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Analysis of flux enhancement at oscillating flat surface membranes

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ABSTRACT

Intensification of microfiltration flux in a novel oscillatory membrane design has been investigated both experimentally and theoretically. Up to three fold increase in flux could be achieved using the proposed design. Modeling of the system was successfully achieved using a modified film theory approach which takes into consideration the end effects of the surface as well as a concentration dependent scaling factor for the diffusion coefficient. The model predictions shows that moderate membrane oscillations at frequencies <25 Hz and amplitudes <0.015 m can be used effectively for intensifying microfiltration as well as other membrane separation processes. Similar to other oscillatory shear enhanced membrane systems, existing filtration models based on Brownian diffusion, shear induced diffusion, and inertial lift were unsuccessful in modeling filtration flux under current design and oscillatory conditions.

1. Introduction

Use of oscillatory motion has been recognized as an effective process intensification (PI) technique that enhances mass and heat transfer rates in many applications, particularly those limited by diffusion such as membrane separation processes [1–4]. The magnitude of enhancement associated with the velocity vector created by periodic excitation of the liquid or the surface is a function of the fluid dynamics and its characteristics in the boundary layer. Although the generation of a relative oscillatory field at the solid–liquid interface can be achieved by either oscillating the solid surface or the fluid surrounding it, the energy dissipation using the former approach is focused on the boundary layer adjacent to the solid/liquid interface rather than the bulk of the fluid medium. Such concept has been investigated by Gomaa et al. [5–8] for enhancing heat and mass transfer rates at solid–liquid interface where significant increase in transfer rates is reported.

To enable proper design and scale up of such technologies, it is essential to understand the fundamental transport mechanisms involved in the process and to quantify its contribution. Different models have been used to describe flux behaviour in crossflow microfiltration (CFMF) [9]. Among those is the film theory model which is based on Leveque one third power law and the use of Brownian diffusivity for particle diffusion [10]. A second model is the shear-induced diffusion (SID) which is based on assuming diffusion enhancement to be due to particles interaction in a shear flow [11,12]. A third approach is based on the production of an inertial lift force away from the wall by the velocity gradient [13]. Another model is based on an analysis of the drag forces on a particle at the membrane surface which determines whether the particles are going to stick or move along the surface due to the tangential flow [14,15]. In all of the above models, deposition of particles on the membrane surface may also be influenced by surface interaction, such as electro-kinetic effects [16].

For oscillatory shear enhanced membrane separation, most investigators have correlated filtration flux to the shear rate at the membrane surface based the well known one third power law for laminar flow over flat surface in which the mass transfer coefficient scales with the shear rate to the power of one third. This implies that the filtration flux for oscillatory shear will always scale with the frequency and amplitude with power ratio equals 1.5. Most correlations however did not follow the one third power law but had the general form $J \propto \gamma^n$ in which J is the filtration flux, γ is the shear rate. Furthermore, the exponent n varied depending on the system as well as the range of the operating conditions even for the same system. For example, for the Vibratory Shear-Enhanced Processing (VSEP) system n was found to be 0.19 for microfiltration of yeast for oscillation frequencies $f < 60$ Hz, but increases for $f > 60$ Hz [17]. Similarly Beir et al. who used an oscillatory hollow fibre membrane system, showed that a maximum critical flux increased with the shear rate to the power of 0.26 for microfiltration of yeast suspension [18] but reported higher flux increase with shear rate to the power of 0.375 for enzyme recovery from aqueous solutions [19].

Abbreviations: CL, Cake layer; CPL, Concentration polarization layer; CFMF, Crossflow microfiltration; MF, Microfiltration; SID, Shear induced diffusion; BC, Boundary conditions; TMP, Transmembrane pressure.

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Such discrepancies added to the fact that deviation of n from 1/3 has not been fully explained, suggest that other mechanisms are likely contributing to the flux enhancement under oscillatory conditions and the magnitude of its contributions depends not only on fluid properties, but also on the system design and operating conditions.

The objective of this work is to address some of the issues mentioned above and to gain better understanding of the fluid mechanics and transfer characteristics at the membrane surface under oscillatory motion. Another objective is to assess the applicability of the existing CFMF models under such conditions, and to develop a model which best describes the present system to enable proper design and scale up methodology for its effective use in membrane separation. The model predictions will then be compared with experimental measurements to validate its accuracy.

