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Transverse vibration as novel membrane fouling mitigation strategy in anaerobic membrane bioreactor applications

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ABSTRACT

While vibratory shear is effective for increasing the shear near the membrane surface, transverse hollow fiber membrane vibration offers additional mass transfer enhancement in terms of generating vortices in the wake of the vibrating surface. In this work, transverse vibration of submerged hollow fibers is explored for enhancing the filtration of anaerobic bioreactor effluents where gas sparging is often undesirable. The critical flux value was increased significantly with the aid of membrane vibration. Even at high mixed liquid suspended solid concentrations, the vibratory system was still able to significantly reduce fouling. In addition to a reduced rate of fouling, fractionation of the fouling layer also showed that a more reversible fouling occurs with vibrational filtration in comparison to traditional fouling limitation method such as gas sparging and crossflow. During the long term constant flux filtration with vibration, a two-stage fouling phenomena was observed, similar with those observed in traditional MBR fouling but with a more extended initial low fouling stage. After the local permeate flux increased above the critical flux, the second rapid fouling stage occurred mainly due to cake formation. By appropriately coupling periodical backwash/relaxation with vibrational filtration, the membrane performance was further improved. At low vibration frequency, filtration with periodical relaxation displayed the best performance, whereas at high frequencies, coupling with periodic backwash was more beneficial.

1. Introduction

Anaerobic membrane bioreactors (AnMBRs) have distinct advantages in treating wastewater, with significantly lower energy consumption than that associated with aerobic MBRs and the potential to generate biogas as an energy source [1–4]. However, in the absence of the gas sparging, AnMBR systems often suffer low shear rates, and fouling mitigation can be a challenge, especially at high solids loadings [2,4]. The biogas produced from anaerobic bioreactor is generally recirculated for natural scouring of the membrane modules [5]. However, such biogas sparging may not be feasible when the biogas production is too low or unstable.

Thus AnMBRs offer a potentially attractive application for dynamic shear enhanced membrane systems, which include ultrasound enhanced membrane system [6], rotational disk and vibrational membrane systems [7]. In such systems, local shear rate and turbulence is increased by vibrating or oscillating the membrane surface or fluid [7]. More energy is thus focused on the filtration surface and less dissipated into circulation of the bulk solution. The vibratory shear enhancement process (VSEP) was the first commercially available dynamic membrane system introduced by Armando and Culkin for flat sheet membranes [8]. Due to high energy requirements and cost of scale up, applications of vibratory systems have been limited to difficult feeds such as those in the pulp and paper mills or high solids loading [7,9,10].

The principle of membrane vibration has also been applied to hollow fibers at lab scale by moving the membrane in a parallel or transverse direction to the axis of the fiber [11–14]. Comparing with VSEP system, relatively low vibration frequency is applied in vibrational hollow fiber systems, which significantly reduces the energy consumption. With the aid of vertical vibrations parallel to the fiber axis, at a frequency of 30 Hz and displacement of 0.2–1.175 mm, the critical flux was improved 2–5 times during the filtration of yeast solution [11]. In our previous study, detailed investigation on transverse vibration was carried out [15]. Transverse vibration could potentially generate higher shear rates and turbulence, due to the added benefit of the secondary flows induced as a result of the interactions between the vortices from the vibrating hollow fibers. In our previous study with model solutions such as yeast and alginate, it was shown that transverse vibration can mitigate cake formation; however, its effect on reducing pore blocking was found to be limited [15]. Similarly, Beier and Jonsson [16] have also reported that the macromolecular concentration had more significant influence on the fouling resistance than yeast particles during filtration with vertical

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vibrations. In another study, Beier and Jonsson further investigated the effect of vibration on the separation and transmission of macromolecules from yeast cells [17].

Currently, most vibrational submerged hollow fiber membrane systems have been investigated mainly with model solutions such as yeast, protein or a corresponding mixture to explore its potential application for bioseparation. The application of such system on MBRs and AnMBR systems have been limited [18,19]. Low et al. applied different mechanical motions, including cross oscillation, lengthwise oscillation and VSEP with an MBR system [18,19]. It was found that with the aid of aforementioned mechanical motions, much higher operation flux can be maintained. Compared with model yeast, protein and polysaccharide solutions, the feed from the bioreactor is much more complex and the corresponding fouling mechanisms would be complicated. The potential use of vibration for AnMBR systems requires much more detailed study not only based on the fouling limitation mechanisms, but also on the foulant structure and reversibility.

In MBR systems, physical cleaning techniques such as relaxation and backwash have been applied as standard operating strategies to limit membrane fouling. Many studies have investigated the effect of relaxation and backwashing conditions on fouling limitation in MBR systems. The fouling could be retarded effectively when appropriate backwash/relaxation conditions were applied [20,21]. Backwash can effectively remove the fouling cake from membrane surface and also some foulants inside the membrane pores. In our previous study with model solutions (yeast, bentonite and alginate), it was found that vibration mainly restricts the cake formation but has limited effect on pore blocking [15]. Coupling periodic backwash with transverse vibration provides an additional means to combat the internal pore fouling.

