Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Power induced by bubbles of different sizes and frequencies on to hollow fibers in submerged membrane systems

*Sepideh Jankhah**, *Pierre R. Bérubé*

Department of Civil Engineering, University of British Columbia, Unit 2002, 6250 Applied Science Lane, Vancouver, Canada

ARTICLE INFO

Article history:
Received 5 May 2013
Received in revised form
16 August 2013
Accepted 17 August 2013
Available online 11 September 2013

Keywords:
Submerged hollow fiber membrane
Shear stress
Hydrodynamic conditions
Fouling
Coarse and pulse bubble sparging
Power transfer

ABSTRACT

To shed light onto the relationship between sparging conditions and fouling control in submerged hollow fiber membranes, the effects of bubble size and frequency on the hydrodynamic conditions induced in membrane system were studied. Two general classes of bubbles were considered: coarse (0.75–2.5 mL) and pulse (100–500 mL). The power transferred (P_{trans}) onto membranes could be used to characterise the multiple effects induced under different sparging conditions. P_{trans} is proportional to root mean square of shear stress (τ_{rms}), the area of zone of influence (i.e. the fraction in the system where high velocity and high vorticity (turbulence) are induced by the bubble) and their rise velocity. At a given sparging rate, the *power transferred* onto membranes was less with coarse bubble sparging than pulse bubble sparging and increased with the size of pulse bubbles. For all cases, the *power transfer efficiency* was consistently higher for pulse bubble sparging than for coarse bubble sparging. The power transfer efficiency to the system was greatest for the small pulse bubbles considered when a small amount of power is required for fouling control. However, when fouling is extensive, large pulse bubbles may be required to generate the required amount of power for fouling control.

1. Introduction

Air sparging is commonly used to reduce the extent of fouling in submerged hollow fiber (HF) membranes (Cabassud et al., 1997; Bellara et al., 1996; Cui et al., 2003; Ozaki and Yamamoto, 2001). However, the relatively high energy requirement associated with air sparging has been a barrier to the widespread adoption of membranes. Minimizing energy requirements can be achieved at optimum sparging conditions that minimizes the fouling rate at lowest energy requirements. However, to methodically find optimum sparging conditions, the mechanism of fouling control through air sparging must be understood. In general, the models developed to describe these mechanisms are based on a force balance between the back-transport induced by air sparging and drag induced by permeate flux (Cui et al., 2003; Akoum et al., 2002; Belfort et al., 1994; Ducom et al., 2002). The back transport of foulants away from the membrane is dependent on the hydrodynamic conditions (i.e. distribution of velocity and vorticity) and the resulting shear stress induced by air sparging onto the membrane surface (Belfort et al., 1994; Drews, 2010). Both the magnitude and variation of the shear stress have been reported to affect the extent of transport (Chan et al., 2007). However, a number of studies have

* *Corresponding author*. Tel.: +1 604 323 6316.
E-mail addresses: sepidehjankhah@civil.ubc.ca (S. Jankhah), berube@civil.ubc.ca (P.R. Bérubé).

0043-1354/$ – see front matter
http://dx.doi.org/10.1016/j.watres.2013.08.020

Abbreviations

A	Electrode area (m^2)
A_b	The area of the bubbles (m^2)
A_z	Area of zone of influence of a rising bubble (A_z)
C_b	Concentration of the oxidizing ion in the bulk (mole/m^3)
D	Diffusion coefficient (m^2/s)
d	Diameter of the probe (m)
d_s	Diameter of the spherical cap (m)
d_e	Bubble equivalent diameter (m)
E_0	The Eötvös number (unitless)
F	Faraday constant (A s/V)
g	Gravitational acceleration; 9.82 (m/s^2)
h	Height of the spherical cap (m)
I	Current (A)
L_z	Length of zone of influence (m)
N	Number of exchanged electrons during the reaction (unitless)
P_{trans}	Power transferred onto membranes (watts)
r	Radius of curvature (m)
Re_b	Bubble Reynolds number calculated (unitless)
Re_c	Bubble corrected Reynolds number (unitless)
τ_{RMS}	Root mean square of shear stress (Pa)
V	Volume of the bubble (m^3)
V_b	Rise velocities of the bubbles (m/s)
V_{bc}	Velocity predicted based on literature (m/s)
W_z	Width of zone of influence (m)
μ	Water dynamic viscosity (Pa s)
$\Delta\rho$	Difference between water density at 17 °C and air density at the same temperature (kg/m^3)
σ	Water–air surface tension (N/m)
τ	Shear stress (Pa)
γ	Shear rate (1/s)

suggested that the variation of shear stress may actually be more important than the actual magnitude (Li et al., 1997; Mores and Davis, 2002; Chan et al., 2011).

