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Effect of bubble characteristics on critical flux in the microfiltration of particulate foulants

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ABSTRACT

Fouling control by bubbling is widely implemented in membrane bioreactors (MBRs), but a mechanistic understanding of the relationship between the bubble characteristics and critical flux is missing. This study is targeted at bridging the gap. A microfiltration setup employing bubbling as a means of fouling mitigation was set up. The direct observation through the membrane (DOTM) technique was used to determine the critical flux of a feed containing micron-sized polystyrene particles, while a high-speed video camera was used to characterize the bubble behavior. The results indicate that (i) the local critical flux ($J_{c,local}$) values increased with height along the membrane and with gas flow rate, but was relatively invariant with liquid flow rate; (ii) with respect to height, the mean bubble velocity and mean bubble area per bubble increased, while the number of bubbles per unit membrane area decreased; (iii) bubble momentum and mean area per bubble had the most positive correlation with $J_{c,local}$; and (iv) the overall critical flux ($J_{c,overall,}$ which is the average of the local critical fluxes) increased linearly with respect to the ratio of gas to total flow rates, and steeply then more gradually with respect to power required. Finally, a comparison between the two two-phase flow systems employed for fouling mitigation (namely, bubbling and fluidized granular activated carbon (GAC)) was carried out.

1. Introduction

Due to the significant advantages over the conventional activated sludge processes, membrane bioreactors (MBRs) have become increasingly popular for wastewater treatment and reuse. However, as with all membrane-based filtration processes, membrane fouling remains a major hurdle that leads to reduced permeability and increased operation cost [1,2]. As fouling worsens with improved membrane permeability, unsteady-state shear methods have been identified as energy-efficient means to mitigate membrane fouling [3]. Unsteady-state shear methods include bubbling [4–6], vibration [7–9], pulsatile flow [10,11], and more recently particle fluidization [12]. The most popular fouling control technique in practical membrane bioreactors (MBRs) is bubbling. The introduction of bubbles has been reported to improve the permeate flux by 43% [13] and the critical flux [14] by up to 1.7 times [15].

The beneficial impact of bubbles on membrane filtration processes has been reported as early as in 1989 by Imasaka et al. [16], who injected the produced methane of an anaerobic digester into the tubular ceramic membrane modules, and found that membrane fouling was reduced at a reasonable energy cost. Since then, significant research on the use of bubbly flow particularly on aerobic membrane bioreactors has flourished [5,15,17–23]. Previous studies have indicated that bubbles are beneficial due to the creation of wakes and secondary flows [24,25] that confer shear stress on the membrane surface [26,27], which leads to the disruption of the polarization layer and contribute towards membrane fouling mitigation [28]. Besides, it was also found that the presence of bubbles enhanced the back-wash efficiency [29,30]. Bubble flow patterns, which are inevitably tied to the effectiveness of fouling mitigation have been categorized into the following according to gas flow rates [5,6,23,31]: (i) bubble flow, whereby small discrete bubbles are uniformly distributed in the liquid phase; (ii) cap-bubble flow, whereby flattened and distorted bubbles exist due to the confinement by the walls; (iii) slug flow, whereby each bubble size spans more than 75% of the width of the filtration module; (iv) churn flow, whereby the slugs are narrower and more distorted, and the flow is more chaotic, frothy and disordered; (v) annular flow, whereby the core and annulus are occupied by the gas and liquid phases, respectively. To optimize the fouling mitigation by bubbles, the influence of gas flow rates [17,32–35], bubble size and frequency

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Nomenclature

$J_{c,local}$	local critical flux (L/(m^2 h))
$J_{c,overall}$	overall critical flux (L/(m^2 h))
h	height assessed (m)
H	total cell height (m)
Q_g	gas flow rate (L/min)
Q_l	liquid flow rate (L/min)
$V_{b,rms}$	mean bubble velocity (mm/s)
V_b	bubble velocity (mm/s)
$P(V_b)$	probability of a bubble having a bubble velocity of V_b
N_b	number of bubbles per unit membrane area (number/mm^2)
A_b	area of bubbles per unit membrane area (mm^2/mm^2)
A_b/N_b	mean bubble area per bubble (mm^2)
P_b	bubble momentum (kg m^{-1} s^{-1})
W_r	power requirement (kW)
m_b	bubble mass (kg)
d_c	depth of the cell (m)
p_i	inlet pressure (kPa)
p_{atm}	atmospheric pressure (kPa)

Greek symbols

σ	standard deviation
ρ_{air}	air density (kg/m^3)
γ	ratio of specific heat at constant pressure to that at constant volume

[20,36–39], and bubble shapes and orientations [26] have been investigated. Some studies found that larger bubbles were more effective at mitigating fouling [20,40] due to the larger shear stress, larger wake regions, stronger secondary flow and the reduction in the risk of foaming. On the contrary, some other studies have found that at the same volumetric flowrate smaller bubbles were better [41,42]. The contradictory conclusions suggest that more factors are at play other than bubble size alone.

