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Filtration flux–shear stress–cake mass relationships in microalgae rotating-disk dynamic microfiltration

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HIGHLIGHTS

- The microalgae cake exhibited a compressibility factor of 0.66.
- Flow fields and local shear stress were simulated using Fluent software.
- The filtration flux obtained in this study ranged from 30 to 100 $L/m^2/h$.
- Increasing shear stress decreased 80% cake mass and enhanced 10-fold filtration flux.
- Cake mass was linearly related to the ratio of filtration flux to shear stress.

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ABSTRACT

Microalgae are promising feedstock for biodiesel production due to their lipid content. Rotating-disk dynamic microfiltration was used for microalgae concentration in this study. The effects of operating conditions, namely disk rotation speed, suspension feed rate, and transmembrane pressure (TMP), on the filtration flux and cake properties are discussed. Because all microalgae cells were rejected by the filter membrane, the main cause of filtration resistance was highly compressible cake that exhibited a compressibility factor of 0.66. An increase in the disk rotation speed led to 40–300% increase in pseudosteady filtration flux. Applying a high TMP yielded high filtration flux at a low disk rotation speed. However, the opposite result was obtained at a high rotation speed. Nearly the same filtration fluxes were produced at a disk rotation speed of 300 rpm even when the TMPs were different. The flow fields in the rotating-disk dynamic microfilter were simulated using software of computational fluid dynamics, Fluent. The shear stress at the membrane surface is a major factor affecting cake formation. A two order-of-magnitude increase in the shear stress by increasing the disk rotation speed will decrease the cake mass by 80% and enhance the filtration flux to about 10 times in the conditions of this study. A linear relationship between mean cake mass and the ratio of filtration flux to mean shear stress derived from the force balance model was verified using experimental data measured in various operating conditions. The methods proposed by this study provide a way to estimate the cake mass and filtration flux directly from operating conditions.

1. Introduction

Microalgae are microscopic organisms that can be sources of food, animal feed, pharmaceuticals, fertilizer, chemicals, biodiesel, and other high-value products. Useful microalgae should be gathered, concentrated, and separated in harvesting steps. By contrast, toxic microalgae should be removed from seawater before desalination or from water sources in tap water treatment processes. To develop effective separation technologies is required in microalgae concentration. Compared with the algae separation and concentration using centrifugal filtration, membrane filtration is an efficient, economic, and environmentally friendly operation.

Membrane filtration has been increasingly used for separating microalgae from drinkable water and seawater in recent years. Hung and Liu [1] used cross-flow microfiltration to separate green algae from freshwater. They demonstrated that filtration flux increased with increasing transmembrane pressure (TMP) in a low-pressure regime. However, a drastic flux decline occurred in a TMP greater than 60 kPa and could not be improved by increasing cross-flow velocity. This was attributed to the high cake compressibility in microalgae filtration [1–4]. Castaing et al. [5] used

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Nomenclature

ΔP	transmembrane pressure (N/m^2)	x	coordinate in the feed direction (m)
Q	feed flowrate (m^3/s)	y	coordinate vertical to the feed direction (m)
q	filtration flux (m^3/m^2 s)		
q_s	pseudo-steady filtration flux (m^3/m^2 s)	*Greek letters*	
R_c	cake filtration resistance (m^{-1})	α_{av}	average specific cake filtration resistance (m/kg)
R_m	membrane filtration resistance (m^{-1})	μ	viscosity of fluid (kg/s m)
t	filtration time (s)	ω	disk rotating speed (rpm)
w_c	cake mass per unit area (kg/m^2)	τ_w	shear stress on the membrane surface (N/m^2)

immersed hollow-fiber microfiltration to remove three types of undesirable microalgae from seawater. They observed that internal membrane fouling occurred at the beginning of filtration, followed by cake formation at a high algae concentration. Internal membrane fouling was observed only at a low algae concentration. The dissolved organic substances and algae size distribution were crucial factors that affected membrane fouling.

Some recent research has focused on rotating-disk dynamic microfiltration. Bouzerar et al. [6] conducted rotating-disk microfiltration of a calcium carbonate suspension. The relationships of permeate flux and filtration resistance with local shear stress and TMP were established. They concluded that the high shear stress induced by the disk rotation efficiently mitigated the cake formation except in the central region at low speeds. To Compare with disk rotation speed, Jaffrin et al. [7] and Moulai-Mostefa et al. [8] discovered that TMP had a minor effect on the permeate flux. The permeate flux was mainly determined by the maximum shear rate and not by internal flow. Increasing the rotation speed or equipping the disk with large vanes was beneficial to flux enhancement. These results were previously demonstrated by Li et al. [9] and Jaffrin [10,11]. Liebermann [12] demonstrated that the rotating filter elements yielded energy savings compared with conventional tubular systems on the basis of the same shear force generated on the membrane surface. The combination of centrifugal and shear forces in dynamic modules was believed to improve the control of cake-layer accumulation, thus extending the system operating life.

