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Operation of passive membrane systems for drinking water treatment

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ABSTRACT

The widespread adoption of submerged hollow fibre ultrafiltration (UF) for drinking water treatment is currently hindered by the complexity and cost of these membrane systems, especially in small/remote communities. Most of the complexity is associated with auxiliary fouling control measures, which include backwashing, air sparging and chemical cleaning. Recent studies have demonstrated that sustained operation without fouling control measures is possible, but little is known regarding the conditions under which extended operation can be sustained with minimal to no fouling control measures. The present study investigated the contribution of different auxiliary fouling control measures to the permeability that can be sustained, with the intent of minimizing the mechanical and operational complexity of submerged hollow fiber UF membrane systems while maximizing their throughput capacity.

Sustained conditions could be achieved without backwashing, air sparging or chemical cleaning (i.e. passive operation), indicating that these fouling control measures can be eliminated, substantially simplifying the mechanical and operational complexity of submerged hollow fiber UF systems. The adoption of hydrostatic pressure (i.e. gravity) to provide the driving force for permeation further reduced the system complexity. Approximately 50% of the organic material in the raw water was removed during treatment. The sustained passive operation and effective removal of organic material was likely due to the microbial community that established itself on the membrane surface. The permeability that could be sustained was however only approximately 20% of that which can be maintained with fouling control measures. Retaining a small amount of air sparging (i.e. a few minutes daily) and incorporating a daily 1-h relaxation (i.e. permeate flux interruption) period prior to sparging more than doubled the permeability that could be sustained. Neither the approach used to interrupt the permeate flux nor that developed to draw air into the system for sparging using gravity add substantial mechanical or operational complexity to the system. The high throughput capacity that can be sustained by eliminating all but a couple of simple fouling control measures make passive membrane systems ideally suited to provide high quality water especially where access to financial resources, technical expertise and/or electrical power is limited.

1. Introduction

Submerged hollow fibre ultrafiltration (UF) is an established technology viable for community-scale water treatment. It is particularly appealing for drinking water treatment because it can achieve up to 4-log removal of colloids, pathogenic bacteria, and viruses in a single process stage. However, the adoption of this technology in small communities or rural areas is currently hindered by the complexity and cost of UF systems (Peter-Varbanets et al., 2010). Most of the complexity is associated with the auxiliary processes used for fouling mitigation, notably backwashing, air sparging and chemical cleaning (Pearce, 2012). The reversal of the permeate flow during backwash promotes the expansion and back transport of accumulated foulants at the membrane surface (Ye et al., 2011) and dislodges material from the membrane pores (Akhondi et al., 2014). The scouring induced onto the membranes by air sparging minimizes the accumulation of foulants at the membrane surface during permeation (Cui et al., 2003) and enhances the back transport of foulants during backwash (Serra et al., 1999). Chemical cleaning using sodium hypochlorite and/or citric acid is used to oxidize and/or dissolve residual foulants that cannot be removed hydraulically by backwashing or air sparging (Porcelli

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and Judd, 2010). The membrane itself is a small portion of the entire system and accounts for only 10–40% of the capital cost of membrane systems (Pearce, 2012).

Passive filtration has been defined as a self-sustained physical transport process of biochemical and other atomic substances across the wall (i.e. membrane) of a living cell (Pont and de Bonting, 1981). UF systems are not normally self-sustained as steady operation is dependent on auxiliary processes such as backwashing, gas sparging and chemical cleaning that act as fouling control measures. However, recent studies have demonstrated the potential of membrane systems to function passively (i.e. without any fouling control measures) over extended periods when operated at an ultra-low permeate flux (Derlon et al., 2014; Kohler et al., 2014; Peter-Varbanets et al., 2010, 2011). The ability to sustain a consistent permeate flux was attributed to the microbial community that establishes itself on the membrane when operated under such conditions. Peter-Varbanets et al. (2010, 2011) determined that the microbial community promoted the development of cavities, channel networks, and heterogeneous structures within the foulant layer. In addition to reducing the resistance associated with the foulant layer, the microbial community could also degrade some of the organic contaminants present in raw waters (Derlon et al., 2014; Kimura et al., 2016; Kohler et al., 2014), further reducing fouling and improving the treatment efficacy of the system.

Although sustained operation is possible without any auxiliary fouling control measures, operation at an ultra low permeate flux is required (Derlon et al., 2014; Kohler et al., 2014; Peter-Varbanets et al., 2010, 2011). To overcome this limitation, it may be beneficial to retain some fouling control measures. However, limited knowledge exists regarding the optimal conditions under which extended operation can be sustained with minimal to no fouling control measures. The present study investigated the contribution of different auxiliary fouling control measures to the permeability that can be sustained. More specifically, the contributions of backwashing, air sparging, and chemical cleaning were considered because these fouling control measures are generally considered to be mechanically and operationally complex. The introduction of permeate flux interruptions (i.e. relaxation periods), as a mechanically and operationally simple fouling control measure, was also considered. The overall goal was to minimize the mechanical and operational complexity of a submerged hollow fiber UF membrane system, hereafter simply referred to as a membrane system, while maximizing its throughput capacity.

