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Experimental study and CFD modelling of a two-phase slug flow for an airlift tubular membrane

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ABSTRACT

The aim of the present study was to develop a computational fluid dynamics (CFD) model to study the effect of slug flow on the surface shear stress in a vertical tubular membrane. The model was validated using: (1) surface shear stresses, measured using an electrochemical shear probe and (2) gas slug (Taylor bubble) rising velocities, measured using a high speed camera. The length of the gas slugs and, therefore, the duration of a shear event, was observed to vary substantially due to the coalescing of gas slugs as they travelled up the tube. However, the magnitude of the peak surface shear stress during a shear event was not observed to vary significantly. The experimental conditions significantly affected the extent to which the gas slugs coalesced. More coalescing between gas slugs was typically observed for the experiments performed with higher gas flow rates and lower liquid flow rates. Therefore, the results imply that the frequency of shear events decreases at higher gas flow rates and lower liquid flow rates.
Shear stress histograms (SSH) were used as a simple approach to compare the different experimental conditions investigated. All conditions resulted in bi-modal distributions: a positive surface shear peak, caused by the liquid slug, and a negative shear peak caused by the gas slugs. At high gas flow rates and at low liquid flow rates, the frequency of the shear stresses in both the negative and positive peaks were more evenly distributed. For all cases, increasing the liquid flow rate and decreasing the gas flow rate tends to result in a predominant positive peak. These results are of importance since conditions that promote evenly distributed positive and negative peaks, are likely to promote better fouling control in membrane system. At high liquid and low gas flow rates, the frequencies obtained numerically and experimentally were found to be similar, deviating by less than approximately 10%. However, at high gas and low liquid flow rates, the differences were slightly higher, exceeding 20%. Under these conditions, the CFD model simulations over predicted the shear stresses induced by gas slugs. Nonetheless, the results indicate that the CFD model was able to accurately simulate shear stresses induced by gas slugs for conditions of high liquid and low gas flow rates.

1. Introduction

A common problem encountered with MBRs is the fouling of the membrane component of the system (Judd, 2006). Air sparging, which generates a gas–liquid two-phase flow, has been documented to be effective at minimizing fouling (Cui et al., 2003). However, the mechanisms by which these flows minimize fouling are not yet completely understood. As a result, a trial-and-error approach is typically used to identify the optimal air sparging conditions that minimize fouling. With the aim of developing better fouling control strategies, the present study focuses on investigating the hydrodynamics induced by air sparging in side stream MBRs with vertical tubular membranes. The choice of this specific configuration is based on the fact that the link between shear and the two-phase slug flow is better controllable in this configuration and that several years of experience with this type of system existed.

Fouling control in vertical tubular membranes has been linked to the hydrodynamic conditions, induced by slug flow, near a membrane surface (Ghosh and Cui, 1999). As presented in Fig. 1, three different zones can be observed in slug flow: (1) a falling film zone, (2) a wake zone, and (3) a liquid slug zone. As illustrated, the direction of the liquid flow changes as a gas slug rises. A number of studies have suggested that it is this change in the direction of liquid flow, and the corresponding change in the direction of the induced surface shear stresses, which promotes fouling control (Ochoa et al., 2007; Rochex et al., 2008). The aim of the present study was to

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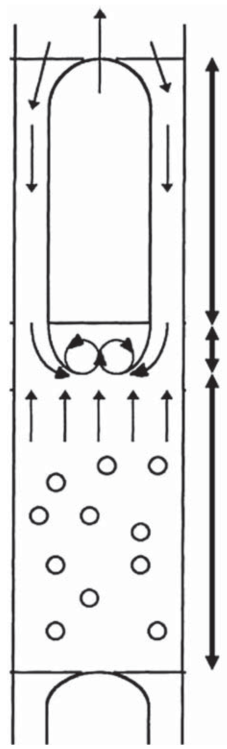

Fig. 1. Zones in the slug flow (after Ghosh and Cui, 1999) (arrows correspond to direction of liquid flow).

develop a computational fluid dynamics (CFD) model to study the effect of slug flow on the surface shear stress in a commercial-scale vertical tubular membrane. Fluent® (Ansys Inc., USA) was used as the modelling platform, and the model was validated using surface shear stresses, measured using an electrochemical shear probe and gas slug rising velocities, measured using a high speed camera. It should be noted that a number of CFD models have been developed to study the effect of slug flow on the surface shear stress in vertical tubular membranes (Taha and Cui, 2002, 2006; Ndinisa et al., 2005; Zheng et al., 2007). However, these models only considered the effect of distinct gas slugs of constant size. On the other hand, the present study considers the effect of gas slugs of variable size, which is typical of commercial-scale vertical air sparged tubular membranes where slugs tend to be of a random size and the slugs tend to coalesce as they rise through the tubes.

