Journal of Membrane Science 455 (2014) 83–91

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Submerged hollow fibre membrane filtration with transverse and longitudinal vibrations

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ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form
24 October 2013
Accepted 16 December 2013
Available online 25 December 2013

Keywords:
Transverse vibration
Longitudinal vibration
Fibre looseness
Packing density
Vibration relaxation

ABSTRACT

A comparative study of transverse and longitudinal vibrations of submerged hollow fibre membranes for fouling control was carried out in this paper. The same membrane module was adopted in the comparison, and the reactor geometry was identical. The orientation between the vibration and membrane fibre directions was the only difference between the two. The feed suspensions included both inorganic Bentonite and organic yeast suspensions. The results showed that transverse vibrations were generally more effective in terms of fouling reduction even at a very low vibration frequency of 1 Hz, which may be attributed to the separating boundary layers and the associated secondary flows around the cylindrical membrane fibres. The difference between the two orientations was very substantial in Bentonite suspensions, but less so in yeast suspensions due to the main membrane foulants of cell debris in the yeast components which caused the pore blockage of the membrane. A small degree of fibre looseness was found to further improve membrane performance with transverse vibrations in both Bentonite and yeast suspensions due to additional lateral fibre movement. The effect of packing density of the membrane bundle in transverse vibrations was also examined. The results showed that at larger vibration amplitudes, a high packing density of fibres can be operated with little membrane fouling, which indicated that the secondary flow generated could overcome the strong permeate flux competition within the bundle under vibrations. Finally, vibration relaxation was tested experimentally in half-on/off switching mode with the energy reduction due directly to the 50% stoppage. The results showed that a short relaxation time interval was generally more favourable for fouling reduction.

1. Introduction

Submerged hollow fibre membranes are now widely used in water and wastewater treatment processes owing to their cost effectiveness and relatively large packing density which can produce high quality effluent with smaller reactor footprints. However, their application is still hindered by issues associated with concentration polarization and membrane fouling. At present, air sparging, with shear stresses generated by the rising bubbles on the membrane surface to sweep away the foulants deposit, is commonly used for fouling mitigation in membrane filtration processes. However, the flux improvement by air sparging can be limited [1] and its energy consumption can be as high as 70% of the total cost [2,3]. Hence, alternative techniques that offer the potential of better efficiencies continue to be explored. Among these techniques are turbulence promoters, Couette motion, pulsations, and vibrations [4]. Turbulence in the reactor can reduce membrane fouling, as it can generate rotational or swirling secondary flows that increase the shear stresses on the membrane, thus enhancing the scouring of the membrane surface [5]. The Couette motion [6,7] and pulsations [8,9] have been used mainly in biotechnological and medical areas.

The present study focuses on the use of membrane vibrations as a fouling control technique for submerged hollow fibre membranes. During vibration, shear stress is generated on the membrane surface by the relative motion between the membranes and liquid, thus the concentration polarization and membrane fouling can be alleviated. The concept of Vibratory Shear Enhanced Process (VSEP) was first presented by Armando et al. in 1992 [10]. It used the torsional vibration of a stack of circular polymer membranes at their resonant frequencies of around 60 Hz, which produced a shear rate at the membrane–liquid interface of about 150,000 s^{-1} to treat a feed suspension containing high solid concentrations. The high shear rate generated was about ten times that obtainable in the typical cross-flow membrane systems, and was effective for foulant removal.

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0376-7388/$ - see front matter
http://dx.doi.org/10.1016/j.memsci.2013.12.042

Postlethwaite et al. [11] studied the flux characteristics of a vibrating microfiltration membrane system at a high biomass loading for protein recovery with a model biological feed stream containing 200–500 g/L *Saccharomyces cerevisae* wet weight and 0.75 g/L bovine serum albumin (BSA). The results showed that the generated shear rate was effective for fouling reduction and can be increased as the amplitude and frequency increased. They also showed that the vibrating system was able to handle broths with high solid loads, thus demonstrating the practicality for industrial applications. Similar results were also obtained by Low et al. [12] for the treatment of fine carbon-loaded wastewater using VSEP. Beier et al. [13] carried out experiments with a vibrating hollow fibre membrane module using yeast suspensions. They confirmed that higher critical fluxes could be achieved through higher vibration frequencies and amplitudes, and the critical flux improved 325% at the maximum vibration frequency and amplitude compared to that at the minimum frequency and amplitude. Recently, Bilad et al. [14] also confirmed the clear advantages of vibrations over conventional aeration process using vibration frequencies of up to 60 Hz for magnetically induced vibration in a submerged membrane bioreactor for treating synthetic wastewater.