Dynamic microfiltration used for microalgae concentration has been explored by some researchers. Ríos et al. [13] evaluated the filtration efficiency of microalgae by using a dynamic membrane filtration module equipped with six staggered disk membranes on two rotation shafts. Their results indicated that a high TMP did not improve microfiltration performance because of severe membrane fouling. Frappart et al. [14] studied the influences of hydrodynamics in the tangential and dynamic ultrafiltration of two microalgae species. They discovered that a dynamic filtration module consisting of a rotating disk yielded a permeate flux nearly twice that of a plane sheet cross-flow filtration system with the same TMP and shear rate on the membrane surface. The difference in flux was attributed to different flow patterns. Although the conclusion that dynamic filtration is economically more efficient than tangential cross-flow filtration was demonstrated by previous studies [13–15], the optimal operating conditions for high permeate flux should be determined by a lot of experimental data. The conditions cannot be related properly to slurry filterability or filter characteristics.

The filter cake formed by microalgae cells always exhibits high specific filtration resistance due to its highly compressible [1–4,13], which may cause extremely low filtration flux. Therefore, understanding how the operating conditions, such as disk rotation speed and TMP, affect the cake properties is necessary to improve filtration performance. In this study, a type of high-lipid-content microalgae, *Chlorella* sp., was concentrated by using a rotating-disk microfiltration module. A 0.1-μm hydrophilic membrane composed of mixed cellulose ester was used in filtration to completely retain microalgae cells. Certain effects of the operating conditions, such as disk rotation speed, feed velocity, and TMP, on the filtration flux and cake properties were measured and are discussed in this paper. The velocity distribution and shear stress on the membrane surface were simulated using computational fluid dynamics (CFD). The filtration flux and cake mass were correlated with shear stress.

2. Materials and experiments

2.1. Materials

The microalgae, *Chlorella* sp., used in the experiments for this study were purchased from the Fisheries Research Institute, Council of Agriculture, Executive Yuan, Taiwan. The purchased microalgae were harvested after the culture step and used directly to prepare 3.25-g/L *Chlorella* sp. suspensions by carefully adding appropriate amount of de-ionized water. The density of microalgae cells was measured through the drying curve using an infrared-ray moisture meter (AND Co., Model: AD-4714A, made in Japan) [16]. The cell density was 1135 kg/m^3 by considering the bound water in the cells. The microalgae cells were observed using a MDS-3600 Microscope and Power Image Analysis (PIA) System produced by Ching Hsing Computer-Tech Ltd. in Taiwan. The cells were spherical and the size of most cells ranged from 2 to 8 μm with a mean value of 3.5 μm. Most constituents in the suspension were alga cells. The protein and polysaccharide concentrations in the extracellular polymeric substances were measured using the Bradford and phenol–sulfuric acid methods, respectively [17], and those concentrations were as low as 5.82 and 17.47 ppm, respectively. A 0.1-μm hydrophilic membrane composed of mixed cellulose ester was used in filtration to retain microalgae cells. The membrane (Catalog #: A010A142C) was manufactured by the ADVANTEC Co. (Japan).

2.2. Rotating-disk dynamic filtration and analyses

Fig. 1 shows a cross-sectional view of the cylindrical filter chamber of a rotating-disk dynamic filter which was made of stainless steel #304. The diameter and height of the chamber were both 38 mm. Two vanes, each with a height of 10 mm, a width of 10 mm, and a thickness of 1 mm, were placed beneath a rotating disk with a diameter of 30 mm. A low circular inlet and a high circular outlet, both with diameters of 9 mm, were connected to the chamber for feed inflow and concentrate outflow. A circular membrane was installed on the porous bottom plate to serve as a filter medium. The filtration area was 1.12×10^{-3} m^2.

A schematic diagram of the dynamic microfiltration system is shown in Fig. 2. A 3.25-g/L *Chlorella* sp. suspension was prepared in the suspension tank and agitated using a magnetic mixer. The suspension was pumped into the dynamic microfilter using a