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Cake formation and particle rejection in microfiltration of binary mixtures of particles with two different sizes

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ABSTRACT

The filtration behaviors were examined in microfiltration of binary mixtures of particles with two different sizes. Dilute suspension of monodisperse polystyrene latexes with particle diameters of 0.522 and 0.091 μm was filtered using the microfiltration membranes with the nominal pore size of 0.3 μm, making them essentially impermeable to larger particles but permeable to smaller particles.

The filter cake comprised of larger particles alone initially formed because smaller particles permeate through the membrane. However, the flux decline became gradually marked since smaller particles were trapped into the pores of the filter cake of larger particles. Eventually, smaller particles were fully rejected, and thereafter the binary cake of both larger and smaller particles grew. This filtration behavior was reflected by both data of flux decline and particle rejection.

The logistic equation was employed to describe the variation of the rejection of smaller particles with the progress of filtration. The flux decline behaviors were well described using the logistic equation on the basis of the resistance-in-series model that the total cake resistance was represented by adding the increased cake resistance caused by the capture of smaller particles to the cake resistance of larger particles alone.

1. Introduction

Recently, clarifying membrane filtration of dilute suspension containing fine particles has been developed specifically to meet the requirement of such water purification processes as drinking water treatment, effluent polishing, and ultrapure water production [1–3]. One of the critical issues in the developments of efficient processes of clarifying membrane filtration is a significant flux decline, resulting from the membrane fouling such as pore blocking and cake formation.

A number of mathematical expressions have been developed over the past few decades to describe the membrane fouling due to pore blocking and cake formation during membrane filtration [4,5]. The classical blocking filtration law [6,7] has been exclusively used in the analysis of clogging behaviors of membranes and cake formation during membrane filtration. The importance of cake formation in filtration is recognized by numerous authors, and the compressible cake filtration model [8] has been extensively employed in the analysis of cake formation during particulate membrane filtration.

When cake formation and pore blocking may be occurring simultaneously, the fouling mechanism becomes more complex. In this case, the total resistance increases with the progress of filtration due to a combination of cake formation and pore blocking according to the resistance-in-series model [9]. Matsumoto et al. [10] developed the combined model describing pore blocking during cake growth.

For instance, when the particles with different sizes and types are present in suspension filtered, the situation is complicated [11–18]. The existence of the filter cake comprised of larger particles rejected by the membrane plays a crucial role in the capture of smaller particles in filtration of binary particulate mixtures which differ in size. The cake layer frequently removes a significant portion of fine particles before they reach the membrane surface [19]. Such behavior is highly important also from the viewpoint of secondary dynamic membranes in membrane filtration [20–22]. Hwang et al. [23] analyzed a rise in the apparent protein rejection in crossflow microfiltration of particle/protein mixtures on the basis of the deep-bed filtration model.

The focus of the present study is to delineate the complicated behaviors of cake formation and pore blocking occurring during dead-end microfiltration under constant pressure conditions using dilute suspension of binary mixtures comprised of the model particles with two different sizes. The flux decline behaviors with the progress of filtration are analyzed on the basis of the resistance-in-series model by using the model equation describing the variation of the rejection of smaller particles.

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Nomenclature

c	solid mass in filter cake divided by cumulative filtrate volume in case where all particles are rejected (kg/m^3)
d_m	nominal pore size of membrane (m)
d_p	particle diameter (m)
k	resistance coefficient in Eq. (4) (m^{n-2} s^{1-n})
m	ratio of mass of wet to mass of dry cake (–)
n	blocking index in Eq. (4) (–)
p	applied filtration pressure (Pa)
R^*	apparent rejection of particles (–)
R_m	membrane resistance including blocking resistance of membrane (m^{-1})
R_t	total filtration resistance to filtrate flow (m^{-1})
r	empirical constant in Eq. (6) (m^{-1})
s	mass fraction of particles in suspension (–)
u_1	filtration rate (m/s)
v	cumulative filtrate volume per unit membrane area (m^3/m^2)
$v_{0,k}$	cumulative filtrate volume per unit membrane area when R_2^* is 0.5 (m^3/m^2)

Greek letters

α_{av}	average specific cake resistance (m/kg)
θ	filtration time (s)
μ	viscosity of filtrate (Pa s)
ρ	density of filtrate (kg/m^3)

