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A uniform shearing vibration membrane system reducing membrane fouling in algae harvesting

Fangchao Zhao [a, b], Yalei Zhang [a], Huaqiang Chu [a, *], Shuhong Jiang [a], Zhenjiang Yu [a], Miao Wang [a], Xuefei Zhou [a], Jianfu Zhao [a]

[a] State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China
[b] School of Environmental and Municipal Engineering, Qingdao University of Technology, 11 Fushun Road, Qingdao 266033, PR China

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ABSTRACT

When a membrane is used to harvest algae, membrane fouling caused by algae and extracellular organic matter (EOM) is a serious challenge. A uniform shearing vibration membrane (USVM) system was devised and applied to reducing membrane fouling in algae filtration. The shear rate produced by USVM is constant because of its uniform circular motion; thus, USVM could stably and significantly mitigate fouling. During the filtration experiments where the frequency was increased from 1 to 5 Hz, the transmembrane pressure (TMP) visibly reduced. Even at a relatively low frequency of 5 Hz, USVM still could stably filter algae and had only slight membrane fouling. Increasing the vibration frequency not only could significantly reduce reversible membrane fouling but could also reduce irreversible membrane fouling. Protein could cause more serious reversible membrane fouling, while humic substances could lead to more serious irreversible membrane fouling. In this study, USVM effectively reduced the deposition of algae cells, protein, polysaccharide and humic substances on the membrane as frequency increased.

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1. Introduction

Microalgae are considered to be a promising biofuel resource, due to the renewable and nontoxic character of microalgae (Bilad et al., 2012; Markou and Nerantzis, 2013; Vasudevan et al., 2012; Zhao et al., 2015b). Biofuels have the potential to alleviate the environmental problem such as the greenhouse gas emissions caused by the use of fossil fuels (Ahmad et al., 2014; Gerardo et al., 2015; Show et al., 2013). However, there are lots of obstacles to economically and efficiently harvest microalgae. Inefficient microalgae harvesting is regarded as a critical limiting factor of algal biofuel production to be used in commercial (Ahmad et al., 2011; Milledge and Heaven, 2012; Pragya et al., 2013). Algal biofuel production must be at an acceptable price with the acceptable financial harvesting, before algal biofuel can realize large-scale utilization (Davis et al., 2014). In fact, there are many methods that can harvest microalgae, such as flocculation, sedimentation, flotation, filtration, centrifugation and any combination thereof (Castaing et al., 2011; Milledge and Heaven, 2012; Nguyen et al., 2013; Pragya et al., 2013). However, most of those technologies are labor intensive, energy consuming or environmentally unfriendly.

As techniques for manufacturing membranes improve and the application of membranes expands, the cost of membranes has steadily declined, which makes membrane technology a promising method for algae harvesting (Bhave et al., 2012; Hwang and Lin, 2014; Zhang et al., 2010). Membrane filtration is effective for harvest algae, and it can completely retain microalgae cells by size exclusion, but the membrane fouling caused by the adhesion of extracellular organic matter (EOM) and algae cells on membrane is still a major problem (Huang et al., 2015; Qu et al., 2015; Wei et al., 2016). Serious membrane fouling not only causes sharp membrane flux declines, but membranes also need frequent cleaning to recover flux, which reduces the efficiency of algae harvesting and impairs the service life of the membrane (Rickman et al., 2012; Zhang et al., 2013a). Thus, reducing membrane fouling and improving membrane flux is very important in algae separation. In fact, generating a shear rate between the membrane surface and liquid is an effective method to reduce membrane fouling; now, the liner vibration membrane (LVM), namely axial vibration and transverse vibration membranes, have been investigated in

* Corresponding author.
E-mail address: chuhuaqiang@tongji.edu.cn (H. Chu).

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filtration (Bilad et al., 2013; Low et al., 2012; Rickman et al., 2012; Zhao et al., 2016a). Although LVM could effectively reduce membrane fouling and improve membrane flux in algae filtration, there is an obvious drawback: the shear rate induced by LVM is not constant, which goes against the vibrating efficiency and stability and sequentially reduces the efficiency and stability of filtration. In this study, a novel vibration membrane (uniform shearing vibration membrane) system is devised and applied to algae filtration. Compared with LVM, the advantages of a uniform shearing vibration membrane (USVM) are the uniform circular motion and the constant shear rate, which will be more effective and stable to mitigate membrane fouling during the algae filtration.

To the best of our knowledge, there had been no such system reported so far. The study of a USVM for fouling mitigation in algae filtration is very important. In this study, a USVM system was designed and the motion character of USVM was elaborated. The filtration experiments were conducted at different frequencies to study the effect of USVM on fouling mitigation. In this study, we hope to provide new and valuable information about membrane fouling mitigation technology available for algae harvesting.

