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Effect of turbulence on fouling control of submerged hollow fibre membrane filtration

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ABSTRACT

In this study, we investigated the effect of turbulence on hollow fibre membrane filtration in terms of membrane fouling performance experimentally. In particular, a special setup with a turbulence generator using a vibrating perforated plate was constructed in the laboratory. The setup enabled the hollow fibre membrane filtration to be carried out within a design ambient with targeted levels of turbulence without mean shears. The non-intrusive laser imaging approach of Particle Image Velocimetry (PIV) was used to quantify the characteristics of the turbulence ambient. Subsequently, by monitoring the rate of trans-membrane pressure (TMP) rise with constant permeate flux experiments using 4 g/L yeast feed suspensions, we obtained unique data sets that revealed the quantitative effects of turbulence on membrane fibre filtration, which are not available in the literature so far. Overall, the results indicated that the presence of turbulence moderated the membrane fouling and reduced the corresponding rate of TMP rise (dTMP/dt). Two key turbulence parameters, namely, turbulence kinetic energy (TKE) and eddy length scale, were found to relate to the membrane fouling reduction, with the rate of TMP rise generally decreasing when TKE or eddy length scale increases. In addition, there exists an optimum eddy length scale beyond which the eddy size (comparable to approximately ten times of the hollow fibre diameter in the present study) has no more influence on the fouling behaviour. A direct comparison between turbulence and membrane vibration for fouling control was also performed. The implications of the present results on the design of membrane bioreactors (MBRs) are discussed.

1. Introduction

The use of hollow fibre membranes in water and wastewater treatment industry has been extensive in the past decades (Celmer et al., 2008; Culfaz et al., 2011; Robles et al., 2013). Higher surface area and excellent mass transfer properties are among the major reasons which lead to this broad usage (Moch, 2000; Culfaz et al., 2011). It is predicted that the high growth of the industry will continue in the near future (Fletcher et al., 2007).

For membrane bioreactors (MBRs), membrane fouling and concentration polarization remain the biggest hurdles for the design and operation. Fouling is defined as internal or external blockage of membrane surface by foulants that accumulate during the treatment process (Drews, 2010), which can result in TMP rises and flux declines. Various approaches, in particular air sparging (Le-Clech et al., 2003; Chan et al., 2011; Jankhah and Bérubé, 2013), have been developed to alleviate the fouling. However, the effect of air sparging had been shown to be limited to a finite extent (Xia et al., 2013), and the energy consumption requirements can be high up to 70% of the total energy cost (Judd, 2006; Drews, 2010; Verrecht et al., 2010). Therefore, the search for a more cost effective alternative continues.

Alternative techniques which have been studied for the fouling control of membranes in recent years include membrane vibrations (Bilad et al., 2012; Kola et al., 2012; Li et al., 2013), Couette motion (Philp et al., 1994), and pulsations (Defrance and Jaffrin, 1999). Membrane vibration produces shear stresses on the membrane surface that can scour and reduce the deposit of foulants. The improvement of membrane fouling depends on the orientation of vibration, which can be either longitudinal or transverse, with the latter shown to be more effective for hollow fibre membranes (Li

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et al., 2014).

The use of turbulence promoters has also been proposed for membrane fouling reduction in the literature. A turbulent environment is generally favoured in the membrane filtration systems as it improves the mass transfer in the system (Pitera and Middleman, 1973; Judd, 2006). Krstić et al. (2002) investigated the effect of a static mixer as a turbulence promoter in a cross-flow microfiltration arrangement. They concluded that the permeate flux improved more than 500% with turbulence for all the membranes studied. The significant improvement in the permeate flux implied a lesser need for high cross-flow velocity which can result in lower energy consumption. Jokić et al. (2010) examined the use of mixers with different configurations to provoke turbulence in a cross-flow microfiltration of yeast suspensions. They also reported a significant increase in the permeate flux.

Other types of turbulence promoters that were studied in cross-flow filtration, included cylindrical inserts (Xu et al., 2003; Zhen et al., 2006), helical inserts (Xu et al., 2003; Zhen et al., 2006; Liu et al., 2012), winding inserts (Xu et al., 2003; Zhen et al., 2006), column cross-section inserts (Zhen et al., 2006), and twisted tape (Popović and Tekić, 2011). Generally, these studies reported in a qualitative manner that the turbulence generated by the promoters decreased the membrane fouling and led to a significant reduction of fouling rate (in terms of the rate of TMP rise) on top of the cross flow effect. However, the quantitative influence of the turbulence alone to the membrane filtration was generally not documented separately due to the difficulty in distinguishing the two effects. The only exception was from Yeo et al. (2007) who investigated the use of air sparging for hollow fibre fouling reduction using advanced laser imaging techniques. They found that the rate of TMP rise during their constant flux experiments can be correlated to both the mean shear and turbulence kinetic energy (TKE) around the fibres induced by the bubbling, and that the two effects were of almost equal importance in the quantitative relationship. Their study remained the only study available in the literature that provided the distinctive influences of turbulence on membrane filtration as far as we are aware.

