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Flux enhancement and cake formation in air-sparged cross-flow microfiltration

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Abstract

The flux enhancement in cross-flow microfiltration of submicron particles by sparged air-bubble is studied. The effects of operating conditions, such as air-bubble velocity, suspension velocity and filtration pressure, on the cake properties and filtration flux are discussed thoroughly. The results show that the pseudo-steady filtration flux increases as the air-bubble velocity and filtration pressure increase. The sparged air-bubble can significantly improve filtration flux, but the flux enhancement is more remarkable in the lower air-bubble velocity region. A gas–liquid two-phase flow model is adopted for estimating the shear stress acting on the membrane surface under various operating conditions. The cake mass can be significantly reduced by increasing the shear stress acting on the membrane surface. However, the SEM analysis illustrates that the particle packing structure becomes more compact as the air-bubble velocity increases. This results in a slightly higher average specific cake filtration resistance under higher air-bubble velocity. Consequently, a minimum flux occurs at the critical shear stress, e.g., $\tau_w = 1.1\ N/m^2$ in this study, when these effects are both taken into consideration. As the shear stress increases by increasing the suspension or gas-bubble velocity, the filtration flux decreases in the low shear stress region but, on the contrary, quickly increases in the high shear stress region. Furthermore, a force balance model is derived for understanding the particle deposition on the membrane surface. The relationship among filtration flux, shear stress and overall filtration resistance is obtained and verified by experimental data.

Keywords: Cross-flow microfiltration; Flux enhancement; Air-bubble sparging; Particle deposition; Cake properties

1. Introduction

Cross-flow microfiltration is an efficient and energy-saving method for separating fine particles from liquids in many chemical, environmental, biochemical and materials processes. Although this filtration mode has many advantages, the flux decline due to the membrane fouling becomes a severe barrier for its further developments and wide applications. In order to enhance the filtration flux and reduce the membrane fouling, many efforts have been paid previously, e.g., placing protuberances onto the membrane surface, placing objects into the flow channel, generating a pulsating flow, producing the Taylor or Dean vortices, etc. [1]. The main concept or purpose of these methods is to produce turbulent perturbations which can restrain suspension particles to deposit on the membrane surface. Based on this concept, increasing the shear stress acting on the membrane surface by sparging air-bubbles into the filter channel may reduce the particle deposition and enhance filtration flux. This method is indeed worth for further development due to its low operating cost and easy operation; however, the complex hydrodynamic phenomena influencing the operating performance should be carefully analyzed.

The effect of sparged air-bubble on the microfiltration efficiency has been investigated by a few previous studies. Mercier-Bonin et al. [2,3] carried out the cross-flow microfiltration of baker yeast and enzyme/yeast mixtures. They claimed that the sparged air-bubble could efficiently enhance the filtration flux and enzyme recovery. Al-akoum et al. [4] used cross-flow filtration for separating yeast cells from an aqueous suspension. They tried to employ three hydrodynamic methods in their experiments to enhance filtration flux, such as a vibration membrane, injecting gas-bubble, and generating Dean Vortices. They concluded that all filtration fluxes were increased by increasing the shear stress acting on the membrane surface using these methods. Derradji et al. [5] and Xu et al. [6] installed a turbulence promoter before the filter membrane. They found

