Journal of Membrane Science 456 (2014) 77–84

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Influence of dissolved air on the effectiveness of cyclic backwashing in submerged membrane systems

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ARTICLE INFO

Article history:
Received 4 June 2013
Received in revised form
20 December 2013
Accepted 20 December 2013
Available online 3 January 2014

Keywords:
Submerged membranes
Hollow fibers
Fouling
Backwashing
Mathematical modeling

ABSTRACT

Backwashing of submerged hollow fiber membranes has been observed to have an unstable impact on the recovery of the membrane permeability. Modeling and experimental results in this study show that the effectiveness of fixed backwash cycles can decrease over time and reach a point at which the backwash effectiveness suddenly decreases. Evidence from transmembrane pressure (TMP) monitoring suggests that the sudden decrease in backwash efficiency occurs when the pressure on the permeate side of the membrane at the end of a backwash cycle does not reach the atmospheric pressure maintained on the feed side. The release of dissolved air on the permeate side of the membrane due to the pressure drop across the membrane was recognized as a major reason for reducing backwash effectiveness. The mathematical model predicts that the minimum backwash duration required to reverse the flow through the membrane by increasing the permeate-side pressure up to atmospheric pressure depends on the pressure at the beginning of the backwash, backwash flow rate, amount of air on the permeate side, membrane surface area, water viscosity, temperature, and the membrane and fouling resistances. These findings have implications for the design and operation of submerged membranes with backwash.

1. Introduction

Submerged membranes are an assembly of membranes positioned in a feed water tank at atmospheric pressure. The liquid to be filtered is fed to the tank and the permeate is removed under suction, either by a pump or by gravity; this insures a low transmembrane pressure (TMP). Retentate is removed continuously or intermittently from the tank and bubbling is applied to produce surface shear [1]. Two types of membranes that are generally used in submerged modules are flat sheets (FS) and hollow fibers (HF). Submerged flat-sheet modules are principally used for high solids content membrane bioreactor (MBR) applications. However, submerged hollow fibers are used for both low solids content feed, such as water treatment, and high solids contents, such as MBRs. The major advantages of hollow fiber membrane modules over other configurations are cost effectiveness, greater packing density, and the feasibility of backwashing [2,3].

Membrane fouling has been the most severe problem and barrier to the increased use of microfiltration (MF) and ultrafiltration (UF) membrane technologies [4,5]. The degree of fouling in submerged membrane systems is a complex function of feed characteristics, membrane properties and operating conditions [6–8]. Inadequate management of the hydrodynamics and unsuitable membrane properties are factors that aggravate membrane fouling [9,10].

Fouling control strategies are required to avoid a decline in membrane permeation due to severe membrane fouling in submerged hollow fiber systems [11–13]. It is possible to minimize fouling by both choosing a suitable membrane material that adsorbs less substances from the feed and by optimizing the operating conditions in the system [14–17].

Backwashing has been incorporated in most hollow fiber filtration systems as one of the standard operating strategies to mitigate fouling. Backwashing is a physical cleaning technique that can facilitate efficient membrane permeation recovery [18]. Backwashing is believed to loosen and detach the fouling cake from the membrane surface that then can easily be removed by crossflow or air bubbles. However, the cake layer might serve as a secondary layer to protect the membrane from internal fouling by macromolecular components. Thus, frequent backwashing can provide a means for macromolecular components to enter the membrane pores [19]. Ye et al. [20] observed a transition from a mixed cake layer of particulates and

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http://dx.doi.org/10.1016/j.memsci.2013.12.053

macromolecules at the beginning of their experiments to a fouling structure dominated by macromolecular components after several filtration/backwashing cycles. The results of a study with seawater showed that cyclic cleaning can reorganize the foulant structure and change subsequent fouling patterns [21,22].

Filtration duration, backwash duration, and backwash flow rate are important parameters that influence the mitigation of membrane fouling in submerged hollow fiber membrane modules. Chua et al. [23] investigated the effect of backwash duration on the membrane fouling of a pilot-scale pressurized hollow fiber membrane module. Prolonged backwash duration was found to be more effective than increasing the air-scouring duration in controlling membrane plugging. Studies by Ye et al. [21] showed that the final TMP and fouling rate decreased by more than 50% with an increase in the backwash duration from 10 to 30 s, while no obvious improvement was observed for any further increase of the backwash duration. An increase in the backwash duration up to 30 s resulted in a slight increase in the percentage of fouling removed. However, it dropped slightly after further increase in the backwash duration. This indicates that an excessive volume of backwash might cause membrane fouling due to residuals in the permeate or a change in the structure of the fouling cake due to the impurities in it.

