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Microalgae harvesting by an axial vibration membrane: The mechanism of mitigating membrane fouling

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ABSTRACT

Membrane fouling by algae and extracellular organic matter (EOM) is a major problem in algae harvesting. In this study, the axial vibration ultrafiltration-membrane (AVM) is able to limit membrane fouling during filtration effectively. A membrane can achieve high critical flux at a high shear rate. During filtration, AVM is capable of operating with less fouling at a constant flux. The result from "extended Derjaguin, Landau, Verwey, Overbeek" (XDLVO) calculation indicates that with the increase of shear rate, it is more difficult for algae to foul the membrane. At a frequency of 5 Hz, the average inertial lift force is 0.024 nN, and the interaction force becomes a long-range attractive force that draws algae to the membrane; there are still certain smaller algae, algae debris and EOM that deposit on the membrane; leading to many algae depositing on the membrane. At a frequency of 10 Hz, the average inertial lift force is 0.12 nN, and there is a long-range repulsive region preventing algae from depositing on the membrane; however, the result shows that the mechanism of fouling mitigation by vibration is preventing algae from approaching the membrane, which reduces the deposition of algae on the membrane.

1. Introduction

Recently, the increasing environmental and energy concerns, such as greenhouse gas emissions, energy security and fossil fuel depletion, have aroused people's attention [1–4]. For many years, researchers have investigated the commercialization of microalgae as a raw material for biofuel [5–7], which could reduce global warming induced by fossil fuels. However, the inefficiency of harvesting microalgae from cultivation broths limits the widespread use of microalgae [8,9]. Membrane separation technology has been proven to be effective at harvesting microalgae and has many advantages: almost complete retention of microalgae, clean effluent water and low energy consumption [10,11]. In addition, Gerardo et al. [12] have reported that the integration of membrane technology in microalgae biorefineries could reduce the cost of microalgae as biofuel feedstock. However, membrane fouling caused by algae and EOM accumulating on and/or inside the membrane is a major challenge [13–16].

Recently, many studies have reported that membrane fouling can be reduced by increasing the shear rate at the membrane

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Abbreviations and symbols: EOM, extracellular organic matter; AVM, axial vibration membrane; VSEP, vibratory shear-enhance processing; XDLVO, extended Derjaguin–Landau–Verwey–Overbeek; F_{TOT}, the total interaction force; F_R, the repulsive force; F_A, the attractive force; F_{LW}, Lifshitz–van der Waals force (N); F_{AB}, Lewis acid–base force (N); F_{EL}, electrostatic double layer force (N); F_D, permeate drag force (N); F_{IL}, inertial lift force (N); IFM, improved flux-step method; TMP, transmembrane pressure (kPa); J_C, critical flux; J, filtration flux; M-New, new PVDF membrane; M-0, membrane at the vibration of 0 Hz; M-5, membrane at the vibration of 5 Hz; M-10, membrane at the vibration of 10 Hz; v_0, velocity amplitude (m/s); y, separation distance (m); y_0, the minimum equilibrium separation distance (0.157 ± 0.009 nm); n_i, the number concentration of ion i in the bulk solution; z_i, the valence of ion i; k, Boltzmann's constant (1.3807×10^{-23} J K^{-1}); T, absolute temperature (K); R_m, membrane hydraulic resistance (m^{-1}); f, vibration frequency (Hz); a, vibration amplitude (m); d, displacement ($d=2a$) (m); r_p, particle radius (m); v_w, permeate water velocity (m/s); ΔG^{TOT}, total interaction energy (mJ/m^2); ΔG^{AD}, free energy of adhesion (mJ/m^2); ΔG^{CO}, free energy of cohesion (mJ/m^2); ΔG^{LW}, LW interaction term (mJ/m^2); ΔG^{AB}, AB interaction term (mJ/m^2); ΔG^{EL}, EL interaction term (mJ/m^2); γ_s^{LW}, LW surface tension components; $\gamma^-{}_l$, electron–donor surface tension components; γ_l^+, electron–acceptor surface tension components; γ_l^{TOT}, total surface tension; ε_0, dielectric permittivity of vacuum($=8.854 \times 10^{-12}$ CV^{-1} m^{-1}); ε, dielectric constant of water ($=78.5$); ζ_m, membrane zeta potentials (mV); ζ_p, particle zeta potentials (mV); κ, inverse Debye length; e, elementary charge; μ_w, solution viscosity (Pa · s); φ_H, hydrodynamic correction factor ($=F/F\infty$); λ_{LW}, characteristic wavelength ($=100$ nm); λ_{AB}, decay length for acid–base interactions in water ($=0.6$ nm); γ, shear rate (1/s); γ_{max}, the maximum membrane shear rate (1/s); ϑ, kinematic viscosity of the fluid (m^2/s); μ, viscosity of the feed fluid (Pa · s); ρ, fluid density (kg/m^3; ω, angular frequency (1/s); θ, contact angle (deg); θ_{wat}, contact angle determined by Milli-Q water (deg); θ_{gly}, contact angle determined by Glycerol (deg); θ_{dii}, contact angle determined by Diiodomethane (deg)