2. Materials and methods

2.1. Description of the setup

A schematic of the experimental setup is presented in Fig. 2. A Plexiglas tube, with dimensions similar to those of a tubular membrane (Nakoryakov et al., 1989; Zheng and Che, 2006) (i.e. length of 2 m, inner diameter of 9.9 mm) was used to collect the measurements needed to validate the CFD model. A measurement cell was located half way along the length of the tube. Surface shear stresses and rising velocities were measured as gas slugs flowed through the measurement cell. A MasterFlex pump and rotameter were used to control the flow of liquid (i.e. electrolyte solution), and a nitrogen gas cylinder and gas flow meter were used to control the flow of gas (i.e. nitrogen) through the system. Nitrogen gas was used instead of air to avoid the oxidation of the ferri- and ferrocyanide in the electrolyte solution. The mixture of nitrogen gas and the electrolyte solution flowed from the Plexiglas tube to a solution storage tank where nitrogen gas was released to the atmosphere. The solution storage tank was submerged in a temperature controlled water bath to maintain the temperature at 20 °C for all experiments. The entire experimental set-up was placed inside an electrically grounded metal wire mesh cage to minimize electromagnetic interferences that can affect the measurements taken using electrochemical shear probes.

A total of 15 experimental conditions, corresponding to flow rates of 0.1, 0.2, 0.3, 0.4 and 0.5 L min^{-1}, for the electrolyte solution, and flow rates 0.1, 0.2 and 0.3 L min^{-1}, for the nitrogen gas, were investigated. Gas slugs were fully developed before reaching the flow cell (Lakehal et al., 2008). For each experimental condition, data was collected for a period of 10 s; and each experimental condition was repeated six times.

2.1.1. Physical properties of the electrolyte solution

Density and viscosity of water with the electrolyte solution was taken from Rosant (1994): 1016 kg m^{-3} and 0.001 Pa s, respectively, at 20 °C. For nitrogen gas, the density and viscosity are 1.17 kg m^{-3} and 1.755×10^{-5} Pa s, respectively, at 20 °C (Incropera et al., 2006)

The surface tension for the water–air and water–electrolyte–air were measured to be 0.075 N m^{-1} (Fisher Scientific Surface Tensiometer 20). Note that the surface tension of the water-nitrogen was assumed to be similar to that of water–air, as it was not practically possible to measure the surface tension with nitrogen gas. To determine the impact of the surface tension on the slug flow (i.e. shape and size of the bubbles), the Weber number (*We*) for the gas can be used:

$$We = \frac{\rho_g U_{TB} d}{\sigma} \qquad (1)$$

where ρ_g is the density of the gas (kg m^{-3}), U_{TB} is the gas slug rising velocity (m s^{-1}), d is the tube diameter (m) and σ is the surface tension (N m^{-1}). When the Weber number is smaller than 1, the surface tension dominates the regime, and when it is larger than 1 the inertial forces dominate the regime. For this study, the slug rising velocities were found to be between 0.6 and 0.9 m s^{-1}, which results in Weber numbers between 0.03 and 0.12. Therefore, in the present study, surface tension significantly affects slug flow. In this study, changes in surface tension of the liquid phase (e.g. adding surfactants) were not considered but they will likely affect the shape of the bubble (inter-phase liquid–gas) and may affect the shear profile near the wall (Clarke and Issa, 1997; Zheng et al., 2007).

2.2. Surface shear measurements

The measurement cell contained two electrochemical shear probes (cathodes) aligned vertically (i.e. in the direction of flow) and separated by a distance of approximately 0.3 mm (Fig. 3). This configuration enabled both the magnitude and direction of the shear stresses to be measured (i.e. the magnitude of the signal from the probe that is upstream provides the true reading and is higher than the magnitude of the signal from the probe that is downstream) (Cognet et al., 1984). Each probe was made using platinum wires (0.5 mm diameter), machined to be flush with the inside of the tube surface (Berube et al., 2006). Because of the machining process the shear probes were observed (digital microscope with Motic Images v2.0 software) to be slightly oval with an average diameter slightly larger than 0.5 mm (i.e. 0.54 mm). The surface of the machined probe was also observed to be uneven, further increasing the actual surface area of the probe. A stainless steel fitting (anode) was located downstream of the shear probes (i.e. measurement cell). A potential of 300 mV was applied between the anode and shear probes (cathode). The electrolyte solution contained ferri- and ferrocyanide as described by (Chan et al., 2007).