The vibration of hollow fibre membranes can be done longitudinally (i.e. along the fibre length) or transversely (i.e. perpendicular to the fibre length). Low et al. [15] rotated the vertical fibres and observed that transverse vibration was less effective because of the unequalled shear forces on the membrane bundle compared with longitudinal vibration. On the other hand, by moving vertical hollow fibres horizontally, Kola et al. [16] observed that the transverse vibration can perform effectively for alginate, yeast, Bentonite, as well as anaerobic mixed-feed suspensions. They suggested that transverse vibration produces more effective shear stress by providing a more disruptive flow regime, which has the potential to induce boundary-layer separations and minimize membrane fouling. Genkin et al. [17] evaluated the effect of longitudinal vibrations over the range 0–10 Hz frequency and 20 mm amplitude and also with coagulant addition on the filtration performance of submerged hollow fibre membranes. Their results showed that at the vibration frequency of 1.7 Hz, the critical flux increased from 17 to 46 LMH with the coagulant addition of 34 mg/L Aluminium Chlorhydrate (ACH). With combined longitudinal and transverse vibrations, a fivefold enhancement in critical flux to 86 LMH was also achieved at 1.7 Hz with the same concentration of ACH addition. They attributed the effect of coagulation to the aggregation of fine particles and evacuation of aggregates away from the membrane surface due to inertial and gravitational forces.

As discussed above, there have been contradictory reports on the relative merits of longitudinal and transverse vibrations for membrane fouling mitigation. The objective of the present study is to further examine the effectiveness of vibration towards membrane fouling control, and to provide a direct quantitative comparison between the two vibration modes. In addition, the vibratory parameters for optimal fouling mitigation in submerged hollow fibre membranes are also further investigated. The parametric scope of our study is wider than the that of previous studies of Low et al. [15], Kola et al. [16] and Genkin et al. [17]. Various combinations of feed characteristics, fibre orientations, looseness, fibre spacing and packing density, as well as vibration relaxation were examined in a series of comprehensive laboratory experiments. The results will be discussed in details in the following after the description of the experimental setup and procedures.

2. Vibration setup

A schematic diagram of the vibration setup is shown in Fig. 1. The setup included the vibration mechanism and the permeate measurement equipment. The test tank was made of Persplex with sizes of 600 mm $(L) \times 500$ mm $(W) \times 600$ mm (H). During the experiments, a small background air bubbling (50 mL/min) was maintained in the tank to keep the feed particles suspended in the reactor. Longitudinal or transverse vibrations were achieved by positioning the fibres vertically or horizontally, respectively. The centre positions of the vertical and horizontal fibres were identical. The membrane module holder was driven by a brushless DC motor (BXM 6200-A, Oriental Motor Co., Ltd.) with a crank moving mechanism. The vibration amplitude could be manually adjusted from 0 to 28 mm at 4 mm intervals, while the vibration frequency could be varied from 0 to 10 Hz. The permeate flow was controlled by a master flex peristaltic pump (Cole-Parmer Instrument Company) together with a needle valve (Swagelok). The suction pressure was measured with a pressure transducer (Precision digital), and the permeate flux with a digital balance (UX 6200H, Shimadzu).

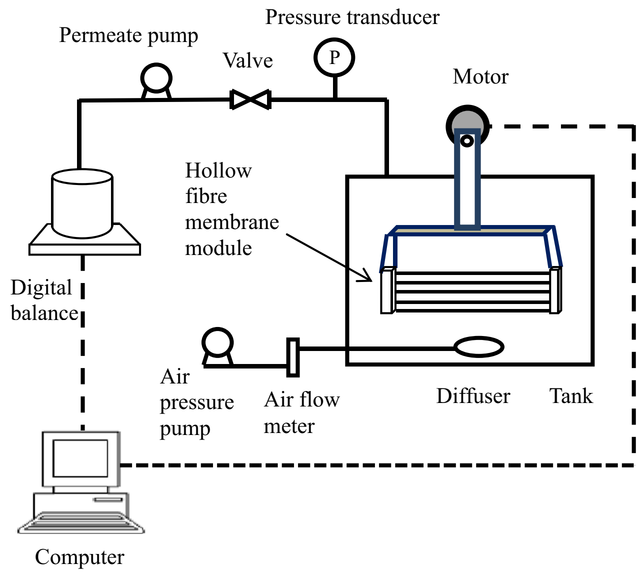

Fig. 1. Schematic diagram of vibration setup.

3. Materials and operating procedures

3.1. Hollow fibres

Polyacrylonitrile (PAN) hollow fibres made by Ultrapure Pte Ltd. in Singapore with inner/outer diameters of 1 mm/1.7 mm and nominal pore size of 0.1 μm were used in the experiments. They were aligned in parallel with both ends fixed to the C shape holding frame using Araldite epoxy. The length of the rod connecting to the motor determined the submergence of the hollow fibres.

3.2. Preparation of feed suspensions

In this study, two kinds of feed suspensions, the inorganic Bentonite (Sigma-Aldrich) and organic dry yeast (Levure Sèche de Boulanger, France) were mixed with tap water as the feed suspensions. They represented the inorganic and organic feeds, respectively. Their characteristics are described in the following.

3.2.1. Bentonite suspension

The formula of Bentonite is $H_2Al_2O_6Si$, with the molecular weight of 180.1 g/mol. The average particle diameter was 5.83 μm with a relative density of 2.4 g/cm^3. The Bentonite particles were first added to tap water and mixed with a magnetic stirrer at 300 rpm