2. Experimental

2.1. Experimental setup

Microfiltration of re-hydrated bakers yeast was conducted using the experimental setup shown in Fig. 1. It consists of a 40 l tank charged with 3 g/L yeast suspension and a low speed stirrer for proper mixing without interfering with the hydrodynamics at the membrane surface. The experiments were conducted at room temperature which was monitored using a temperature sensor and was in the range of $22 \pm 2\,^{\circ}$C. The physical properties of the yeast suspension are listed in Table 1. The filtration unit consisted of a rectangular hydrophilic MF membrane (GE OSMONIC Laboratory) with pore diameter of 0.22 μm housed in one side of a tapered flat surface. The membrane was held in its place by means of wire gauze and a protective sheath to prevent it from rupture, and was firmly housed in the filtration unit by sealing its edges. A tubular arrangement connected the membrane housing to a peristaltic vacuum pump driven by a variable speed motor which provided the necessary trans-membrane pressure (TMP) while allowing the permeate flow to circulate back to the filtration tank to maintain constant concentration. To account for the pressure drop contributed by the tubing, plain water was used at constant flow rate without the membrane and the pressure drop was recorded. This was subtracted from the measured pressure drop during membrane microfiltration to get the actual TMP. To prevent vacuum changes caused by cake formation and to maintain constant TMP a feedback control scheme was implemented to control the vacuum pump speed.

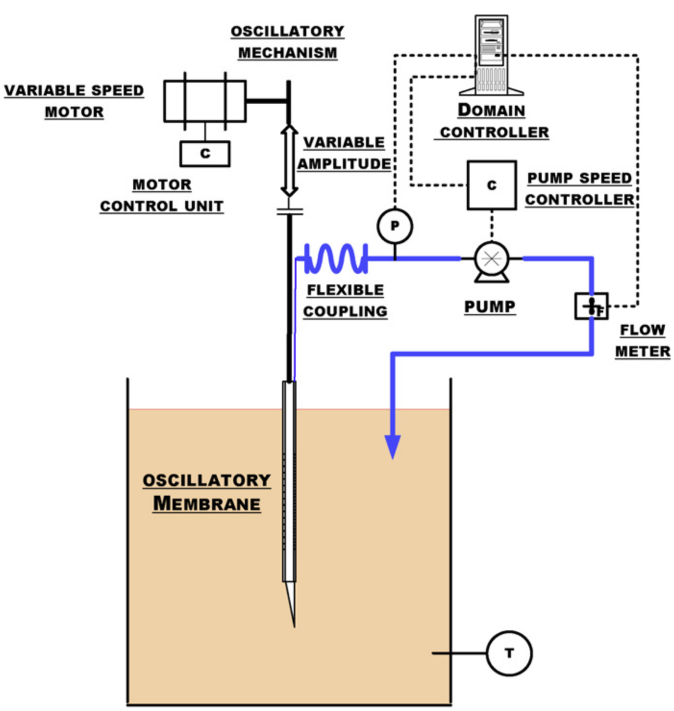

Fig. 1. Experimental setup.

Table 1
Physical properties of the yeast suspension.

Fluid density (kg/m^3)	Fluid viscosity (kg/m s)	Solid concentration (kg/m^3)	Cake porosity[a] (−)	Yeast density[a] (kg/m^3)
1000	0.001	3	0.26	1130

[a] Ref. [36].

Table 2
Range of experimental conditions.

Oscillation amplitude (m)	Oscillation frequency (Hz)	Trans-membrane pressure difference (kPa)
0.003, 0.012, 0.02, 0.03	5, 10, 15, 18, 20, 25	20, 35, 50, 60

The filtration unit was oscillated vertically using an adjustable eccentric driven by a variable speed motor. A tachometer and a light-emitting sticker attached to the motor displayed the frequency of in Hz, while the amplitude was measured using a micrometer. Data acquisition and control were performed using National Instruments USB-6008 card. Table 2 gives the range of operating variable and experimental conditions used in this investigation.

2.2. Materials and methods

The yeast suspension was prepared using water, dextrose and salt adjusted to a pH 5.0–7.0. The solution was used to precondition the membrane and adjust the temperature of the unit, after which active dry yeast was added and stirred for 30 to achieve uniform suspension. After each experiment the membrane was physically cleaned by scraping off the cake layer followed by back flush at oscillating frequency of 15 Hz for 10 min at a high pump-drive speed. The collected permeate was sent back to the tank to maintain a constant concentration. The unit was then further cleaned using running water and soft brush for 1 min. The membranes were kept in 0.5% sodium metabisulphite solution to stop bacterial growth, and were replaced when cleaning did not restore plain water flux to within 5% of it original value.

3. Results and discussion

Generally, membrane oscillation resulted in increasing filtration flux, with enhancement factor E reaching as high as ~3, where,

$$E = \left. \frac{(J)_{with\ Oscillation}}{(J)_{no\ Oscillation}} \right|_{t=60\ \mathrm{min}} \qquad (1)$$

The flux values taken after 1 h correspond to the typical time needed to reach quasi-steady state conditions, and is comparable to that used by other investigators [19,20]. Figs. 2 and 3 show the intensification effect of the oscillation amplitude and frequency on the flux enhancement factor respectively. As expected increasing the frequency is more effective than the amplitude, which support the dependency of the flux on the surface shear rate.