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A new folded plate membrane module for hydrodynamic characteristics improvement and flux enhancement

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ABSTRACT

To intensify the air scouring efficiency and reduce the membrane fouling, a new folded plate membrane module (FPMM) was designed by modifying the configuration of conventional flat sheet membrane module (FSMM). The hydrodynamic characteristics near the folded plate membrane surface, and its filtration performance in different operating conditions were studied. The particle image velocimetry (PIV) measurement results showed that, the higher flow velocity, the stronger turbulence, and more vortices existed near the folded plate membrane surface. The stable flux of the FPMMs had an increase of 17.8–57.7% over that of the FSMM, and the optimal vertical inclination angle was 15°. Moreover, in the filtration process, the flux enhancement of the FPMM was affected by the aeration intensity, yeast suspension concentration and trans-membrane pressure (TMP).

1. Introduction

Regarded as a good combination of conventional activated sludge (CAS) system and advanced membrane separation process, membrane bioreactor (MBR) has been gaining worldwide popularity and attention for their outstanding advantages over CAS, such as higher effluent quality, smaller footprints and less sludge production [1,2]. However, the further development of MBR has been limited by the issue of membrane fouling existed in the process of filtering the activated sludge [3].

In fact, almost all commercial MBRs use the technique of air scouring to reduce membrane fouling [4], because it not only can provide dissolved oxygen to microorganisms during the aerobic biodegradation process, but also can scour the membrane surface and generate a high cross-flow velocity without using the recirculation pump. Unfortunately, it was reported that the FSMM had a lower air scouring efficiency compared with the helical membrane module and the ladder-type FSMM at the same aeration intensity [5,6]. Therefore, modifying the configuration of the FSMM to improve the air scouring efficiency without increasing energy consumption is particularly critical.

So far, studies on the configuration modification of FSMM have been rarely reported. In 2000, Scott et al. reported a new corrugated membrane module inside which the corrugated membrane sheet existed [7]. As a kind of membrane separation devices, the corrugated membrane module improved the permeate flux due to the increased shear effects on the membrane surface, but this membrane module with an inside corrugated structure is not suitable to be used in MBR. In recent years, several studies on the helical membrane module were reported [6,8,9]. These studies showed that the helical membrane module enhanced turbulence and increased permeate flux without increasing energy consumption. However, the helical membrane module and the ladder-type FSMM previously designed by our research group [5] have a similar problem that they will obviously reduce the packing density of membrane module in MBR.

Based on the above discussions, in this paper, a new FPMM was designed for fouling mitigation and flux enhancement. Optimization of the vertical inclination angles and measurements of hydrodynamic characteristics using particle image velocimetry (PIV) technique were conducted, and the effect of operating conditions (e.g., aeration intensity, yeast suspension concentration and TMP) on flux enhancement was investigated.

2. Materials and methods

2.1. Membrane module

As shown in Fig. 1(a), the FPMM is made up of the inside folded plate support spacer and two pieces of cover membrane. The nom-

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Nomenclature

A	effective membrane area (m^2)	R_t	total resistance of the polluted membrane (m^{-1})
ΔH	water head drop (m)	R_m	intrinsic resistance of the clean membrane (m^{-1})
J	permeate flux ($L\,m^{-2}\,h^{-1}$)	R_c	fouling cake layer resistance (m^{-1})
K	filtration constant ($min\,L^{-2}$)	R_p	membrane pore blocking resistance (m^{-1})
K'	filtration constant ($kg^{0.5}\,m^{-1.5}$)	t	filtration time (min)
ΔP	trans-membrane pressure (TMP) (kPa)	Δt	filtration time interval (h)
q	collected permeate water volume during the corresponding time interval (L)	μ	dynamic viscosity of permeate water (Pa s)
Q_0	initial flux rate (L/min)	u^*	gas–liquid two-phase flow velocity ($m\,s^{-1}$)
V	accumulated permeate water volume during the corresponding filtration time (L)	ϕ	geometric hindrance coefficient of membrane module (–)
V_L	back-transport velocity of the filtered colloidal particles ($m\,s^{-1}$)		

inal pore size of microfiltration membrane is 0.2 μm, membrane material is polyvinylidene fluoride (PVDF), and membrane dimension is 100 mm × 200 mm (width × height). The vertical inclination angle is defined as the included angle between the inclined membrane surface and the vertical direction shown in Fig. 1(b), and the vertical inclination angles of the FPMMs are 20°, 15°, 10°, 5° and 0° from left to right in Fig. 1(a) and (b), respectively. The FSMM with the vertical inclination angle of 0° is seen together with the folded membrane modules.

