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Mitigation of particle deposition onto membrane surface in cross-flow microfiltration under high flow rate

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ABSTRACT

We investigated the effects of flow rate, particle diameter and initial flux on fouling mitigation in cross-flow microfiltration of suspensions containing silica and PMMA particles. Regardless of the difference in PMMA and silica, the fouling mitigation was more effective at a larger flow rate and larger particle diameter, due to sufficient hydrodynamic lift force. Lower initial flux was also shown to be better for the mitigation of fouling. Fouling was completely prevented when cross-flow filtration of particles with 1.5 μm of diameter was carried out under a flow rate of 30 L min^{-1} and 4.0×10^{-5} $\text{m}^3\,\text{m}^{-2}\,\text{s}^{-1}$ of initial flux. We also demonstrated that classification of bi-dispersed particles using membranes could be achieved by the cross-flow microfiltration, where fouling by larger particles than the pore size was completely prevented because of the sufficient hydrodynamic lift force and only the smaller particles permeated through the membrane. This classification remained stable for 3 h while maintaining the flux and permeation of the smaller particles.

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1. Introduction

Microfiltration (MF) processing is widely used in various fields such as water purification, wastewater treatment [1,2], food industry [3–5], and pharmaceutical applications [6,7]. It is also used as a pretreatment prior to reverse osmosis (RO) and nanofiltration (NF) processing, and the performance of RO and NF processing often depends on the performance of MF processing [8]. When filtration of colloidal suspensions is carried out using MF membranes, fouling by colloidal materials inevitably occurs, resulting in significant performance degradation. A crucial and feasible technique to mitigate or completely prevent fouling by such colloidal materials needs to be developed for MF processing.

Although several studies have investigated surface modification of MF membranes to mitigate fouling by proteins or macromolecules, in particular using hydrophilic polymers and zwitterionic polymers as surface modifiers [9,10], the situation may be different from fouling by colloidal suspensions because colloidal materials are much larger in size; therefore, the dominant reason for fouling differs. When attempting to mitigate fouling by colloidal materials, the use of external forces is important. One of the typical methods applied is aeration [11]. When aeration is coupled with MF processing, the generated bubbles vibrate the membrane mechanically and sweep the fouling materials away from the membrane surface. In fact, this technique is widely used in submerged membrane bioreactors for wastewater treatment; however, aeration is generally an energy-consuming processing. Another potential method is direct application of an electric field to the membrane surface [12–15]. In the 1980s, electro-ultrafiltration was developed [16,17], and the electric field applied vertically to the ultrafiltration membranes effectively acted on charged macromolecules that had fouled the membrane surfaces. This method can also be coupled with MF processing to mitigate fouling. Wakeman and Williams [15] demonstrated that the cleaning effect increased with the strength of the electric field. However, to achieve efficient fouling suppression, an excessive amount of energy is also required for the electric field. The use of an ultrasound was also studied. Specifically, Chai et al. [18] demonstrated the cleaning effect of ultrasound-associated cleaning of a membrane fouled after filtration of peptone solution at 45 kHz. However, the ultrasound-associated cleaning technique is also an energy-consuming process that is not scalable.

The most feasible external force that can be used to mitigate fouling in MF processing is the hydrodynamic lift force, which is also referred to as shear-induced diffusion. This force is attributed to cross-flow velocity. The lateral migration of particles in the direction normal to the velocity gradient occurs when there are particles in a flow with a velocity gradient. Notably, the only energy required for this is that utilized by a circulation pump,

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which means it is scalable. Additionally, when compared with other techniques, this method is an energy-saving process. The effects of cross-flow velocity on flux have been extensively reported by many authors [19–29]. Mikulasek et al. [21] carried out filtration of titanium dioxide under different cross-flow velocity and reported that higher cross-flow velocity resulted in higher steady state flux. Li et al. [22] carried out filtration experiments on latex particles with different diameters and found that particles deposited on the membrane surface increased when smaller particles were filtered. Indeed, these studies have successfully demonstrated that higher steady state flux was obtained under higher cross-flow velocity. However, the steady state flux was much lower than the initial flux, and fouling by the colloidal materials occurred even in these cases. It is known that fouling suppression by particles can be achieved by sufficient cross-flow velocity; however, it is not clear if complete fouling prevention can be achieved without decreasing the initial flux of as high as $10^{-5}\,m^3\,m^{-2}\,s^{-1}$ order. Additionally, if we can achieve such an ideal cross-flow microfiltration, a novel situation in which only smaller particles less impacted by hydrodynamic lift force can permeate through MF membranes while completely preventing the deposition of larger particles onto the pores of the membranes can be developed as a novel classification technique for polydispersed particles using membranes.