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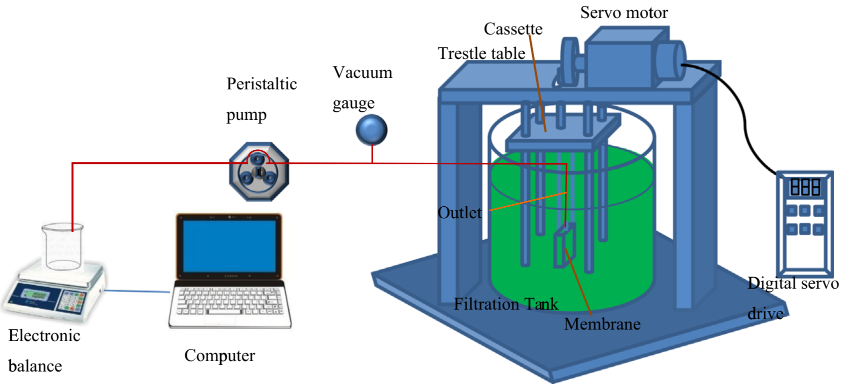

Fig. 1. Schematic diagram of the axial vibratory membrane (AVM) system.

surface due to the alleviation of algae deposition [17–19]. The surface shear rate can be enhanced by creating a relative motion between the membrane and the feed stream. Many studies have reported that vibrations or rotations of the membrane can create high surface shear rate, which can efficiently reduce membrane fouling and improve the flux [17,19–22]. The vibratory shear-enhance processing (VSEP) proposed in 1992 by Armando et al. has a very wide range of industrial applications [17,18,23], while there are few industrial applications of the transverse or axial vibration membrane due to its smaller shear rate (low frequency or amplitude). Some studies have shown that it is difficult for a transverse or axial vibration membrane to simultaneously achieve high amplitude and high frequency [21,24]. For VSEP, the maximum shear rate (γ_{max}) at the membrane rim is approximately $1.4 \times 10^5\ s^{-1}$ at a resonant frequency of 60 Hz and amplitude of 2.5 cm [17,23]. A magnetically induced membrane vibration could achieve a vibration frequency of up to 60 Hz, but the amplitude usually only reaches 2 mm at most [21]. Beier et al. [25] have shown that the vibration membrane could achieve an amplitude of 4 cm with a frequency of 10 Hz. Compared with the VSEP system, the transverse or axial vibratory membrane system has low vibration frequency, which significantly reduces the energy consumption [19,24,26]. Many studies have shown that the transverse or axial vibration membrane could offer an efficient fouling control with a high flux, and the vibration has been proven to be economically attractive [19,25,27].

In the present study, an axial vibratory membrane (AVM) system is proposed as a shear enhancement device for controlling membrane fouling in filtrating microalgae. Although increasing shear rate can reduce membrane fouling and enhance flux, there is little research on the mechanism of fouling mitigation. In this study, the separation performance of AVM is studied; moreover, the interaction forces on algae near the membrane surface are calculated to explain the mechanism governing the deposition and release of biofoulants in the AVM system.

2. Materials and methods

2.1. Cultivation of microalgae

Chlorella pyrenoidosa (*C.pyrenoidosa*, FACHB-9) was obtained from the Institute of Hydrobiology at the Chinese Academy of Sciences in China. *C.pyrenoidosa* was cultured in a Basal medium with 1 g/L of glucose. The algae was inoculated in a 50 L glass tank and placed in an incubator (GZX-300BS-III, CIMO Medical Instrument, China). The temperature of the incubator was maintained at 30 ± 0.5 °C. The cultured conditions were as follows: light/dark = 12 h/12 h, light intensity = 127 μmol/m^2.s. When algae achieved the stationary growth phase after 10 days of cultivation, the biomass concentration was 0.55 g/L. In the filtration experiment, the concentration was adjusted to 0.2 g/L by adding distilled water.

2.2. Experimental setup

An axial vibratory membrane system was set up to assess the filtration performance of the membrane under various vibration conditions. The schematic diagram of the AVM is illustrated in Fig. 1. The membrane module, installed on a cassette, could be vibrated using a 400 W servo motor (60FSM-04030, USA) at any frequency up to 15 Hz with an amplitude of 4 cm. However, due to the limitations of the site, in this study, we did not simultaneously use high frequency and amplitude. The frequency was controlled using a digital servo drive (FDS15A-400X, USA). The amplitude could be adjusted from 0.5 cm to 4 cm stepwise, increasing by 0.5 cm. The tank had a working volume of 50 L. The membrane that was made of PVDF with a nominal pore size of 0.1 μm had a total membrane area of 0.02 m^2. The filtrate was pumped using a variable speed peristaltic pump (BT100-LJ, Kejian, China). The flux was automatically recorded using an electronic balance connected to a computer. A vacuum meter was installed on the module to measure the transmembrane pressure (TMP).

2.3. Filtration experiment

The critical flux (J_C) was measured using an improved flux-step method (IFM) [28]. The applied initial flux, step height and step duration were 10 L/m^2h, 3 L/m^2h and 15 min, respectively. An arbitrary minimum increase in the TMP ($\Delta P/\Delta t$) of 20 Pa min^{-1} was regarded as the reasonable estimate of critical flux. In this study, the critical flux was determined at different levels of vibration frequency and amplitude.

In the continuous filtration tests, the filtrations were conducted at frequencies of 0, 5 and 10 Hz with an amplitude of 1 cm. 40 L/m^2h was selected as the constant flux of the continuous filtrations. For the membranes at frequencies of 0, 5 and 10 Hz, 40 L/m^2h was the super-critical flux, critical flux and sub-critical flux, respectively.

2.4. Analytical methods

The zeta potential of microalgae cells was determined via dynamic light scattering (DLS) using a Malvern Zetasizer, NANO ZS (Malvern Instruments Limited, UK) at 25 °C. The zeta potential of the membrane surface was determined using a streaming potential analyzer (EKA1.00, Anton-Paar, Swiss), following the procedure described by Childress and Elimelech [29]. The fluid dynamic