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Determination of cake porosity using image analysis in a coagulation–microfiltration system

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Abstract

Porosity of a cake layer formed through particle deposition plays an important role in the filtration performance of low-pressure membranes. An experimental analytical method for the direct measurement of cake porosity in a coagulation–microfiltration was developed using a CLSM and image analysis technique. A series of aggregates suspensions with different sizes and fractal dimensions were prepared with 0.1 μm of fluorescent polystyrene latex beads. Microfiltration of each suspension was carried out to form a cake layer whose porosity was measured using CLSM with an optical section of 2 μm and an image analysis program. To validate this method, measured porosities were compared with those calculated from specific cake resistances using the Carman–Kozeny equation. The two sets of porosities were in good agreement, confirmed statistically by a *t*-test. Based on this analysis technique, the effects of size and fractal dimension of aggregates on cake porosity and compressibility were investigated under various operating pressures. For low fractal dimensions the cake porosity was barely dependent on the fractal dimension of aggregates, whereas for high fractal dimensions it decreased with increasing fractal dimension.

Keywords: Porosity; Cake; CLSM; Microfiltration; Fractal; Image analysis

1. Introduction

Cake layer formation through particle deposition plays an important role in the filtration performance of low-pressure membranes. The build-up of cake increases the hydraulic resistance to fluid flow, thereby reducing permeate flux. The hydraulic resistance of the cake strongly depends on several factors including porosity of the cake as well as physical properties of the particles (size and shape factor). Among these factors, cake porosity is of great interest because it is closely related to the structure and compressibility of cake.

Different approaches have been proposed to estimate the cake porosity in low-pressure membrane filtration. The classical means for estimating cake porosity is to use compression-permeability (C-P) cells [1–3]. However, the reliability of the C-P cell tests depends heavily on experimental device and conditions. Theoretical methods based on the Carman–Kozeny equation and/or force analysis have been developed to estimate cake porosity [2–5]. Use of electrode type sensing probes [6] and high-energy radiation [7] have also been attempted to measure the cake porosity. Nevertheless, these methods have a limitation that they are nothing but indirect analysis of cake porosity.

Recently, techniques for direct investigation of aggregates or cake layer have been developed using a confocal laser scanning microscope (CLSM) and image analysis tools [8,9]. These techniques allow calculating parameters such as porosity without destroying the samples and have potential for analyzing the structure of cake in membrane filtration. They have been usually applied in the area of microbiology [10–14], but have hardly used for analyzing the porosity of cake layer which is formed from chemical flocs.

In this study, we established an experimental method for the direct analysis of cake porosity using a CLSM and image analysis technique. To validate this method, measured porosities were statistically compared with those calculated from specific cake resistances using the Carman–Kozeny equation. Based on this analysis technique, the effects of size and fractal dimension

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of aggregates on cake porosity were investigated under various operating pressures in a coagulation–microfiltration system.

2. Background for the determination of cake porosity

2.1. Determination of cake porosity using a CLSM and image analysis

Cake porosities were determined based on the optical sectioned images obtained by CLSM through the following procedures: (i) All the sectioned color images were converted to gray-scale images having intensity values of 0–255 (0 for black and 255 for white) (Fig. 1a). These gray-scale images were inverted and then converted to binary images by thresholding, e.g., partitioning the images into only black and white pixels at an arbitrary threshold value using Image-Pro plus (Media Cybernetics Inc., USA) (Fig. 2). (ii) The cake porosity was calculated using the partitioned images by ISA3D (Image Structure Analyzer in three dimensions) program [8]. ISA3D estimates the pixel values between sectioned layers through linear interpolation so as to obtain a porosity profile which can be integrated by the following equation to give the cake porosity ($\varepsilon_{\mathrm{CLSM}}$):

$$\varepsilon_{\mathrm{CLSM}} = \frac{(\mathrm{AT})\int_0^{\mathrm{Th}} (\mathrm{AP})_z\,\mathrm{d}z}{(\mathrm{AT})\,(\mathrm{Th})} = \frac{\int_0^{\mathrm{Th}} (\mathrm{AP})_z\,\mathrm{d}z}{(\mathrm{Th})} \qquad (1)$$

