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Ultrasound-assisted forward osmosis for mitigating internal concentration polarization

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ABSTRACT

Internal concentration polarization (ICP) severely limits water flux performance in forward osmosis (FO). We investigated the use of ultrasound to mitigate ICP. Various parameters affecting the performance of the novel ultrasonically-assisted FO were studied, such as ultrasonic frequency and constant versus pulsed operation. With either deionized water or polyphenolic tannin solution as the feed and sodium sulphate as the draw solution, the water flux was nearly doubled for a thin film composite FO membrane upon the application of a 20 kHz ultrasound, with stronger enhancement achieved when the ultrasound was applied to the support layer of the membrane. High frequencies of 573 and 1136 kHz had much weaker effects. Pulsed application of ultrasound can significantly reduce the energy consumption of sonication. For the first time, the current study provides compelling evidence that ultrasonic vibrations applied to porous support structure of an FO membrane is highly effective in mitigating ICP.

1. Introduction

Forward osmosis (FO) is an emerging membrane separation process driven by an osmotic pressure difference across a membrane. The process does not require hydraulic pressure nor heating, and it can be a low-energy alternative to conventional pressure-driven, e.g. nanofiltration (NF) and reverse osmosis (RO), or thermal driven separation processes [1–4]. However, FO is still facing challenges such as fouling [5,6] and concentration polarization (CP) [7,8]. Both external concentration polarization (ECP) and internal concentration polarization (ICP) take place in FO processes, where ECP occurs at the solution-membrane interfaces and ICP occurs within the porous support layer of the membrane [7,9].

It is known that a hydrophilic substrate [10,11] and a smaller membrane structural parameter [12–14] are effective against ICP. Existing approaches in mitigating ICP and fouling include chemical substrate modification [11,15,16], incorporating nanomaterials [17–20], alternative substrate fabrication methods (e.g., electrospinning nanofibers substrate [21]), and redesign of the FO membrane structure (e.g., double-skinned FO membrane [22–24] or alternative supporting structure [25]). Nevertheless, structural optimization alone is not adequate to completely eliminate ICP; the FO flux efficiencies reported for existing commercial FO membranes are typically lower than 50% [26]. Unlike ECP, ICP cannot be easily mitigated by changing hydrodynamic conditions such as increasing cross flow rate or turbulence [9]. Therefore, alternative mitigating methods are needed.

The critical importance of ICP in FO prompts us to explore ultrasound as a mitigation method. According to the existing literature, main ultrasonic applications in membrane filtration include minimizing membrane fouling and chemical cleaning [27,28] and enhancing disinfection due to production of hydrogen peroxide and hydroxyl free radicals [29,30]. Cavitation has been considered as the primary ultrasound cleaning mechanism [31,32], while acoustic streaming (without cavitation) has appeared as an important addition in the transport of particles away from the surface [33,34]. The increase of ultrasound frequency result in increase of the threshold for cavitation [35], but in higher bubble travel speed and lower bubble density, which are also considered to be important in detaching fouling from membrane surface [36]. However, cavitation can produce harmful effects, for example membrane pore dilation and breakage were observed at 12.3 kW/m^2 power density using 40 kHz frequency [37].

Despite that the use of ultrasound in membrane processes has been well documented, the existing literature has largely focused on pressure-driven membrane processes with a major emphasis on fouling prevention and cleaning. Although ultrasound can potentially offer a unique solution for concentration gradient control in porous supports

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of FO membranes, its systematic application in ICP control is not yet reported. The objective of this study was to develop an ultrasound-assisted FO to mitigate ICP and thus enhance FO water flux. In this work, FO testing procedures were established to evaluate the operational parameters of ultrasound on FO membranes.

2. Materials and methods

This study focuses on forward osmosis (FO) of water and tannin by sodium sulphate with the aid of ultrasonic vibration. The porous support layer (SL) was placed against the draw solution and the active layer (AL) against the feed solution.

