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Comparative analysis of physical cleaning operations for fouling control of hollow fiber membranes in drinking water treatment

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ABSTRACT

The combined effect of air scouring, backwashing and relaxation on the fouling reduction of a hollow fiber PVDF ultrafiltration membrane was investigated using factorial designs of experiments. The investigation was carried out to test and compare the efficiency of three physical cleaning operational regimes, specially: air scour, backwashing, and relaxation. Beneficial dependencies between the operations for fouling reduction were identified and examined in this study.

The use of a three operation regime under continuous flow conditions was found to be more effective for fouling reduction compared air assisted backwashing and air assisted relaxation with fouling reductions 2.5 and 3 times lower, respectively. While the use of a short backwash duration showed negligible impact on fouling reduction, a longer backwash duration was found to work in synergy with a high air flow rate and a short relaxation duration for the reduction of fouling. The use of a regime involving long backwash duration (20 s), short relaxation duration (5 min.) and high air flow rate (15 LPM) was identified as the optimal regime for fouling reduction while minimizing permeate production losses due to backwash and relaxation operations in this study.

1. Introduction

Advancements in membrane technology over the past decade have led to the emergence of hollow fiber membrane ultrafiltration as a sound alternative to conventional methods of drinking water treatment [1,2]. The use of ultrafiltration (UF) in the production of drinking water has shown great promise due to its ability to remove contaminants such as turbidity, organic matter and pathogenic organisms (protozoa, bacteria and some viruses) from source waters [1–3].

While the removal of these contaminants ensures a higher quality of drinking water, studies have identified turbidity causing particles and natural organic matter (NOM) in source waters as key contributors to the phenomenon of membrane fouling [3,4]. Fouling occurs due to the clogging of membrane pores and/or the buildup of a cake layer on the membrane surface. This fouling results in an increase in the transmembrane pressure (TMP) with a corresponding decrease in membrane productivity either through increased energy requirements or an associated decrease in permeate output [5]. Consequently, fouling is highly unfavourable and continues to be a major focus of membrane research.

Membrane fouling is controlled in two main ways: pretreatment techniques such as coagulation, filtration, and microstraining [3,6] or through membrane cleaning operations. Cleaning operations are categorized into physical and chemical cleaning operations and target different levels and types of fouling. Physical cleaning operations are used to target fouling which is easily removed from the membrane surface and pores and employ physical processes like backwashing, air scouring and relaxation to remove foulants off the membrane surface [7,8]. Chemical cleaning targets fouling that have a strong adhesion to the membrane surface or in the membrane pores and makes use of various chemicals (acids and alkalis) [3,6,7,9]. Both types of membrane cleaning are aimed at recovering membrane permeability. Physical cleaning slows down the loss of membrane permeability overtime but eventually chemical cleaning is required to restore a greater amount of the initial permeability. Excess use of chemical cleaning is detrimental to the well being of the membrane and can be costly. For instance a study by Wang et al. [10] found that sodium hypochlorite was responsible for weakening the membrane as well as changing membrane properties by removing surface modifications. Studies have also shown that the use of sodium hypochlorite causes an increase in the effective pore size of the membrane [11,12]. Since physical cleaning precedes chemical cleaning, the proper optimization of physical cleaning operations can prove to be beneficial for the purpose of reducing the frequency of chemical cleaning thus lowering costs while maintaining the wellbeing of the membrane.

The physical cleaning operations of backwashing, air scouring and relaxation are fundamental operational strategies incorporated

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into membrane bioreactor designs for the treatment of wastewater [13]. However literature on the application and effects of these operations in membrane filtration for drinking water purposes is sparse. While studies have shown that periodic backwashing is effective in removing the gel/cake foulant layer off the membrane surface and thus reduce fouling [14,15], a recent study by Ye et al. [13] showed that periodic backwashing only loosens foulants while another mechanism is required to actually move the foulants off the surface of membranes. Yigit et al. [16] and Remize et al. [17] showed that backwashing was effective in removing surface fouling when assisted by air scouring which played the major role of pushing the loosened foulants off the membrane surface. While air assisted backwashing has proved helpful in reducing fouling and restoring membrane permeability, Metzger et al. [18] found that the constant removal of the cake layer by air assisted backwashing promoted irreversible fouling via pore blocking due to continuous adsorption of smaller particles on the membrane surface in the absence of a cake layer [15,22]. As such, the efficiency of backwashing as a cleaning operation is dependent on the duration, interval and even strength of the operation [19].

