanced Processing and transverse vibration membrane process harvesting microalgae [19,20]. In fact, the membrane's vibration can create high surface shear rate on the membrane surface, which is capable of efficiently reducing membrane fouling. Now there are more and more studies on linear vibration membrane (transverse or axial vibration membrane) process [18,21–23]. Compared with the submerged aeration membrane (SAM) system, the linear vibration membrane system at a relatively low frequency or amplitude can effectively improve flux and reduce membrane fouling [24]. There were literatures reporting that transverse vibration of hollow fibre membrane was superior to axial vibration of hollow fibre membrane in reducing membrane fouling [25,26]. Although the transverse vibration of hollow fibre membrane had a better performance due to the separation boundary layers than axial vibration in reducing membrane fouling, there were also a risk of fibre breakage which would be more serious with the increase of frequency or amplitude [25]. Thus, in order to reduce the risk of fibre breakage, the vibratory

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http://dx.doi.org/10.1016/j.memsci.2016.06.022
0376-7388/

intensity (frequency or amplitude) of transverse vibration cannot be too high, which go against increasing shear rate.

In our previous study, we have compared SAM and AVM and found that vibration had a more obvious effect on reducing membrane fouling [24]. Although we have investigated the mechanism of fouling mitigation by increasing shear rate (frequency or amplitude) [15], why frequency has a more significant effect on increasing flux than amplitude is still unclear and needs further study. In addition, increasing frequency can effectively reduce reversible membrane fouling induced by algae cells deposition [15], but whether increasing frequency can also reduce the irreversible membrane fouling caused by EOM is lack of the relevant research. Thus, the irreversible membrane fouling will be investigated by scanning electron microscope (SEM) and fourier transform infrared spectroscopy (FTIR) analysis. Micro-membrane can't effectively reject EOM, because the pore size of membrane is too large compared with the size of EOM. High content of EOM in effluent water will adversely affect the subsequent water treatment [27,28]. Therefore, the effect of increasing frequency on the rejection rate of EOM will also be studied.

2. Theory

In this study we apply axial vibratory membrane to filter algae solution. In AVM system, the vibration was applied to produce shear rate, which can effectively reduce the membrane fouling. The shear rate can be expressed by Eq. (1) [22]:

$$\gamma=\frac{dv}{dy}=v_0\sqrt{\frac{\omega}{2\vartheta}}e^{-\sqrt{\left(\frac{\omega}{2\vartheta}\right)}y}\left[\sin\left(\omega t-\sqrt{\left(\frac{\omega}{2\vartheta}\right)}y\right)-\cos\left(\omega t-\sqrt{\left(\frac{\omega}{2\vartheta}\right)}y\right)\right] \quad (1)$$

where y is the separation distance between the particle (algae) and the membrane (m), v_0 is the velocity amplitude ($=a\times\omega$) (m/s), ϑ is the kinematic viscosity of the solution ($=\mu/\rho$) (m^2/s), ρ is the fluid density (kg/m^3), μ is the viscosity of the feed fluid (Pa s), ω is the angular frequency ($=2\times\pi\times f$) (1/s), f is the frequency (Hz) and a is the amplitude (m). Obviously, shear rate changes with the vibration amplitude, frequency and separation distance. Fig. 1 shows that the shear rates at different distances from the membrane surface vary over one rotational cycle at the frequency of 10 Hz and amplitude of 1 cm. It was obvious that the shear rate produced by AVM acted near membrane surface and decreased with the increase of separation distance. At the distance of 1 mm and above 1 mm, the shear rate is almost negligible.

Reportedly, shear had significant influence on the lysis of algae and caused the release of IOM, which not only influenced the water quality, but also caused severe membrane fouling [29,30]. However, for different algae species, algae cells can withstand different levels of shear action based on their cell wall structure [29]. As shown in Fig. 1, the shear action induced by vibration can be ignored at the distance of about 1 mm from membrane surface. Also, above 1 mm the shear action can be ignored. It means that in theory algae cells locating 1 mm and above 1 mm away from membrane will not be influenced by shear. Therefore, AVM can reduce the effect of shear on algae cells, which may cut down on the lysis of algae and the release of IOM.

