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Evaluation of fouling deposition, fouling reversibility and energy consumption of submerged hollow fiber membrane systems with periodic backwash

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ABSTRACT

The filtration behavior and energy consumption of submerged hollow fiber membranes were investigated in a dead-end mode under constant flux operation with periodic backwash. Various operating parameters such as filtration flux, feed concentration, backwash duration, backwash strength, and the aid of air scouring during backwash were investigated to optimize the filtration performance and energy consumption. Baker's yeast was used as the model foulant. The transmembrane pressure (TMP) profiles obtained with this model foulant indicated the existence of two regions: a low fouling region followed by a high fouling region. In the low fouling region, periodic backwash could effectively remove the fouling layer. The percentage of reversible fouling by backwash was significantly lower in the second region which led to a rapid increase in TMP. The Taguchi experimental design method was used to determine the critical parameters, the effect of individual parameters and the optimum conditions. Since the transition into the second region of filtration is not favorable, the fouling rate in the first 10 cycles, the net permeate volume and specific energy consumption at the end of the first region were chosen as the design method responses. The results showed that filtration flux and feed concentration have significant effects on the membrane fouling rate. In order to maximize the net permeate volume, filtration flux, backwash duration and backwash strength were found to be the most important parameters, which must be carefully selected. To minimize the specific energy consumption, filtration flux, backwash duration and aeration rate during backwash were the most important factors.

1. Introduction

Low-pressure membrane systems, including microfiltration (MF) and ultrafiltration (UF) membranes have become a common technology for drinking water treatment. The application of submerged membrane systems have become increasingly popular in surface water treatment, wastewater recovery for indirect potable reuse and pre-treatment of reverse osmosis (RO) processes because of the lower energy consumption and the higher permeate quality. Submerged hollow fiber membranes with greater packing density and the feasibility of backwashing have been widely used [1–4].

Membrane fouling has been the most severe problem and barrier to the increased use of MF and UF membrane technologies [5,6]. The degree of fouling in submerged membrane systems is a complex function of feed characteristics, membrane properties and operating conditions [7–9]. Inadequate hydrodynamic management and unsuitable membrane properties are factors that encourage or exacerbate membrane fouling [10,11].

Fouling control strategies are required to avoid decline in permeability due to severe membrane fouling in submerged hollow fiber systems [12–14]. It is possible to minimize fouling by both choosing a suitable membrane material with less adsorption of substances in the feed water and optimizing the operating conditions in the system [15–18]. Two types of fouling phenomena are distinguished for microfiltration and ultrafiltration. The first type is known as filtration-induced macrosolute or particle deposition, which occurs as external fouling or cake formation on the top surface of the membrane. This fouling is caused by

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particles that are larger than the membrane pores, and is often reversible and nonadhesive [12].The second, which can occur with or without filtration, is macrosolute (e.g., humic substances, proteins, etc.) or particle adsorption onto the membrane or into the membrane pores [19,20]. This attachment depends on the specific intermolecular interactions between the particles and the membrane. This type of fouling is usually irreversible and adhesive [21–23].

Application of backwashing (reversal of permeate flow through the pores) with air scouring during backwash is a common physical approach to remove fouling in submerged systems [24]. Backwash is believed to loosen and detach the fouling cake from the membrane surface that can easily be removed by crossflow or air bubbles. However in some cases the cake layer might serve as a secondary layer to protect the membrane from internal fouling by macromolecular components. Thus, frequent backwash could provide additional opportunities for macromolecules to enter the membrane pores [25]. Ye et al. [26] observed a transition from a mixed cake layer of particulates and macromolecules at the beginning of the experiment to a fouling structure dominated by the macromolecules after some filtration/cleaning cycles. The results of a study with sea water showed that cyclical cleaning can reorganize the foulant structures and change subsequent fouling patterns [27]. The first few cycles showed more significant irreversible fouling than the following cycles while the percentage of irreversible fouling became constant after some cycles. The reason is that there is more chance of pore blocking for the new membrane than the used membrane. Thus pore blocking can be the most dominant fouling mechanism in the first few cycles [27,28].

Filtration duration, backwash duration, and backwash flow rate are important parameters in the fouling of submerged hollow fiber membranes. Ye et al. [27] investigated the effect of filtration duration (from 1200 to 5400 s per cycle) on membrane fouling of real seawater filtration while other operation parameters were kept constant. It was found that the final TMP after 16 h filtration and the percentage of reversible fouling which can be removed by backwash did not increase when filtration duration increased from 1200 to 3600 s. Further increase in filtration duration (from 3600 to 5400 s) promoted membrane fouling due to formation of a more compact cake layer which was more irreversible.