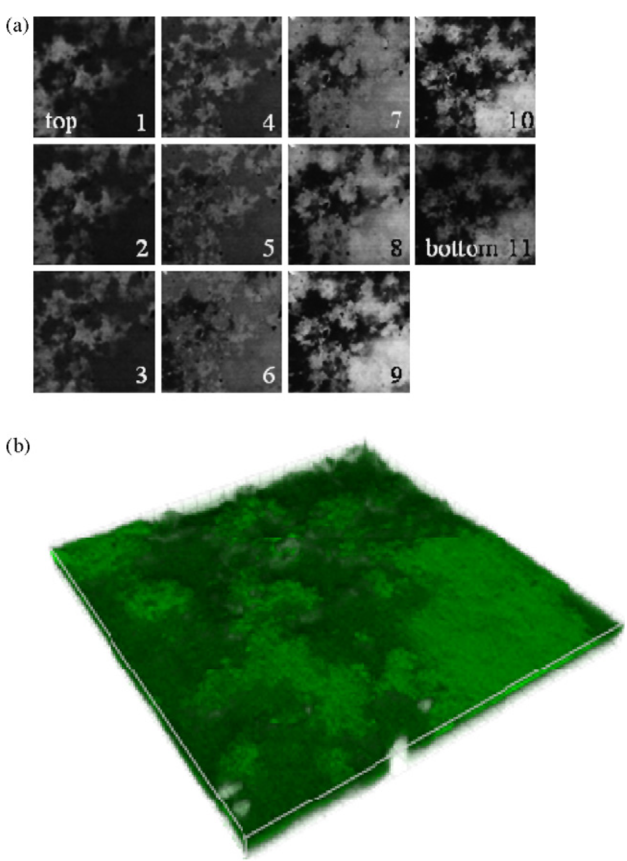

Fig. 1. CLSM images for run B at TMP of 40 kPa: (a) gray-scale images. Black parts correspond to vacancy. The size of each image is 506 μm × 506 μm. (b) A cake image in three dimensions reconstructed by IMARIS.

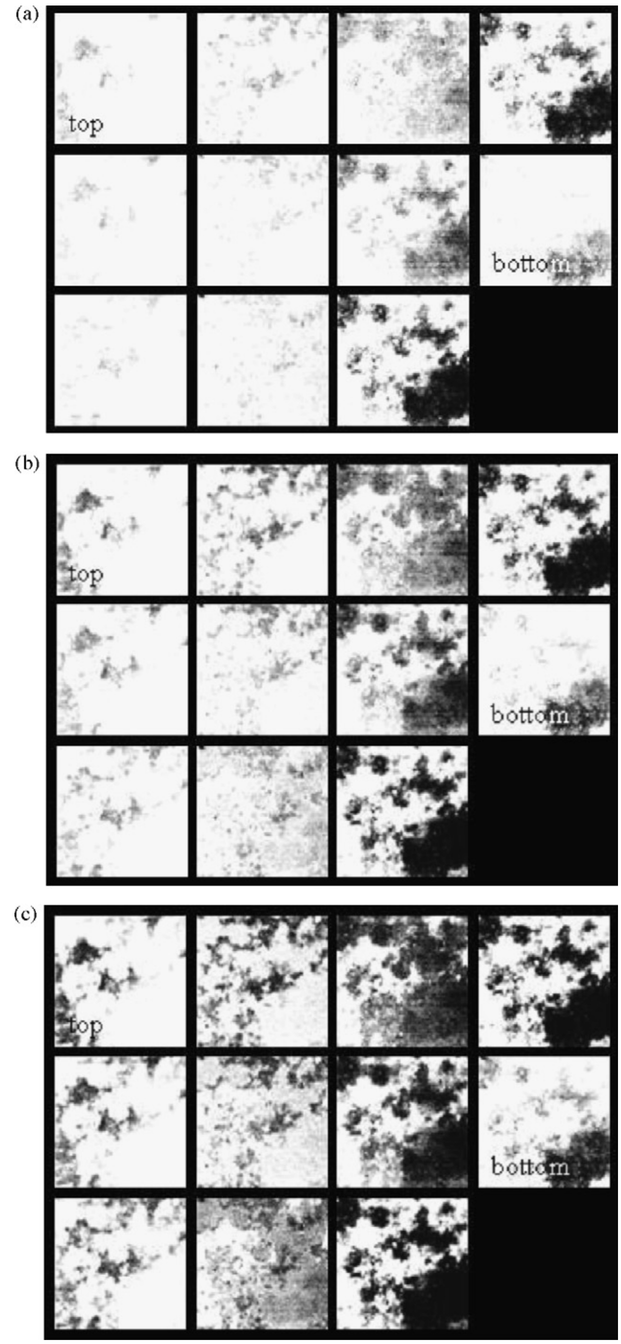

Fig. 2. CLSM images for run B at TMP of 40 kPa: binary images thresholded with a threshold value of (a) 120; (b) 150; (c) 180. White parts correspond to vacancy.

where (AT) is the total area of the image (field of view); $(\mathrm{AP})_z$ the areal porosity at distance z from the bottom; (Th) is the cake thickness, 20 μm in this study. (iii) The volumetric cake porosities thus obtained were compared with those estimated from the model developed in the previous study [15] which can predict the cake porosity based on packing and fractal geometry of aggregates. (iv) Procedures (i)–(iii) were repeated for the same specimen, only changing threshold values. Then one best threshold value was selected if it gave rise to an experimental porosity approaching most closely to the porosity estimated