Subscripts

1	larger particles
2	smaller particles

2. Materials and methods

2.1. Materials

The particles used in the experiments were monodisperse polystyrene latexes (PSL) with particle diameters of 0.522 and 0.091 μm and true density of 1.05 g/cm^3 (Dow Chemical Japan Ltd., Japan). It should be stressed that the effect of particle sedimentation on filtration behaviors examined in this work is negligible small, judging from the diameters and density of particles [24]. The thick suspension provided from the manufacturer was diluted with ultrapure, deionized water produced by purifying tap water through ultrapure water systems equipped with both Elix-UV20 and Milli-Q Advantage for laboratory use (Millipore Corp., USA). The mixed particulate suspension was prepared by mixing each single particulate suspension. The weight fraction of particles in the mixed suspension was maintained at 1.0×10^{-4} for larger particles and ranged from 1.0×10^{-5} to 4.0×10^{-4} for smaller particles, and was set to very low values in order to simulate clarifying membrane filtration, which is encountered in advanced treatment in drinking water treatment, effluent polishing, and ultrapure water production.

2.2. Experimental apparatus and technique

Fig. 1 illustrates a schematic layout of the experimental setup used to carry out dead-end microfiltration experiments, in conjunction with the appearance of filtration. An unstirred batch filtration cell with an effective membrane area of 3.14 cm^2 was utilized in this research in order to promote fouling in filtration operation. Microfiltration experiments were performed using suspension of binary mixtures under conditions of a constant pressure varying over the range 49–294 kPa by adjusting the applied filtration pressure automatically by a computer-driven electronic pressure regulator by applying compressed nitrogen gas, as shown in the figure.

The membrane employed is mixed cellulose ester microfiltration membranes (Advantec Toyo Corp., Japan) with a nominal pore size of 0.3 μm, and the SEM image of the membrane is shown in Fig. 2. As shown later, the membranes are essentially impermeable to larger particles but permeable to smaller particles since two types of constituent particles larger and smaller than the pore size of membranes were chosen as the binary mixture.

The filtrate was collected in a reservoir placed on an electronic balance connected to a personal computer to collect and record mass vs. time data every 5 s. The weights were converted to volumes using density correlations. The values of the filtration rate at various volumes were computed by numerical differentiation of the volume vs. time data. The reservoir was replaced over measured time intervals in order to measure the temporal variation of

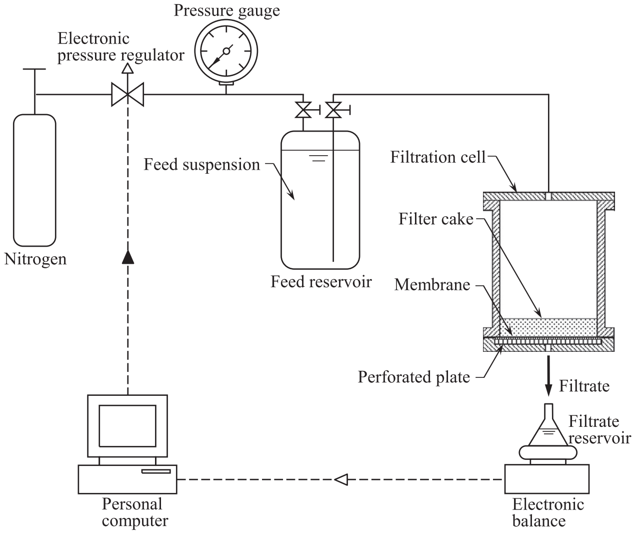

Fig. 1. Schematic layout of experimental setup for dead-end microfiltration.

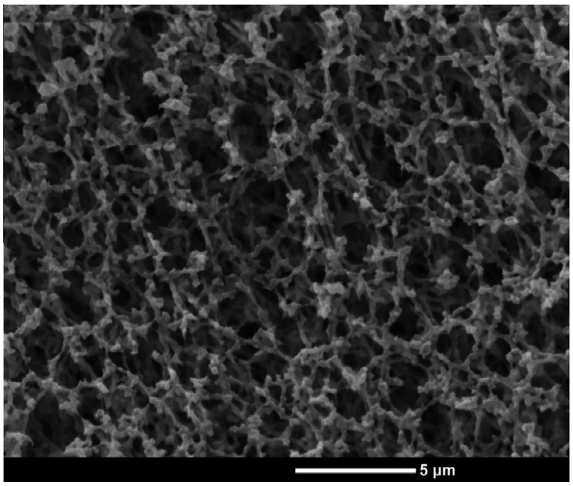

Fig. 2. SEM image of membrane used.