In terms of engineering application, considering that turbulence can be generated by different means (air sparging, jet, grid, etc.), it is critical to confirm in a quantitative manner the role of turbulence in the membrane filtration processes. Although the positive effect of turbulence on mass transfer and fouling mitigation have been discussed in earlier studies (Liu et al., 2012), the quantitative details related to the physical mechanisms were not addressed. The primary objective of this study is therefore to determine the sole effect of turbulence on membrane filtration, which has not been performed before. With the improved understanding, we can then evaluate in a quantitative manner the balance between the energy dissipating aspect of turbulence agitation and its beneficial use towards membrane fouling control, and ultimately the cost effectiveness of the different approaches using turbulence and cross-flows in a membrane system can be appraised.

In the present study, we quantify the effect of turbulence on hollow fibre membrane filtration in a comprehensive manner by means of a special experimental setup that enabled the hollow fibre membrane filtration to be carried out in a design ambient with various targeted levels of turbulence without mean shears. The non-intrusive laser imaging approach of Particle Image Velocimetry (PIV) was used to quantify the characteristics of the ambient turbulence. Subsequently, by monitoring the rate of TMP rise during constant flux membrane filtration experiments, unique data sets were acquired that revealed the effects of turbulence without the presence of cross-flows. In particular, we identify the quantitative effects of two key turbulence parameters, namely, TKE and eddy length scale (or eddy size) on the membrane filtration. In the following, the experimental setup and methods are first described. The experimental results are then discussed in details.

2. Experiments

2.1. Main experimental setup

A schematic diagram of the main experimental setup is shown in Fig. 1. The setup included a test tank, a turbulence generator, a motor and a membrane module. The test tank was made of Persplex with dimensions of 50 cm (L) × 40 cm (W) × 50 cm (H). The turbulence generator had a vibrating perforated plate connected to a DC brushless motor with a crank moving mechanism which can be operated in a range of diverse frequencies and strokes. The details of the perforated plate will be described in the later section of materials and experimental procedures.

During the experiments, several parameters, such as frequency and stroke, were varied to establish a turbulent environment in the test tank. The membrane module was attached onto a holding bracket located above the turbulence generator plate. The position of the module can be shifted within a range of 10–20 cm from the plate, so that the module can be placed under different turbulent conditions. The membrane filtration equipment included a peristaltic pump, a balance, a data logging system and a pressure transducer. The permeate flux was controlled and monitored by a MasterFlex peristaltic pump (Cole-Parmer) with a digital balance (UX6200H, Shimadzu) and the data logging system, while the TMP was measured by a pressure transducer (Precision digital).

2.2. Experimental setup for Particle Image Velocimetry

PIV was used in this study to quantify the turbulence characteristics inside the test tank. It is an optical method to determine the velocity vectors in a two dimensional flow field. The principle of PIV can be found in earlier references (Yeo et al., 2006; Li et al., 2013) in details. Here, a Litron product PIV system was used that included a dual-cavity frequency doubled Q-switched pulsed mini Nd:YAG laser with an energy level of maximum 400 mJ per pulse, and a CCD camera with a resolution of 1008 × 1018 pixels. The corresponding pixel size in the physical image windows was approximately 0.2 mm. Polyamide seeding particles with particle size of 50 μm were chosen as flow field tracers. The seeding density was adjusted to ensure that about 8–10 particles were usually observed within an interrogation area (IA) which was typically taken as 32 × 32 pixels with 25% overlap. The difference in density between the particles and flow should be small to avoid a significant velocity lag. For this purpose, using neutrally buoyant particles i.e. particles with identical density as the fluid would be beneficial (Melling, 1997). In this case, the density of seeding particles was 1030 kg m^{-3} which was very close to water.

To conduct the PIV measurements, a sheet of green light generated by the laser with a wavelength of 532 nm was illuminated onto the flow field in a double-pulse manner (the typical time interval between the double pulses was 2 ms). The images were then taken by the CCD camera perpendicular to the light sheet with the frequency at 5 Hz. The typical sampling duration was 140 s, i.e., a total of 700 double-pulsed images were taken for data processing. This duration was previously shown to be adequate for the statistical analysis of the turbulence fluctuations for grid-generated turbulence (Cheng and Law, 2001). To determine the instantaneous PIV vector maps, we conducted the cross-correlation analysis using the Dantec Dynamic Studio software with range and moving average validations. Subsequently, the time average of the experimental results was used for the analysis of the turbulence effect on membrane filtration performance in this study. Using