



Fouling of submerged hollow fiber membrane filtration in turbulence: Statistical dependence and cost-benefit analysis



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ABSTRACT

In the present study, we expanded the scope to a full range of turbulence conditions with a total of 79 experiments, to establish the statistical dependence between the energy consumption due to turbulence dissipation and improved productivity with reduced membrane fouling so that the cost-benefit tradeoff can be evaluated. The turbulence was generated by vibrating perforated plates. Increasing vibration frequency/stroke or solidity of the perforated plate resulted in more intense turbulence inside the reactor, and that the eddy length scale increased with solidity in general. Hollow fiber membrane filtration experiments were then performed within the turbulence ambient in both inorganic Bentonite and organic yeast suspensions. The variance analysis of the results further confirmed the link between the membrane fouling rate and both turbulence kinetic energy and eddy length scale and their cross interactions, as well as that an optimum eddy length scale existed beyond which its influence diminished. Higher TKE induced more fouling reduction, but it also required larger power consumption. A cost-benefit analysis of membrane fouling in turbulence is then presented for evaluation of the tradeoff between membrane filtration performance and power consumption. Finally, the effect of turbulence on membrane filtration performance was also examined in conjunction with the fiber bundle characteristics of the membrane module. An optimized fiber spacing and fiber looseness were identified that consistently performed the best in all experiments, allowing the fluctuating turbulence eddies to penetrate and mobilize the fibers in the most efficient manner against fouling.

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1. Introduction

At present, membrane filtration has a significant overall market share of ~15% in the water treatment industry [1]. Various types of membranes, such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF), are used in different filtering operations [2]. Among them, hollow fiber (HF) membranes are used extensively due to their distinct advantages of better flexibility and higher surface to volume ratio [3,4].

The most prominent issues associated with membrane applications, and HFs in particular, are fouling and concentration polarization [5]. Currently, the method for fouling control primarily utilizes shear stress generation by the relative motion between the surrounding fluid and membranes [6,7]. To achieve this, various techniques have been proposed in the literature, such as crossflow [8,9], air sparging [10,11], pulsation [12,13] and membrane

vibration [14]. With crossflow and air sparging, the shear stress is generated by moving the fluid surrounding the membrane surface. The action typically produces a turbulent environment inside the reactor at the same time, which is also generally favored in membrane filtration due to the enhancement in mass transfer [15]. Alternatively, in membrane vibration, the membrane moves actively instead relative to the surrounding fluid. This relative motion also produces shear stresses on the membrane surface which reduces membrane fouling. The crossflow velocity [16,17], aeration intensity [18,19] and operating characteristics of membrane vibration [20] are important factors that govern the effectiveness among these methods.

A higher crossflow velocity or aeration rate typically intensifies the shear stress on the membrane surface as well as the turbulence in the reactor [21]. Other means of augmentation have also been implemented to further increase the turbulence intensity, such as using turbulence promoters in crossflows [22,23]. Krstić et al. observed that the use of static mixer improved the permeate flux by more than 700% [24]. At the same time, the flux enhancement was also associated with a great increase in energy consumption, which would be undesirable since high operational

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costs hinder the membrane usage [25]. Thus, although the positive influence of turbulence on membrane filtration has been generally confirmed in the literature both in terms of fouling prevention and mass transfer improvement, the statistical dependence between the two is yet to be quantified sufficiently for cost-benefit evaluation. To our knowledge, only a limited number of attempts have been made so far to decipher the underlying effect of turbulence on membrane filtration [26,27]. In particular, Pourbozorg et al. developed a unique laboratory reactor with turbulence ambient but without the presence of mean flows to examine membrane fouling in shear-free turbulence, and presented indicative results [27].

In HF membrane filtration, fiber spacing (FS) and fiber looseness are also important factors for optimizing performance. Postlethwaite et al. [28] illustrated that a larger spacing among HF membranes in a membrane module can enhance the permeate flux. Li et al. also investigated the impact of fiber spacing on fouling performance with membrane vibration, and found that reducing the fiber spacing had an adverse impact on the fouling [20]. In commercial applications, Mahendran et al. suggested a range of 1–5% for fiber looseness [29]. The effect of fiber looseness had been studied in conjunction with fouling control mechanisms such as aeration [7,30] and membrane vibration [20,31]. These studies generally pointed out that an increase in fiber looseness would be advantageous due to the fiber movement as well as shear enhancement. However, the influence of fiber bundle characteristics of fiber spacing and fiber looseness on the effect of turbulence in submerged membrane filtration has not been studied before.