The shear rate on the membrane surface (y=0) can be expressed as

$$\gamma=v_0\sqrt{\frac{\omega}{2\vartheta}}[\sin(\omega t)-\cos(\omega t)] \quad (2)$$

where t is time (s), ω angular frequency (1/s) and v_0 is velocity amplitude (m/s). The maximum shear rate [21,31] can be shown as

$$\gamma_{max}=2^{0.5}(\pi f)^{1.5}d\vartheta^{-0.5} \quad (3)$$

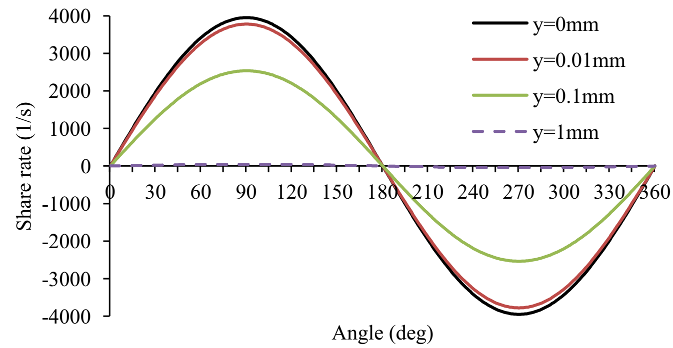

Fig. 1. Shear rates at different distances from the membrane surface at the frequency of 10 Hz and amplitude of 1 cm.

where d is the displacement (d=2a).

3. Materials and methods

3.1. Cultivation of microalgae

Chlorella pyrenoidosa (*C.pyrenoidosa*, FACHB-9) was purchased from the Institute of Hydrobiology at the Chinese Academy of Sciences, which was cultured in Basal medium. 2.0 g/L glucose was added into medium for algae heterotrophically growing. The algae were inoculated in a 25 L glass tank. In the culture process, the temperature was maintained at 30 ± 0.5 °C. In incubator (GZX-300BS-III, CIMO Co., China), the light/dark was set to 12 h/12 h, and the illumination intensity changed from 2000 to 5000 lx with time. After 15 days of cultivation, algae achieved the stationary growth phase, and the concentration of algae was about 1.2 g/L. The required amount of algae was about 80 L, thus, in the filtration experiment, the concentration was adjusted to approximately 0.3 g/L by adding distilled water.

3.2. Experimental setup

AVM system was designed to assess the performance of membrane filtrating algae by increasing frequency. The schematic diagram of AVM is shown in Fig. S1. The membrane frame is a square (11 × 11 cm), installed on a cassette, and could be vibrated by a servo motor (60FSM-04030, USA). On the membrane frame, there is an outlet connecting a tube and the permeate can be taken away through the tube using a peristaltic pump. The frequency could be controlled by a digital servo drive (FDS15A-400X, USA) and the amplitude could be stepwise regulated from 0.5 cm to 4 cm (step =0.5 cm). The working volume of the tank was 50 L. The total membrane area of the hydrophilic PVDF membrane (nominal pore size of 0.1 μm) was 0.02 m^2. The hydrophilic membrane was bought from a company (Minglie, China) and the membrane frame was homemade. The change of the flux was recorded by an electronic balance connected to a computer. The transmembrane pressure (TMP) was measured by a vacuum controller gauge.

3.3. Filtration experiment

Critical flux (J_C), a quantitative parameter, is regarded to be the flux above which the membrane fouling will be fast aggravated. Selecting an appropriate operation flux under the critical flux (sub-critical flux) can prolong the membrane's service life and increase filtrating effciency. In this study, an improved flux-step method (IFM) was utilized to determine the critical flux [32]. The step increasement, initial flux and step duration were 3 L/m^2h,