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Nomenclature

A	cross-sectional area of the filter channel, (m^2)
C_1	correction factor defined in Eq. (11)
C_2	correction factor defined in Eq. (12)
C_3–C_6	coefficients defined in Eqs. (15)–(17)
d_p	diameter of particles, (m)
F_i	net interparticle force, (N)
F_n	drag force exerted on particles in the filtration direction, (N)
F_t	drag force exerted on particles in the suspension flow direction, (N)
f_c	friction coefficient between particles
H	the clearance of the filter channel, (m)
L_f	the length of the filter channel, (m)
n	the empirical exponent in Eqs. (3) and (4)
P	hydraulic pressure, (N/m^2)
ΔP	filtration pressure, (N/m^2)
Q	volumetric flow rate, (m^3/s)
q	superficial velocity of filtrate or filtration flux, (m^3/m^2 s)
q_s	pseudo-steady state filtration flux, (m^3/m^2 s)
R_c	resistance of the filter cake, (m^{-1})
R_m	resistance of the filter membrane, (m^{-1})
R_t	overall filtration resistance, (m^{-1})
u	superficial velocity, (m/s)
v	true velocity, (m/s)
W	the width of the filter channel, (m)
w_c	mass of dry cake per unit area, (kg/m^2)
X	the parameter defined in Eq. (2)
x	distance from the inlet of filter channel in suspension flow direction, (m)
Greek Letters	
α_{av}	average specific filtration resistance of cake, (m/kg)
ϕ_g	the multiplier defined in Eq. (1)
ϕ_l	the multiplier defined in Eq. (1)
λ	void fraction in gas–liquid two-phase flow
μ	viscosity of liquid, (kg/s m)
θ	gas injection factor defined in Eq. (18)
ρ	density, (kg/m^3)
τ_w	shear stress acting on the membrane surface, (N/m^2)
Subscripts	
g	gas
l	liquid
go	gas-only
lo	liquid only
tp	two phase

that the fluxes were increased 180% and 2.5-fold, respectively, under air-bubble sparging. Mikulášek et al. [7] and Pospišil et al. [8] also found the existence of air-bubble flow could increase the filtration flux. They derived a correlation between flux and hydrodynamic conditions based on the material balance and the filtration equation. However, the used parameters, e.g., gas-flow factor, should be determined in experiments.

Chang and Fane [9,10], Chang et al. [11], and Fane et al. [12] used organic hollow fibers with different arrangements to perform cross-flow filtration of yeast cells. They tried to introduce the air-bubbles flowing among hollow fibers in order to restrain membrane fouling and enhance filtration flux. The effects of the orientation and clearance of fibers, the fiber diameter, and the ratio of liquid to gas flow rate on the filtration flux were discussed. A dimensionless group based on hydrodynamics was set as the parameter to simulate the flux distribution in the axial direction of hollow fibers [10,12]. They also found in experiments that the fouling could be reduced more efficiently by the air-bubbles if the fiber axis was parallel to the fluid flow direction. In conclusion, increasing the shear stress and generating vortices were efficient ways to enhance filtration flux.

As mentioned above, most previous studies used experimental analysis methods to understand the flux enhancement by sparged air-bubbles. Although the operating variables can be correlated into some empirical equations, most parameters should be determined by performing a series of experiments, and the results are hard to relate to actual hydrodynamic conditions. In this study, hydrodynamic models for calculating the shear stress acting on the membrane surface and the critical condition for particle deposition are derived. Effects of operating conditions, such as the velocities of air-bubble and suspension flows and the filtration pressure, on the filtration flux and cake properties are discussed.

2. Theory

2.1. Shear stress acting on the membrane surface

Fig. 1 shows a schematic diagram of a multi-phase cross-flow microfiltration in a two-parallel-plate microfilter with a porous bottom plate. The suspension flows across the membrane surface tangentially, while the filtrate permeates vertically. Fine particles are carried by the liquid to migrate in the filter channel, and some of them have opportunities to arrive at the membrane surface and deposit stably to form a filter cake. Since the cake growth is limited by the shear stress produced by the tangential multi-phase flow, to estimate the shear stress is the main gate for understanding the filtration performance. In this study, the

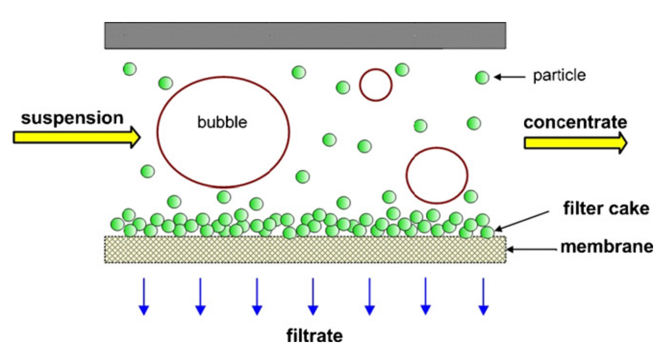

Fig. 1. Schematic diagram of multi-phase cross-flow microfiltration.