The size and frequency (i.e. flow) of sparged bubbles have been reported to affect the hydrodynamic conditions (Ndinisa et al., 2006), as well as the magnitude and variability of shear stress induced on to membranes and fouling control (Ye, 2012; Yeo et al., 2007). However, the effect of sparging conditions on the hydrodynamic conditions remains unclear.

The objective of the present research was to quantify the effect of sparged bubble size and frequency on the hydrodynamic conditions and the shear stress induced by gas sparging in submerged hollow fiber membrane systems. The hydrodynamic conditions in the system were characterized in terms of the distribution of liquid velocity and vorticity (turbulence) in the system. The shear stress on the membrane fibers were characterized in terms of magnitude, variability and distribution. The effect of bubble size on the hydrodynamic conditions and shear stress was assessed for coarse and pulse bubble sparging.

2. Material and methods

All experiments were performed in a 1 m wide, 2 m high and 15 cm thick rectangular Plexiglas system tank. A test module containing seven test fibers, each 2 m long, was placed vertically at the centre of the tank. The space between the test fibers in the module was 7 cm. Shear probes were fixed half way along the height of the test fibers in the module. The fibers were loosely held in the module with 1% slackness between the top and the bottom bulkheads. Air spargers were fixed at the bottom of the centre of the tank (Fig. 1). Two types of sparger were used: a coarse bubble sparger that generated small bubbles of about 0.75 and 2.5 mL and a pulse bubble sparger that generated 150, 300 and 500 mL bubbles. Pulse bubbles larger than 500 mL were not considered, as these are not stable and tend to break apart (Clift et al., 2005). Sparging flow rates were selected to generate discrete single rising pulse bubbles, pulse bubbles at a frequency of 0.25 Hz and pulse bubbles at a frequency of 0.5 Hz.

The shear stresses induced by sparged bubbles at the surface of the test fibers were measured using an electrodiffusion method (EDM) (Berube and Lei, 2006; Mitchell and Hanratty, 1966; Berube and Lei, 2006; Mitchell and Hanratty, 1966). For this purpose, electrochemical shear probes were installed on Teflon test fibers with a similar diameter as that of hollow fiber membranes (Berube and Lei, 2006; Berube and Lei, 2006). The reagent used for the electrochemical measurements contained 0.003 M Ferricyanide, 0.006 M Ferrocyanide, and 0.3 M potassium chloride in deoxygenated, de-chlorinated tap water (Fulton et al., 2011). A limiting diffusion current of 550 mV was selected as described by Mitchell and Hanratty (1966). Measurements were collected at a frequency of 200 Hz, for a duration of 2 min, and a water temperature of 17 °C. A stainless steel anode was used in all experiments.

The magnitude of shear stress was obtained from the current measured at the probes using the quasi-steady state Leveque relationship presented in Equation (1) (Sobolik et al., 1998).

$$I = 0.862\, n\, A\, F\, c_b\, D^{2/3}\, d^{-1/3} \gamma^{1/3} \quad (1)$$

where D = diffusion coefficient (m^2/s), d = diameter of the probe (m), γ = shear rate (1/s), F = Faraday constant (A s/V), A = electrode area (m^2), n = number of exchanged electrons during the reaction [–], C_b = concentration of the oxidizing ion in the bulk (mole/m^3), and I = current (A).

Calibration of the probes was done ex-situ prior to all experiments as presented in Fulton et al. (2011). Because of the turbulent nature of the hydrodynamic conditions in air-sparged membrane systems, the flow conditions at the proximity of the probes are highly transient. Therefore, the magnitude of shear calculated by the steady state solution (Equation (1)) was corrected to account for the non-steady state conditions (Tihon et al., 1995; Wein, 2010).

Imaging of bubbles was performed using a high-speed high-resolution camera (Phantom Miro 4, with 800 × 640 pixel resolution) and VidPIV software (Oxford Lasers). Two