In Pourbozorg et al. [27], the effect of shear-free turbulence on the fouling control of submerged hollow fiber membrane filtration was investigated in a laboratory reactor. Quantitative details were reported from 15 experiments of dead-end filtration of organic yeast suspensions, linking the fouling rate to the turbulence kinetic energy (K) and eddy size (L) in a quantitative manner for the first time in literature. The current study focuses on establishing in a comprehensive manner the relationship between membrane fouling and turbulence characteristics, by performing extensive experiments in the same setup as Pourbozorg et al. [27]. A total of 79 experiments with a wide range of turbulence characteristics were performed for this objective, and the turbulence kinetic energy and integral length scale were measured using the non-intrusive Particle Image Velocimetry (PIV) approach. The full set of data enabled the determination of the statistical relationships and cost-benefit evaluation. In addition, since the fouling rate is also highly dependent on the operating characteristics of the hollow fiber membrane module [32], we included the examination of the effect of fiber spacing and fiber looseness in this study. In the following, the experimental setup and methods are first described briefly. The experimental results are then discussed in details.

2. Experimental setup and operating procedures

2.1. Experimental setup

The experimental setup was adopted from our recent study of Pourbozorg et al. [27] with a schematic diagram shown in Fig. 1. Here, only the essential details are given for brevity. The test tank was made of Perspex with dimensions of 500 mm (length) $\times$ 400 mm (width) $\times$ 500 mm (height). The membrane filtration system comprised of an automated control, HF membrane modules, digital balance, pressure transducer, and permeate pump. The automated control was used to monitor the permeate flux and record the transmembrane pressure data. The HF membrane module consisted of sixteen (in 4×4 pattern) Polyacrylonitrile

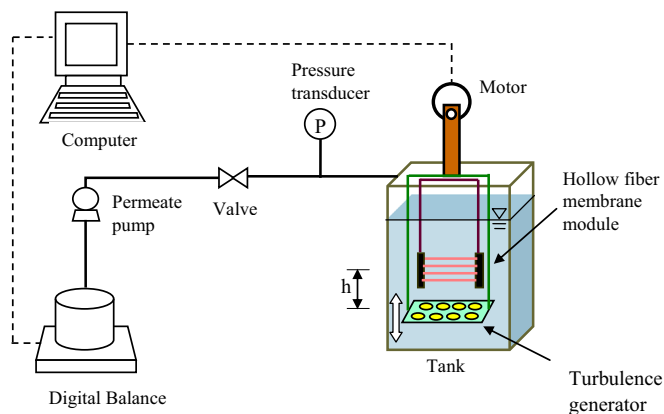


Fig. 1. Schematic diagram of experimental setup (from [27]).

(PAN) fibers (product of Ultrapure Pte Ltd. in Singapore) with inner/outer diameters of 1.0/1.7 mm and length of 30 cm. It was submerged into the tank using a holding bracket that can adjust the module's position. The fibers were placed in the horizontal orientation so that membrane filtration can be carried out uniformly across the length of the hollow fibers without the effect of the gravity, and subjected to the uniform turbulence generated parallel to the grid. The permeate was extracted with a peristaltic pump (Masterflex product), and a digital balance (UX6200H, Shimadzu) recorded the weight of the permeate at a specific short time interval which was then converted to the membrane flux (held constant at $15 \pm 1\%$ L/(m² h) in all the experiments). Electronic pressure transducers (Precision Digital) were installed to measure the real time pressure data during the membrane filtration. A total of five turbulence generators were used in this study, with details described in the next section of materials. The vibration of the turbulence generators was driven by a DC motor in a sinusoidal manner with a crank moving mechanism. The vertical distance between the generator and the center of HF membrane module is indicated as h in Fig. 1. The vibration stroke (S) could be manually adjusted from 4 to 16 mm, while the vibration frequency (f) could be varied from 1 to 5 Hz to induce different turbulence intensities inside the reactor.

2.2. Materials

2.2.1. Bentonite and yeast

In this study, the feed included both the inorganic Bentonite and organic yeast suspensions. The Bentonite (Sigma-Aldrich) particles and yeast (saf-instant, Levure Seche de Boulanger, France) were the same as those used in Li et al. [20], with nominal particle sizes of 5.83 μ m and 4.95 μ m, respectively. They were chosen for their availability and widespread usage in microfiltration. In addition, both can form a cake layer on the membrane surface, and their sizes are within the range of shear induced diffusion.

2.2.2. Turbulence generators

The turbulence generators were made of Polyvinyl Chloride (PVC) perforated plates. They had the same plate area (A_t) of 29 cm $\times$ 17 cm but different numbers of square shaped voids of 1 cm $\times$ 1 cm (details listed in Table 1) to make solidities (S_r) of 18%, 30%, 40%, 50% and 60%, respectively, with S_r defined as:

$$S_r = \frac{A_s}{A_t} \quad (1)$$

where A_s is the total solid area. It is expected that higher solidities would generate more intense turbulence inside the reactor.

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