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Effect of spacer and crossflow velocity on the critical flux of bidisperse suspensions in microfiltration

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ABSTRACT

Crossflow microfiltration is a popular application spanning various industries. Although the impacts on fouling of feed bidispersity, crossflow velocity (CFV) and spacer, all of which are present in practical operations, are known separately, the understanding of the interplay of these three factors on fouling is lacking. Accordingly, this study used the Direct Observation Through the Membrane (DOTM) technique to characterize the critical flux of monodisperse and bidisperse polystyrene particles in both the absence and presence of a spacer over a range of CFV values. The results indicate that (i) the combined effects of both bidispersity (d_p=3 μm and 10 μm) and spacer gave the highest J_{crit} values for the smaller particles throughout the CFV range investigated; (ii) bidispersity was more effective in enhancing J_{crit} at a lower CFV, while the presence of a spacer was more effective at a higher CFV; (iii) a higher CFV diminished the enhancement induced by bidispersity more than that by the spacer; and (iv) comparisons between models and experimental data reveal that shear-induced diffusion models based on monodisperse particles are deficient for bidisperse mixtures, because they cannot allow for particle size segregation effects that occur in flowing mixed systems.

1. Introduction

Microfiltration has widespread applications including wastewater and food. As with all membrane-based separation processes, membrane fouling is an inevitable problem that needs to be addressed. In practical operations, crossflow of the feed is used to induce shear on the membrane surface to mitigate concentration polarization and fouling [1,2]. As a means of quantifying the onset of fouling, Field et al. [3] proposed the term 'Critical Flux', which is the permeate flux beyond which fouling becomes significant. Subsequently, Bacchin et al. [4] introduced the concept of 'Sustainable Flux' to incorporate notions of economic and environmental sustainability. Sustainable flux is qualitatively related to Critical Flux. Notably, the underpinnings of critical flux (J_{crit}), which is a function of various parameters, provide important operational and design heuristics [4–6].

Conventional techniques used to measure J_{crit} are based on indirect measurements (e.g., flux-pressure measurements, mass balance, and fouling rate analysis), which are convenient but not informative of the mechanisms leading to fouling. With the advent of non-invasive observation techniques, the precision associated with the determination of J_{crit} and the elucidation of the underlying mechanisms have been significantly improved. The Direct Observation Through the Membrane (DOTM) technique is one such technique allowing for the direct visualization of the interaction of particulate foulants with the membrane; in particular, it has been verified that the onset of the first deposition occurs earlier than the onset measurable changes in membrane resistance detected via indirect means [4,7]. DOTM has been proven to be a useful technique for studying the fundamentals of foulant deposition and foulant-membrane interactions, and has been used in characterizing the following particulate foulants: polystyrene (also known as latex) and glass particles [7–12], yeast [7,8], algae [8,13], and bacteria (sub-micron) [14].

In a previous DOTM study of bidisperse mixtures of particles it was observed that the presence of the larger particles increased the J_{crit} of the smaller particles, and only the smaller particles were observed on the membrane [9]. The explanation provided was that the enhancement of J_{crit} of the smaller particles was due to augmentation of shear-induced diffusivity of the smaller particles in the boundary layer by the larger particles. This mechanism would be dependent on crossflow velocity (CFV) and eddy promotion, as achieved by spacers [14,15]; neither of these factors was examined

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in the earlier work. Therefore this study reports on the effect of a range of crossflow velocities (CFVs), and operation with and without spacer. In addition, the results have been compared with models for monodisperse and bidisperse particle systems, and for systems with spacers.

2. Experimental description

2.1. Experimental setup and materials

The experimental setup using the Direct Observation Through the Membrane (DOTM) technique [7] is shown in Fig. 1. The setup consisted of a light microscope (Zeiss Imager.A2 m) coupled with a camera (Axiocam 105 Color), a feed pump (Micropump Inc, GJ-N25.PF/S.A), a permeate pump (Cole Palmer; Masterflex L/S 7519–20/85), a cross-flow acrylic membrane cell (with total channel dimensions of 105 mm length by 35 mm width by 3 mm height; the feed and permeate channel heights were respectively 2 mm and 1 mm), three pressure transmitters (Cole Palmer; Transducer 206) to characterize the pressures in the membrane cell (namely, feed inlet pressure, feed outlet pressure, and permeate inlet pressure), a feed solution container, a permeate container placed atop a balance (Kern; 572) to quantify permeate flux, and a computer to log pressure signals from the pressure transmitters and mass from the balance via Labview (2014–64 bit).

The membrane used was an Anodisc membrane (Whatman, Germany), which was a circular disk with a diameter of 47 mm and had a nominal pore diameter of 0.2 μm. The Anodisc membrane has high porosity and straight-through pores, making it transparent when wet, as required by DOTM. A piece of A4-size paper was cut into a smaller rectangular area with dimensions of 55 mm by 135 mm, from which a square area of 27 mm by 27 mm was cut in the center. After that, an Anodisc membrane was centered and pasted with glue between two pieces of these cut-outs, such that the active membrane area was 27 mm by 27 mm.