2. Materials and methods

2.1. Cultivation of microalgae

Chlorella pyrenoidosa (*C. pyrenoidosa*) was acquired from the Institute of Hydrobiology at the Chinese Academy of Sciences in China. Basal medium based on the previous study (Zhao et al., 2015b) was used for algae cultivation. *C. pyrenoidosa* was inoculated in 3 L glass flasks, and before inoculation, the Basal medium was sterilized. The glass flasks were placed in an incubator and cultivated for 50 days, and the concentration of algae reached 0.4 ± 0.03 g/L. During the cultivation of microalgae, there was no gas supply. The cultivation conditions were as follows: temperature $30 \pm 0.5\,^{\circ}C$, light intensity 127 μmol/m^2·s and light/dark = 14 h/10 h.

2.2. Experimental setup

A uniform shearing vibration membrane system was designed and applied to the filtration of algae to verify the effect of increasing frequency on reducing membrane fouling. The USVM was operated with a uniform circular motion (Not rotating), just like a shaker; therefore, unlike other vibration membranes with a variable shear rate, USVM had a constant shear rate induced by the uniform motion. Thus, the effect of shear action on reducing membrane fouling should be more stable and efficient.

A schematic diagram of the USVM is shown in Fig. 1(a). The membrane module installed on a cassette was vibrated in algae filtration. The frequency could be adjusted using a digital servo drive and the amplitude could be adjusted by changing the breadth of the bent axle. The filtration tank had a 20 L working volume.

2.3. Filtration experiment

The filtration experiments were conducted at 1, 3 and 5 Hz, with an amplitude (radius of rotation) of 2 cm. During filtration, the operational flux was kept at 30 L/m^{2}h. The concentration of algae applied in filtration was approximately 0.4 g/L. The Polyvinylidene fluoride/Polyethylene terephthalate (PVDF/PET) membrane (Minglie, Shanghai, China) had an effective area of 0.02 m^2. The membrane is hydrophilic, and the water contact angle is $53.5 \pm 1.7^{\circ}$. The nominal pore size of membrane is 0.1 μm and the average algae cells radius is 2 μm. Thus, the membrane theoretically can retain all algae cells. The filter liquor was pumped using a rotary drive peristaltic pump. The flux was automatically recorded by an electronic balance connected to a computer, and TMP was measured using a vacuum meter.

2.4. Measurement of membrane fouling rate

After filtration, two pieces of fouled membranes were cut using a knife. Using a 300 mL cup-type filtration vessel under the pressure of 0.05 MPa, one membrane was used to assess the total membrane fouling, and then this membrane was rinsed with pressurized tap water to assess the irreversible membrane fouling (Qu et al., 2012a; Zhao et al., 2016b). Finally, the rinsed membrane was used for SEM. For the other membrane, the algae on the membrane were flushed using 250 mL water and collected to measure the content of the algae; then, the membrane was rinsed with pressurized tap water to remove the reversible foulants; and finally, the membrane was soaked in a 0.5 g/L NaOH solution for 2 h to acquire the irreversible EOM (Zhang et al., 2011).

The membrane fouling was divided into reversible membrane fouling rate (RF), irreversible membrane fouling rate (IF) and total membrane fouling rate (TF) (Zhao et al., 2016b, 2017). The reversible fouling, irreversible fouling and total fouling were calculated as follows:

$$TF = 1 - \frac{J_b}{J_n} \quad (1)$$

$$IF = 1 - \frac{J_a}{J_n} \quad (2)$$

$$RF = TF - IR \quad (3)$$

where J_n is the water flux of a new membrane (L/m^{2}h), J_b is the water flux of a fouled membrane before rinsing (L/m^{2}h) and J_a is the water flux of a fouled membrane after rinsing (L/m^{2}h).

2.5. Analytical methods

The algae solution was centrifuged at 4000 rpm for 10 min using a high-speed centrifuge; then, the supernatant liquid was filtered using a 0.45-μm filter to obtain the EOM solution. The polysaccharide and protein contents were measured using the anthrone-sulfuric acid method and the modified Lowry method (Zhao et al., 2017), respectively. TOC was measured using a total organic carbon analyzer (TOC-VCPH, Shimadzu, Japan). The fluorescence excitation-emission matrix (EEM) spectra of EOM solution was determined via fluorescence spectrophotometer (F-4500, Hitachi, Japan). The algae concentration was measured using the method of OD_{680}, and the correlation equation between OD_{680} and algae concentration was shown in Fig. S1. After filtration, the scanning electron microscope (SEM) was used to observe the fouling condition of the membranes (Phenom Pro, China).

3. Results and discussion

3.1. Analysis of the motion of the USVM

As shown in Fig. 1(b), the movement trail of the USVM is circular. In this study, a random point on membrane was selected to study, and its movement trail was also circular. In fact, the motion of the USVM was uniform and circular. USVM can produce a shear rate near the membrane by the vibration, and due to the uniform velocity, the shear rate induced by USVM was constant. Compared with USVM, the velocity and shear rate induced by LVM were not

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