As in the case of backwashing, studies have shown that relaxation is helpful in reducing surface fouling [2,13,19]. Relaxation is where permeate production is halted for brief time intervals versus backwashing where the flow is reversed through the membrane system. While Tian et al. [2] found that relaxation alone removed foulants off the membrane surface; Ye et al. [13] found that air scouring was required to remove surface foulants loosened by relaxation. Ye et al. [13] also found that air assisted relaxation was less effective than air assisted backwashing which contradicted findings by Wu et al.[19].

Previous studies have taken into consideration the effects of combining relaxation and air scouring [13] as well as backwashing and air scouring [12,13] in drinking water treatment. In both cases, air is responsible for moving foulants loosened by relaxation and backwashing away from the membrane surface and thus plays an important role in the physical cleaning of the membrane. The efficiency of air scouring is dependent on the air flow rate as well as the frequency of air flow [2,20]. While continuous air scouring was found to be more efficient at controlling fouling than intermittent air scouring [2], the use of intermittent fouling is more cost effective [21].

Studies examining the effect of all three physical cleaning operations on fouling reduction appear to be limited. In this research, the effects of a physical cleaning regime incorporating air scouring, backwashing and relaxation on the reduction of fouling in a bench scaled hollow fiber ultrafiltration membrane system is investigated. Factorial designs of experiments were employed to investigate the effects of relaxation duration and frequency on fouling reduction as well as to identify benefits of air scouring, backwashing and relaxation in a cleaning regime.

2. Materials and methods

2.1. Experimental apparatus

A ZW-1 hollow fiber ultrafiltration membrane (Zenon/GE, Oakville, Canada) with a nominal pore size of 0.04 μm was used at a flux of 38 LMH (permeate flow of 30 mL/min). The system was operated under vacuum with a pressure range between 0 to −8.7 psi (0 to −0.6 bar); pressure was monitored using a Cole Parmer high accuracy pressure transducer (Model No. EW-68075-02). A schematic of the bench scaled apparatus can be seen in Fig. 1. The air scour rate was set at 5 or 15 standard LPM and was monitored with an AALBORG GFM37 flow meter (0–15 LPM). The air was passed through a filter before passing by the membrane module. Both the pressure transducer data and the air flow-rate data was continuously logged over time using a data logger. The entire set up was built in duplicate. Membranes were chemically cleaned in place between each experiment following manufacture recommended protocols. Membrane permeability was checked at the start of every experiment and membranes were replaced once the initial permeability was at 85% of the original value. The membranes were rinsed with distilled water before being placed back in operation. The membrane system was either operated in dead-end mode (100% recovery of feed flow in permeate stream) or continuous flow mode (80% recovery of feed flow in permeate stream). A system schematic is shown in Fig. 1.

2.2. Feed water

Synthetic surface water was prepared in distilled water with the following conditions: pH of 7–8 (adjusted with sodium hydroxide as necessary); organic carbon comprised of Sigma Aldrich Technical Grade Humic Acid (3 mg/L TOC) and Sigma Aldrich 20 μm cellulose (3 mg/L TOC) intended to mimic a challenging surface water source; kaolin clay was added to the feed water for a final turbidity of 20 NTU. Water hardness was simulated as 150 mg/L $CaCO_3$ to mimic a moderately hard source water, and was comprised of reagent grade sodium bicarbonate (67 mg/L) and calcium sulphate (129 mg/L).

2.3. Experimental design

2.3.1. Relaxation parameter effects

The impacts of relaxation parameters on continuous versus dead-end flow operation were examined with respect to relaxation duration and frequency. The operational conditions can be seen in Table 1. For each experiment, fouling was measured in terms of TMP (mbar) every 15 s during filtration and relaxation periods and at every second during periodic backwashes over a 24 h experimental run. Line 170: Air was supplied continuously in this experiment at 5 LPM. A fixed flux of 38 LMH was used for both filtration and backwash conditions. Relaxation duration and frequency parameters were based on values reported in literature [19,20].

2.3.2. Cleaning operation effects

The effects of air flow rates, backwash durations and relaxation durations on fouling minimization were studied using a 2^3 factorial designs. The factorial design experiments can be seen in Table 2 along with the cleaning operational parameters involved. The 2^3 factorial experiments made use of continuous flow operation with 80% recovery and were performed over a five-day period. TMP was recorded at regular intervals during each flow and relaxation operation.

2.3.3. Cleaning operation exclusion test

A fractional 2^3 factorial experimental design was employed to investigate the impact of cleaning parameter exclusion on membrane fouling (see Table 3). Continuous flow operations with 80% recovery and 38 LMH forward flux were used for the experiments and as in all previous factorial design of experiments, fouling was measured in terms of TMP (mbar) at regular time intervals over a two-day experiment period.