The well-acknowledged advantages of introducing bubbles into membrane-based filtration processes necessitates a more mechanistic understanding of the relationship between the bubble characteristics and critical flux. This forms the goal of the current study. The direct observation through the membrane (DOTM) technique [43,44] was used to determine the critical flux of a feed containing micron-sized polystyrene particles, while a high-speed video camera was used to characterize the bubble behavior. The specific questions addressed were: (i) how do the local critical flux values and local bubble characteristics (namely, velocity, bubble-membrane contact area, number of bubbles, bubble momentum) vary with height along the membrane, gas flow rate, liquid flow rate, and energy input; (ii) how do the local critical flux values correlate with the local bubble characteristics; (iii) how does the overall critical flux (average of the local values) relate to the flow rates and energy input; and (iv) how do the extent of fouling mitigation and energy cost compare between unsteady-state achieved by the employment of bubbles versus fluidized granular activated carbon (GAC) particles [44].

2. Materials and methods

2.1. Experimental setup

The vertical DOTM setup used to measure the critical flux during microfiltration, whereby bubbling was employed for mitigating membrane fouling, is depicted in Fig. 1. Specifically, as opposed to the conventional DOTM setups [43] whereby the membrane and hence the focal plane is horizontal, the membrane was oriented vertically in this case to facilitate the bubbling. This is similar to our previous study on the improvement of the critical flux of micron-sized particulate foulants when millimeter-sized granular activated carbon (GAC) particles were fluidized [44]. The key component of the DOTM setup is the Zeiss microscope coupled with a color video camera (Axiocam 105 color) to focus through the permeate and the membrane such that the focal plane is on the feed-membrane interface.

The feed suspension, which was continuously stirred at 250 rpm using a magnetic stirrer (AS ONE; REXIM RS-1D), was circulated by a gear pump (Cole-Parmer, 75211-15), and the liquid flow rate (Q_l) was measured by a variable-area flowmeter (Dwyer, 0.1–1.25 L/min). The liquid flow rate (Q_l) ranged between 0.3 and 1.0 L/min, which correspond to superficial liquid velocity range of 0.033–0.11 m/s; the lower bound was limited by the sensitivity of the flowmeter while the upper bound was because higher pressures restricted the injection of bubbles. Bubbles were generated by an air pump (Hiblow, HP-20, Japan), with the gas flow rate measured by a variable-area flowmeter (Dwyer, 0.2–2.5 L/min). Gas flow rate (Q_g) values were controlled

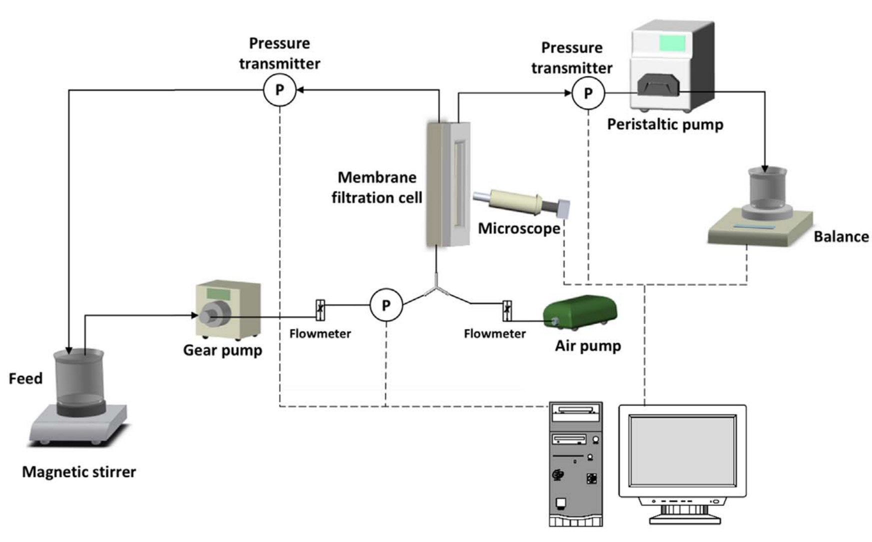

Fig. 1. Schematic of the vertical DOTM setup.