2.2. Filtration experiments

The test set-up of filtration experiments at constant TMP is shown in Fig. 2. The effective volume of bioreactor is 6 L. Membrane module was placed vertically in the center of bioreactor, the aeration device was installed under the membrane module to generate rising gas bubbles, and the vertical distance between the bottom of membrane module and the aeration device was 20 mm. Filtration experiments were conducted in a gravitational filtration mode, at constant TMP 4.9 kPa or 9.4 kPa from a water head drop (ΔH = 500 mm or 960 mm). The active dry yeast (Dalian Xinghe Yeast Co., Ltd.) suspension was selected as the filtration solution, the size of particles is 8.4 μm, and the yeast suspension concentration was 3.5 g/L or 4.5 g/L. The aeration intensity was adjusted by a gas rotameter. Permeate water was continuously collected using a measuring cup placed on an electronic balance connected with a computer to record the accumulated weight of permeate water during a fixed time interval. The liquid level in the bioreactor was kept constant through a balance tank.

2.3. The PIV measurements

Similar to several previous papers, the PIV technique was used to characterize the features of flow fields near the membrane surface [6,10,11]. The PIV unit (TSI, USA) consists of a charge coupled device (CCD) camera with 1600 × 1400 pixel to capture the images, a high power double-pulsed laser light source, a synchronizer to simultaneously control the camera shutter and the laser pulsing, and a signal processing system to obtain information of flow fields. A standard fast Fourier transformation (FFT) cross-correlation algorithm was applied and the Gaussian peak detection algorithm was employed to identify the velocity vectors. According to the obtained instantaneous velocity vectors, the time-averaged velocity fields, the turbulence intensity fields and the vortex fields can be obtained through INSIGHT 3G post-processing software.

As shown in Fig. 3, during the process of PIV measurements, the purified water was pumped from an inlet at the bottom of bioreactor, the direction of laser light irradiation was perpendicular to the direction of CCD camera, and the interrogation area was 60 mm × 40 mm (height × width). Due to the limitation of experimental conditions, the flow fields near the 0°, 10°, 15° and 20° folded plate membrane surface were measured in liquid phase without aeration. Nylon particles (mean particle diameter is 50 μm, the mass friction is 0.05%) were used as tracer particles.

2.4. Data calculation and analysis methods

2.4.1. Permeate flux

The permeate water within a period of time was continuously collected using measuring cup placed on an electronic balance connected with a computer. Thus, the computer can record the weight of permeate water once a minute, the permeate flux J ($L\,m^{-2}\,h^{-1}$) is calculated as:

$$J = \frac{q}{A\Delta t} \tag{2.1}$$

where A is the membrane area (m^2), Δt is filtration time interval (h), and q is the collected permeate water volume during the corresponding time interval (L) [9]. Additionally, in order to ensure the accuracy of experimental data, the data presented in this study were average values of three parallel experiments.

2.4.2. The stable flux enhancement (%)

In all filtration experiments, the process of flux decline generally included three obvious stages: the rapid decline stage, the slow decline stage and the stable decline stage. Therefore, the stable flux is calculated as the average flux in the stable decline stage. In order to compare the difference of stable flux between the FSMM and the FPMM, the stable flux enhancement was defined as the following formula:

$$\text{The stable flux enhancement } (\%) = \frac{J_s' - J_s}{J_s} \times 100\% \tag{2.2}$$

where J_s' is the stable flux of FPMM, J_s is the sable flux of FSMM ($L\,m^{-2}\,h^{-1}$).

2.4.3. Filtration resistance

Resistance can be calculated by the Darcy's law:

$$R_t = (R_m + R_c + R_p) = \frac{\Delta P}{\mu J} \tag{2.3}$$

where R_t is the total resistance of the polluted membrane, R_m is the intrinsic resistance of the clean membrane, R_c is the fouling cake layer resistance and R_p is the membrane pore blocking resistance (m^{-1}); ΔP is TMP (kPa); J is permeate flux ($L\,m^{-2}\,h^{-1}$); μ is dynamic viscosity of permeate water (Pa s) [12–14].