The effect of the backwash flow rate on membrane fouling limitation for real seawater filtration was investigated with other conditions kept constant by Ye et al. [21]. They observed the lowest final TMP after 16 h of filtration when the backwash flux was 1.5 times the filtration flux. A further increase in the backwash flux to twice the filtration flux was found to increase the final TMP. This implies that the backwashing changes the fouling rate during the filtration cycle. Similarly, the percentage of fouling removed by backwashing increased slightly to a maximum at a backwash flux of 1.5 times the filtration flux and it dropped slightly when the backwash flux was twice that of the filtration flux. These studies indicated that there is an optimum backwash flux to mitigate fouling. As was found for excessive backwash duration, an excessive backwash flux can cause convection of permeate-side impurities to the membrane pores or residual fouling layer that results in irreversible fouling and a higher fouling rate. The existence of an optimum backwash flux in mitigating fouling was also reported by Chua et al. [23]. They found that an increase of backwash flow rate up to twice that of the permeate results in some process improvement; however, no further benefits were observed for any further increase in the backwash flow rate.

The release of dissolved air in the feed owing to the TMP and its accumulation on the permeate side of submerged membrane modules have been reported in prior studies [24,25]. This accumulation of air on the permeate side is thought to be the major reason for the observed unstable response to backwashing. The specific objectives of this study were the following: (1) to study the effect of dissolved air on the effectiveness of backwashing; (2) to develop a model that incorporates the effect of dissolved air on the backwashing; and (3) to obtain experimental corroboration of the model predictions.

2. Model development for the effect of trapped air

The model developed here applies to ultrafiltration run in the continuous dead-end mode to remove micro-particulates from a feed tank maintained at atmospheric pressure P_{atm} into which a bundle of hollow fiber membranes are submerged; the permeate is removed by maintaining a vacuum on the lumen side. Periodic backwashing is used to mitigate membrane fouling. However, air released owing to the TMP as well as air trapped in the system prior to startup can accumulate on the permeate side of the system. For backwashing to occur, the permeate-side pressure has to exceed the feed-side pressure. The compressibility of the air accumulated on the permeate side delays attaining sufficient pressure for backwashing. The focus of the model development is to interrelate the time required to achieve effective backwashing with the relevant system parameters.

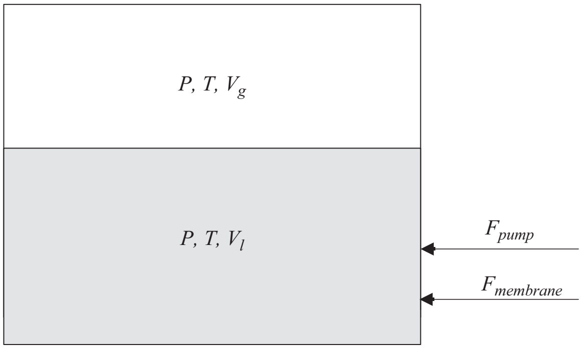

Fig. 1. A schematic of the control volume; V_g and V_l show the volume of gas and volume of liquid in the permeate side of the membrane, respectively.

Fig. 1 shows a schematic of the control volume V_t considered in the model development. This control volume consists of the entire volume connected to the permeate-side of the membrane that includes the lumen volume of the hollow fibers, piping volume, and pulsation dampener if any. This control volume consists of a volume of liquid V_l and a volume of air V_g that results from the air trapped initially at startup as well as the release of air from the permeating liquid owing to the TMP. Upon initiating backwashing more liquid enters the control volume at a volumetric flow rate F_{pump}. Liquid also enters the control volume at a volumetric flow rate $F_{membrane}$ owing to permeation caused by the lumen pressure initially being less than the pressure on the feed side. The pressure P in the control volume is determined by the number of moles of trapped air n, the prevailing temperature T, and the instantaneous air volume, which decreases owing to the inflow of liquid. Backwashing cannot begin until the pressure in the control volume exceeds P_{atm}, the pressure maintained on the feed side. The hypothesis advanced here is that the duration of the backwash cycle must exceed the time predicted by the model for the pressure in the control volume to reach P_{atm}.

The control volume V_t in Fig. 1 is equal to sum of the liquid and the air volumes:

$$V_t = V_l + V_g \tag{1}$$

For the low pressures of interest here the pressure, volume, temperature and number of moles of air are interrelated by the Ideal Gas Law:

$$PV_g = nRT \tag{2}$$

where R is the gas constant. Differentiating Eq. (2) with respect to the time t:

$$P\frac{dV_g}{dt} + V_g\frac{dP}{dt} = 0 \tag{3}$$

If it is assumed that the tubing walls are rigid, water is incompressible, the fouling layer resistance is constant before initiating backwashing, and the change in the volume of the system components on the permeate side due to a change in the pressure is negligible, the time rate-of-change of the gas volume after backwashing is initiated is equal to the total flow rate of liquid into the permeate side, which is equal to the sum of that due to the backwash pump and that due to the permeation because of