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Harvesting algal biomass for biofuels using ultrafiltration membranes

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ABSTRACT

The objective of this paper is to develop efficient technologies for harvesting of algal biomass using membrane filtration. Foulants were characterized using scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy. Anti-fouling strategies were established, such as using air-assisted backwash with air scouring, and optimizing operational conditions. A model was also developed to predict the flux decline and final concentration based on a resistance-in-series analysis and a cake development calculation. The results showed that the buildup of the algal cake layer and adsorption of algogenic organic matter (AOM) (mainly protein, polysaccharides or polysaccharide-like substances) on the membrane caused membrane fouling. The cake layer buildup was removed by conducting an air-assisted backwash every 15 min. The adsorbed AOM could be removed by soaking the membrane in 400 mg/L NaClO for 1 h. In our experiment the algal suspension was concentrated 150 times, to give a final cell concentration of 154.85 g/L. The harvesting efficiency and average flux were 46.01 g/(m^2 h) and 45.50 L/(m^2 h), respectively. No algae were found in the permeate, which had an average turbidity of 0.018 Nephelometric Turbidity Units (NTU). The flux decline predicted by the model under different conditions was consistent with the experimental results.

1. Introduction

Recently, algal biomass has been recognized as a promising alternative source of raw material for biofuel production (Hu et al., 2006, 2008), but the lack of an economical and efficient method to harvest algal biomass is a major problem (Wang et al., 2008). Algal biomass harvesting is a challenge because of the small size of the algal cells (3–30 μm in diameter), their similar density to water, and the large volumes of water that must be handled to recover the biomass.

Algae harvesting requires one or more solid–liquid separation steps, including the concentration and drying processes. The most commonly used concentration technologies are coagulation, flocculation, flotation, centrifugation, filtration (both screen and membrane) and gravity sedimentation (Carmichael et al., 2000; Heasman et al., 2000; Munoz and Guieysse, 2006; Wang et al., 2008; Amin, 2009). Among these methods, membrane technology is promising. As manufacturing techniques improve and the range of applications expands, the cost of membranes has steadily decreased, which may make it possible to use membrane technology for algal harvesting. Most importantly, membrane filtration can remove protozoans and viruses from used algal culture medium while retaining residual nutrients; thus the algal cultivation medium can be recycled. Furthermore, no coagulant is added which simplifies subsequent oil refining and the use of the residual biomass.

A polyacrylonitrile (PAN) ultrafiltration membrane with a 40 kDa molecular weight cutoff was found to be satisfactory for the continuous recovery of two marine microalgae (*Haslea ostrearia* and *Skeletonema costatum*) (Rossignol et al., 1999). Petrusevski et al. (1995) examined a tangential flow filtration system for the concentration of living freshwater phytoplankton from large volumes of reservoir water with low algal biomass. Samples were concentrated 5–40 times using a 0.45 μm pore-size membrane. Further increases in the concentration factor are difficult and costly due to increased membrane fouling as biomass concentration increases. Understanding membrane fouling by the biomass and developing anti-fouling strategies are critically important for sustainable biomass concentration using membrane technology. However, only a few reports on the algae/water separation process have described the fouling of membranes and solutions for the fouling (Babel et al., 2002; Her et al., 2004; Kwon et al., 2005; Hung and Liu, 2006; Liang et al., 2008). In these cases the biomass concentration remained constant during the treatment process, while in an algal biomass harvesting process, the algal concentration continues to increase which makes membrane fouling more severe.