2. Materials and methods

2.1. Bench-scale submerged hollow fibre membrane systems

Three different configurations of bench-scale submerged hollow-fibre membrane systems were used and presented in Fig. 1.

The ***conventional bench-scale systems*** (Fig. 1a) were used to assess the contribution of backwashing to the permeability that can be sustained. Each system consisted of a cylindrical system tank (diameter: 155 mm; height: 1270 mm; working volume: 19 L), three custom membrane modules (three 430 mm strands/module, 0.00717 m^2 filtration area/module) made from ZeeWeed 500 type hollow fiber UF membranes with a nominal pore size of 0.04 μm (GE Water and Process Technologies), permeate/backwash pumps (Masterflex, model 7520-35) connected to each module, an air sparging system, a waste line, and a permeate/backwash tank. Backwashing was performed for 10 min after every 240 min of permeation at a flow equivalent to that of the permeate flux. The permeate/backwash pump flow was monitored and adjusted daily to ensure that it remained constant. Air for sparging was continuously introduced through a coarse bubble sparger located at the bottom of the system tank. Because of the constant flow operation, changes in permeability could be assessed based on changes in trans-membrane pressure, which was measured and logged every 3 min (Omega Engineering, pressure transducer model PX243A-15BG5V; Onset, data-logger/software HOBOware U12). Because of differences in the intrinsic clean water permeability of the virgin membrane module used, which ranged from 2.10×10^{-13} to 5.07×10^{-13} m (i.e. 0.75×10^2 to 1.82×10^2 $Lm^{-2}hbar^{-1}$), the permeability during the filtration tests was normalized with respect to a membrane's clean water permeability (which was similar to the permeability at the start of a filtration test). The filtration tests were performed in triplicate for a period of 2 months (unless the trans-membrane pressure exceeded a maximum allowable value of 55 kPa, in which case, the system operation was terminated).

The ***gravity siphon bench-scale systems*** (Fig. 1b) were used to determine the maximum permeate flux that can be sustained without backwashing, assess the contribution of air sparging to the permeability that can be sustained, and assess the efficacy of chemical cleaning. The gravity siphon systems were similar to the conventional systems, except that a constant hydrostatic pressure, rather than a constant pumped flow, provided the driving force for permeation. In addition, intermittent air sparging, and wasting were introduced and backwashing was eliminated. A timer (ChonTrol Corporation, model X) and solenoid valve were used to control the air addition and a manual valve located at the bottom of the system tank allowed for daily wasting at 10% of the system tank volume. Wasting was performed when air was added to ensure the system contents were fully mixed. The hydrostatic pressure was provided via a siphon. To establish a stable siphon, the systems were first primed for 10 days with constant (pumped) permeate flux operation at 10 $Lm^{-2}h^{-1}$. Following priming, the pumps were removed and the downstream end of the permeate line for each membrane module was submerged in a permeate tank. The elevation of the permeate tank was then adjusted to generate the hydrostatic pressure needed to produce an initial permeate flux of approximate 25 $Lm^{-2}h^{-1}$ at the start of a 10 day acclimatization period, implemented to accelerate the establishment of a microbial community on the membrane. Continuous air sparging was provided during the priming and acclimatization periods. Following acclimatizing, the elevation of the permeate tank was set to generate the constant hydrostatic pressure needed to produce the permeate flux of interest at the start of a filtration test. Because of the constant pressure operation, changes in permeability could be assessed based on changes in the permeate flow, which was measured manually on a daily basis. The clean water permeability of the different virgin membrane modules used ranged from 2.62×10^{-13} to 3.42×10^{-13} m (i.e. 0.94×10^2 to 1.23×10^2 $Lm^{-2}hbar^{-1}$), and decreased by approximately 50% during priming and acclimatization period. The permeability of the membranes during the filtration tests was normalized with respect to the permeability of the end of the priming and acclimatization period (i.e. start of the filtration tests), which ranged form 4.50×10^{-13} to 5.83×10^{-13} m (i.e. 1.62×10^2 to 2.09×10^2 $Lm^{-2}hbar^{-1}$). Filtration tests were conducted for 2 months following the priming and acclimatization periods.

The ***gravity down-flow bench-scale systems*** (Fig. 1c) were used to assess the contribution of permeate flux interruptions (i.e. relaxation cycles), and further assess the contribution of air sparging, to the permeability that can be sustained. As with the gravity siphon systems, a constant hydrostatic pressure provided the driving force for permeation and no backwash was provided. However, because of the down-flow configuration, no priming was required to establish a stable hydrostatic pressure, and for simplicity, no acclimatization was provided. Each system consisted