However, inappropriate backwash conditions can also have some adverse effect on fouling control. Frequent backwash can remove the protective cake layer (secondary layer) resulting in more internal fouling. High strength backwash using permeate might also increase the chances of internal pore blocking [22]. The reorganization of fouling cake during filtration with periodical backwash would also result in irreversible fouling deposition after long term operation [23]. It has been reported that the aeration intensity during the backwash can also significantly influence the structure of the fouling cake, resulting in a more irreversible or even irrecoverable fouling after long term filtration [24]. Thus, in AnMBR applications, the effect of vibration enhanced filtration with periodical relaxation/backwash on fouling rate and foulant structure needs to be investigated.

In this work, the novel application of transverse vibration as a fouling limitation strategy during the filtration with secondary effluent from an anaerobic bioreactor was examined, along with the effect of increasing mixed liquid suspended solids (MLSS) concentration. Corresponding fouling mechanisms and foulant structures with transverse vibration, which have not been previously explored, were investigated during the long term constant flux filtration. The performance of the system was also compared to that of gas sparging and crossflow velocity. Furthermore, the novel combination of vibration enhanced filtration coupled with periodical relaxation/backwash was investigated to provide greater range of operation strategy for application in AnMBR systems.

2. Theory

Shear rate enhancement during membrane filtration significantly influences the rate of fouling and varies depending on the operating conditions used. The Reynolds number (Re) can be utilized to characterize performance while using different fouling limitation methods. The Reynolds number is defined in varying ways for the different fouling mitigation methods:

$$\mathrm{Re}_{Gas} = \frac{U_g R_H}{\nu} \quad (1)$$

$$\mathrm{Re}_{Liq} = \frac{U_L R_H}{\nu} \quad (2)$$

$$\mathrm{Re}_{Vib} = \frac{VD}{\nu} \quad (3)$$

where Re_{Gas}, Re_{Liq}, and Re_{Vib} are the Reynolds number when using gas sparging, crossflow velocity and vibration respectively, U_g is the upflow gas velocity, U_L is the liquid crossflow velocity, R_H is the hydraulic radius, V is the stream velocity, D is the membrane diameter and ν is the kinematic viscosity.

The Reynolds number is indicative of the hydrodynamics of the bulk feed. However, the local shear rates near the membrane surface can be significantly different. For example, air scouring can generate shear transients around the bubbles depending on the bubble path, size and shape [25]. In the case of transverse vibration system, shear rate in the bulk feed varies from that at the membrane vicinity due to the secondary flows induced by the interactions of vortices. The shear rate and consequently performance improvement associated with transverse vibration can be strongly influenced by these secondary flows. The change in velocity near the membrane surface as a result of displacement has been used to estimate the shear rate in such cases [26,27].

The velocity of a cylinder (u) oscillating harmonically in a fluid at rest with amplitude A and angular frequency ω has been defined by Schlichting and Gersten [27] as

$$u = 2V\ \sin\frac{x}{R}[\cos(\omega t) - \exp(-\eta)\cos(\omega t - \eta)] - \frac{3V^2}{\omega R}\left[\left(\sin\frac{x}{R}\right)\left(\cos\frac{x}{R}\right)\right] \quad (4)$$

$$\eta = \sqrt{\frac{\omega}{2v}}\, y \quad (5)$$

where V is the stream velocity ($V = \omega A$), x is the distance from the center of the cylinder in x direction, R is the radius of the cylinder, t is the time, v is the kinematic viscosity and y is the distance in the y direction.

Assuming the shear rate (γ) during transverse vibration is due to the vibration alone as the crossflow velocity is insignificant:

$$\gamma = \frac{du}{dy} \quad (6)$$

$$\frac{du}{dy} = \left(2V\ \sin\frac{x}{R}\right)\left(\sqrt{\frac{\omega}{2\nu}}e^{-\sqrt{\frac{\omega}{2\nu}}}\right)\left[\left(\cos\left(\omega t - \sqrt{\frac{\omega}{2\nu}}y\right) - \ \sin\left(\omega t - \sqrt{\frac{\omega}{2\nu}}y\right)\right)\right] \quad (7)$$

The time average shear rate ($\bar{\gamma}$) can be evaluated at any given point around the membrane circumference using Eq. (8) [11].

$$\bar{\gamma} = \frac{\sum_{i=0}^{1000}|\gamma(t = i/1000)|}{1000} \quad (8)$$

3. Methods and materials

3.1. Anaerobic bioreactor

The anaerobic reactor used in this study was a membrane coupled upflow anaerobic sludge blanket (MUASB) reactor. Instead of using the traditional three phase separator, the top end of the bioreactor was split into a sedimentation zone and a bioreactor zone. A maintenance membrane located in the sedimentation zone was used to treat the wastewater to the required tertiary