Chua et al. [29] investigated the effect of backwash duration, on the membrane fouling of a pilot pressurized hollow fiber membrane module. Prolonged backwash duration was found to be more effective than increasing air scouring duration in controlling membrane plugging. Studies by Ye et al. [27] showed that the final TMP and fouling rate decreased by more than 50% with the increase of backwash duration from 10 to 30 s while no obvious improvement was observed for further increase of backwash duration. Also, the increase of backwash duration up to 30 s resulted in a slight increase in the percentage of fouling removed by backwash. However it dropped slightly after further increase in backwash duration. This indicates that excess backwash volume might also cause membrane blockage or change the structure of the fouling cake due to residual impurities in the backwash fluid.

The effect of backwash flowrate on the membrane fouling limitation for real seawater filtration was investigated with other conditions kept constant by Ye et al. [27]. They observed the lowest final TMP after 16 h of filtration in the case where the backwash flux was 1.5 times the filtration flux. Further increase in backwash flux to twice the filtration flux was found to increase the final TMP. This implies that backwash changes the fouling rate during the filtration cycle. Similarly, the percentage of fouling removed by backwash increased slightly to a maximum for a backwash flux of 1.5 times the filtration flux and dropped slightly when the backwash flux was twice that of the filtration flux. These results indicate the existence of an optimum backwash flux in fouling limitation. Similar to excessive backwash duration, it seems that excessive backwash flux also causes convection of impurities from the permeate side to membrane pores or the residual fouling layer which results in less reversible fouling and higher fouling rate. The existence of an optimum backwash flux in fouling limitation was also reported by Chua et al. [29]. They found that an increase of backwash flow rate up to twice that of the permeate flow rate resulted in process improvement, but no further benefit was observed for further increase in the backwash flow rate. Overall, an increased backwash flux was found to be slightly more effective than increased backwash duration when the same amount of backwash volume was being used [27,30].

It has been reported in studies that air scouring during backwash can assist fouling removal and improve backwash efficiency [31,32]. While the backwash is expected to detach the cake layer from the fiber, air scouring removes the loosened deposits away from the membrane surface [31,32]. The effect of aeration during backwash on the membrane fouling during seawater filtration was investigated by Ye at al. [27]. Their results showed that backwash with a moderate air flow rate had a lower final TMP and slowed down the fouling rate more effectively than a high air flow rate. In other words, high air flow rate actually limited the benefit of air scouring and did not improve reversibility. This unexpected high fouling rate observed in the high air flow rate was attributed to the bubble shape difference (slugs vs. small bubbles) at different air flow rates.

The Taguchi method is a fractional factorial type of method for designing experiments. This method involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Unlike the factorial design methods that test all possible combinations, the Taguchi method tests several pairs of combinations and collect the necessary data to determine the effect of each parameter and the most influential parameters.

The aim of this study was to investigate the filtration behavior and energy consumption of submerged hollow fiber membranes over an extended period of time in dead-end mode under constant flux operation with periodic backwash. Previous studies, point to the importance of several factors that may interact. Therefore in this work the Taguchi experimental design method was used to determine the critical parameters, the contribution of individual parameters and their interactions and the optimum conditions [33,34]. The operating parameters studied were filtration flux, feed concentration, backwash duration, backwash strength, and the aid of air scouring during backwash in order to optimize the filtration performance and energy consumption.

2. Materials and methods

2.1. Equipment setup

The experiments were performed using a bench scale submerged hollow fiber membrane system. A schematic diagram of the submerged hollow fiber unit is shown in Fig. 1. The membrane bundle comprised seven fibers of 15 cm length. The membrane bundle was immersed in a Plexiglas tank with 10 cm width, 30 cm length and 40 cm height. The bottom end of the hollow fibers bundle was sealed and permeate was extracted from the upper part of the bundle. The amount of permeate withdrawn was controlled by a peristaltic pump (Cole-Parmer, model 07523-80) which was used for suction of permeate and also backwashing of hollow fibers. At the same time, the same amount of permeate was fed into the tank to maintain a constant feed concentration by the peristaltic pump B (Cole-Parmer, model 07523-80). Permeate was