The particles used as model foulants were monodisperse polystyrene (also known as latex) particles (Fluka, Sigma Aldrich) with particle diameters (d_p) of 3 and 10 μm. The particle concentration used in the feed for each experiment was 0.05 g/L, regardless of whether a monodisperse (i.e., 3 μm) or bidisperse mixture (i.e., 3 and 10 μm particles in 1:1 volumetric ratio) was investigated.

The spacer used is shown by Fig. 2, whereby each grid had dimensions of 3 mm by 3 mm, and was angled at 45° to the feed and permeate streams. A spacer was always used on the permeate side of the membrane to enhance the mechanical integrity of the membrane to enable it to lay flat throughout the experiments. On the other hand for the feed side, a spacer was added only in some of the experiments to understand the effect of a spacer vis-a-vis that without.

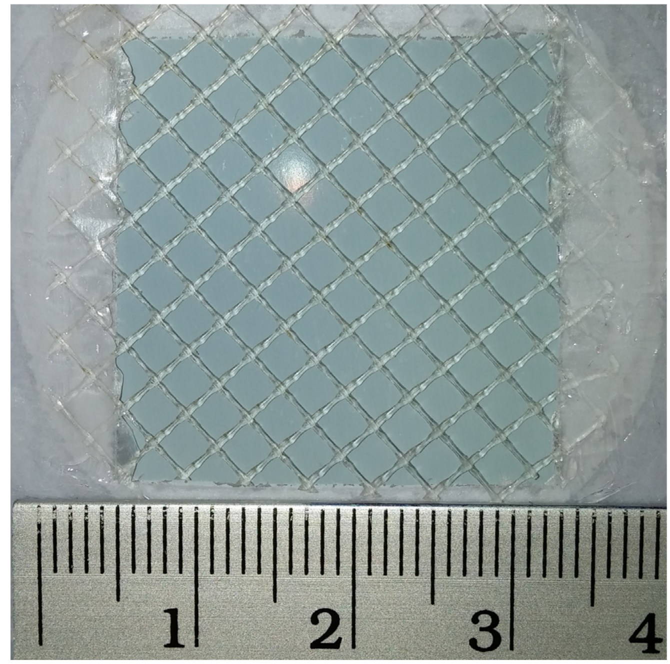

Fig. 2. Photograph of the spacer used. Each grid had dimensions of 3 mm by 3 mm, and was angled at 45° to the feed and permeate streams.

2.2. Method for determining critical flux (J_{crit})

Critical flux (J_{crit}), defined as the maximum flux above which the membrane fouls [3], was determined by the flux-stepping method. The initial permeate flux was set at 5 l/m^{2}h for 10 min, after which the flux was increased by 5 l/m^{2}h every 10 min. At each flux, one image was taken at the first minute then another at the ninth minute. Each image was analyzed using ImageJ for the rate of change of surface coverage (C), based on the formula employed by Wicaksana et al. [13]:

$$\frac{\Delta C}{\Delta t} = \frac{C_{9th\ minute} - C_{1\ st\ minute}}{t_{9th\ minute} - t_{1st\ minute}} \quad (1)$$

Two notes are worth highlighting regarding the image area characterized. Firstly, the area had dimensions of 0.416 by

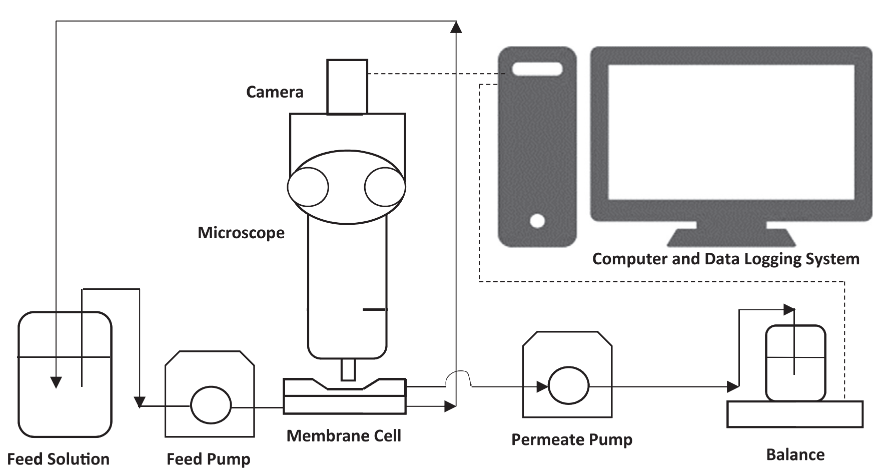

Fig. 1. Direct Observation Through the Membrane (DOTM) experimental setup.