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Nomenclature

A	membrane filtration area (m^2)
a	diameter of the algae along the longer axis (m)
b	diameter of the algae along the shorter axis (m)
C_0	initial algal concentration (g/L)
C_b	volume concentration of algae in the bulk solution (%)
$C_{(i,j)}$	algal volume concentration at step j in filtration cycle i
C_f	final algae concentration (g/L)
CF	concentration factor
C_w	volume concentration of algae at the membrane surface (%)
D_B	Brownian diffusion coefficient
d_{ecd}	equivalent circular diameter of the algae (m)
d_p	equivalent volume radius (m)
d_{pi}	range of algal radius (m)
D_s	shear-induced diffusion coefficient
F_d	permeation drag force that moves the algae toward the membrane surface
F_B	Brownian diffusion force
F_s	shear-induced diffusion
F_l	lateral inertial lift force
I	channel height (m)
i	number of the filtration cycle
j	number of the calculated step at each cycle
J_0	flux of the membrane before the initial filtration cycle ($m^3/(m^2\ s)$)
J_s	permeation flux at steady state ($m^3/m^2\ s$)
k_c	specific cake resistance (m^{-2})
k_{cr}	cake growth rate (m/s)
k_B	Boltzmann constant
L	membrane module channel length (m)
n	number of total cycles in the concentration process
p_i	percentage of particles of d_{pi} in the total particles
Q	permeate flow rate (m^3/s)
Q_{n-1}	flow rate after the $n-1$ backwash (m^3/s)
Q_n	flow rate after the n backwash (m^3/s)
r	flux recovery after backwashing
R_c	cake resistance (m^{-1})
R_m	inherent membrane resistance
R_{ir}	backwash irreversible resistance due to strong attachment, adsorption or chemical bonding
$R_{ir(n-1)}$	backwash irreversible fouling resistance after the $n-1$ backwash
R_{irn}	backwash irreversible fouling resistance after the n backwash
U_m	cross-flow velocity (m/s)
V_0	initial volume of the algal suspension (L)
v_B	algal transport velocity due to Brownian diffusion (m/s)
v_l	algal transport velocity due to lateral inertial lift (m/s)
V_f	final volume (L)
VRF	volumetric reduction factor
v_s	algal transport velocity due to shear-induced diffusion (m/s)
$V_{T(i,j)}$	total volume of the permeate at step j in filtration cycle i
$t_{interval}$	interval between the calculation steps
T	temperature (K)
T_{BW}	backwash interval

Greek symbols

δ	cake thickness (m)
ΔP	transmembrane pressure (Pa)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
η	algal concentration productivity ($g/(m^2\ h)$, dry weight)
τ_W	wall shear stress (s^{-1})

This study focused on developing an efficient membrane technology for algae biomass concentration. Foulants were characterized and anti-fouling strategies were developed; the feasibility of using a cross-flow membrane ultrafiltration process to harvest and dewater algal suspension were evaluated and a model was developed to predict the flux decline, algae concentration, and volumetric reduction factor achieved in the concentration process.

2. Methods

2.1. Characterization of algal suspension

The green microalga, *Scenedesmus quadricauda*, used in the study was isolated in the Phoenix metropolitan area. *S. quadricauda* was chosen as a test organism because it is ubiquitous in the water environment and is often selected for algae-based wastewater treatment and for production of biofuels (Chen, 2001; Omar, 2002; Ma et al., 2004; Awasthi and Rai, 2005; Mata et al., 2010). This strain was used as a production strain in the authors' laboratory for biodiesel production due to its rapid growth potential, high oil content (35–60% of dry weight), and robustness to environmental conditions (Hu, personal communication).

Fresh algal suspensions were obtained from our outdoor panel photobioreactors. BG11 culture medium was used to grow the algae (Andersen, 2005). pH of the culture ranged from 7.0 to 8.9 during the experimental period. Daily maximum temperature was 35 °C and minimum temperature was 15 °C. Daily maximum solar intensity was 1900 μmol/(m^2 s). Size distributions of the algal particles were determined by micro-flow imaging (MFI) (DFA 4100, Brightwell Technologies Inc., ON, Canada). The morphology and shape of the algal cells were observed by light microscopy.

2.2. Membrane system and algal concentration process

The batch algal concentration experiment employed a lab scale hollow fiber polyvinylchloride (PVC) ultrafiltration (UF) membrane module (LU8A-4A) provided by Litree Co. (Hainan, China). The PVC membrane is low cost, with robust mechanical strength, high permeability, and excellent chemical properties (e.g., acid, alkali and chlorine resistance) (Zhang et al., 2009). The molecular weight cut-off (MWCO) of the PVC membrane was 50 kDa, and the filtration area was 0.125 m^2. The batch experiment was run under a constant pressure of 34.5 kPa. The cross-flow mode was used with a cross-flow velocity of 0.17 m/s. Flow rates were recorded every minute during the experiment. After each test, the membrane module was cleaned with deionized water or NaClO, depending on the fouling of the membrane. Flux was tested using deionized water before a subsequent run.

To reduce the dilution of the algal suspension by permeate during the backwash process, and in place of using the backwash pump, compressed air was used to push permeate into the housing through the membrane and then out of the module. To enhance backwash efficiency, during the backwash process pulsated air scouring was used to flush foulants from the membrane. In pulsated air scouring, the fiber was scoured with air from top to bottom for 6 s, then from bottom to top for 6 s. The volumetric reduction factor (VRF) and concentration factor (CF) of the algae