In this study, we present the systematic results of filtration experiments of PMMA and silica particles with different diameters under high flow rate. We then demonstrate classification of bi-dispersed particles as a novel technique by utilizing the results of the cross-flow microfiltration.

2. Experimental

2.1. Cross-flow filtration tests under high flow rate

Cellulose mixed ester (MCE) microfiltration membranes (Toyo Roshi Kaisha, Ltd., Japan) with a nominal pore size of 0.3 μm were used. Two types of silica particles (Nippon Shokubai Co., Ltd. Japan) and two types of PMMA particles (Soken Chemical & Engineering Co., Ltd., Japan), both of which were monodispersed and spherical, were used. Table 1 shows the average particle diameter and coefficient of variation (CV) values of these particles as determined with a laser diffraction particle size analyzer (LA-950V2, HORIBA, Ltd., Japan). The average diameters of these particles are larger than the pore sizes of the membranes used, and we checked to ensure that no particles permeated through the membranes in any of the experiments because the turbidities of the permeates measured by a turbidity meter (2100N, HACH, Ltd., U.S.) were the same as that of pure water.

Table 1
Average diameter of silica and PMMA particles.

	Silica 1.5	Silica 0.6	PMMA 1.5	PMMA 0.6
Average diameter (μm)	1.18	0.50	2.21	0.52
CV (%)	7.43	6.71	6.83	9.89

Pictures of the membrane housing and a schematic diagram of the experimental setup are shown in Figs. 1 and 2. As for the membrane housing, the channel height, total length and effective membrane area are 1.0 cm, 54.7 cm, and 50 cm^2, respectively. The feed concentration was fixed to 100 ppm in all experiments. The retentate and permeate were fully recycled to keep the concentration of the feed constant during the tests. Each filtration test was performed for 180 min, the flow rate was set at 10, 15, 20, 25 or 30 $L\,min^{-1}$ and the initial flux was set at $4.0 \times 10^{-5}\,m^3\,m^{-2}\,s^{-1}$ with 0.06 kPa of applied pressure. In that condition, the average cross-flow rate was calculated to be 0.7, 1.0, 1.3, 1.7 or 2.0 $m\,s^{-1}$. Moreover, filtration tests were conducted under initial flux values of 2.0×10^{-5} and $3.0 \times 10^{-5}\,m^3\,m^{-2}\,s^{-1}$ and a flow rate of 20 $L\,min^{-1}$ to investigate the effects of the initial flux on steady-state flux when silica particles with a diameter of 0.6 μm were used. After the filtration tests, the membranes surfaces were observed by a field-emission scanning electron microscope (FE-SEM, JSM-6701F, JEOL Ltd.).

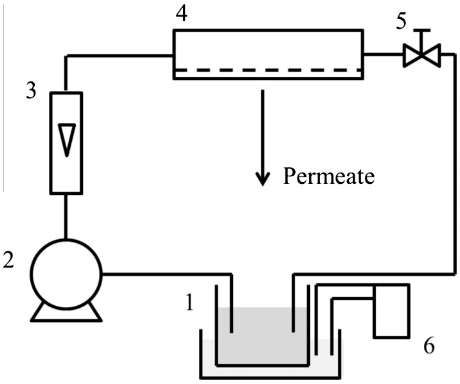

Fig. 2. Schematic diagram of the experimental setup. 1. Feed tank; 2. Pump; 3. Flow meter; 4. Membrane housing; 5. Valve; 6. Thermostat.

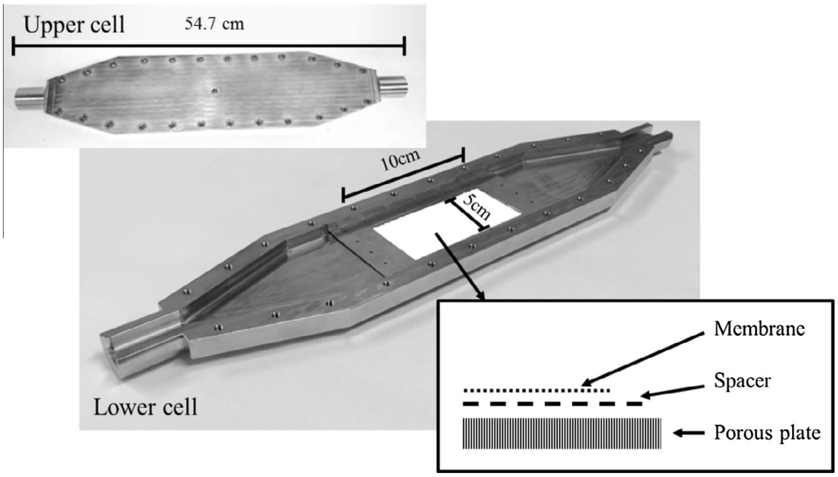

Fig. 1. Pictures of the membrane housing.

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