2.1. Materials and chemicals

2.1.1. Test solutions

Tannin, derived from wood bark, was used as a model biochemical to be concentrated using FO. Tannin exists as a polyphenolic compound based either on flavan-3-ol monomers (condensed tannins, also called proanthocyanidins), or on gallic or hexahydroxydiphenic acid esters linked to a sugar moiety (hydrolysable tannins). Its molecular weight ranged from 500 to 3000 Da [38].

Sodium sulphate (anhydrous, analytical grade, Merck KGaA), a commonly used salt in the paper and pulp (P & P) industry, was used to prepare draw solution at 20 wt% concentration. Tannin (4.4 g/L) and deionized water were used as feed solutions in the FO process. Since tannin is produced as a useful P & P bioproduct that requires further concentration, its coupling with sodium sulphate in FO avoids the need of draw solution regeneration in the context of P & P water reuse. With deionized water as feed, after water flux and temperature were stabilized, the flux was continuously measured over at least 1 h. Both the feed and draw solutions were in close loops. The effect of draw solution dilution on FO water flux was evaluated using control experiments (i.e., tests without the application of ultrasound). Similar approaches are adopted in the FO fouling literature [6,8].

2.1.2. Membranes

The membranes used in the study were two different type FO membranes from Hydration Technology Innovations LLC (HTI): thin-film composite polyamide on polysulfone (denoted as TFC) with embedded support, and cellulose triacetate (CTA) cartridge membrane with an embedded polyester screen mesh.

2.2. Forward osmosis test system

Forward osmosis experiments were conducted in a custom-built laboratory-scale crossflow filtration test unit (Fig. 1). Two types of membrane filtration cells were tested (Fig. 2) including a SEPA module mounted with a 20 kHz transducer (A =140 cm^2) and a Sterlitech module with high frequency transducer of 573, 858 and 1136 kHz frequencies (A =42 cm^2). In all experiments, the active layer of membrane faced the feed side. The same flow of 1.2 L/min was applied on both sides of the membrane. Pressure levels did not differ between experiments, thus they do not have effect on the results. All the filtration experiments were performed at an operating temperature of 40 °C for the dissolution of Na_2SO_4 at 20% concentration by weight. The same temperature was applied on both sides of the FO membrane.

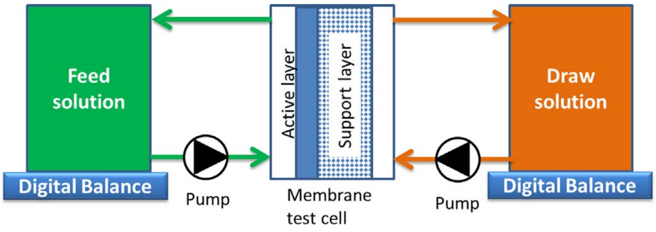

Fig. 1. Experimental FO filtration set-up. Close loops were used for both feed solution and draw solution. Temperature, conductivity and weight of both feed solution and draw solution were measured and recorded by an online data logging system.

2.3. Ultrasound

The ultrasonic vibration in SEPA module (Fig. 2b) propagates along the metallic module casing, therefore the electric power is distributed around the module. In Sterlitech module (Fig. 2c), the front aluminium mass of the ultrasonic transducer is directly in contact with the sample liquid, hence only a fraction of the ultrasonic power is distributed to the module structure.

Both high frequency and low frequency ultrasound were applied. While low frequency ultrasound favours the formation of hotspots (i.e., cavitation), high frequency ultrasound tends to have a more evenly distributed effect [31–35]. In the current study, high frequency ultrasonic tests were performed using Sterlitech module mounted with commercially available high frequency ultrasonic transducer (573, 858, and 1136 kHz, Meinhardt Ultraschalltechnik). Low frequency ultrasound was performed using a commercial 20 kHz transducer. The applied ultrasound power spanned over 50–300 W. Here the ultrasonic transducer was in direct contact to the sample liquid. Ultrasonic power (in Watts) was measured from electric power consumed by all ultrasonic equipment, i.e. generator, frequency and power control, and transducer itself. Based on the existing literature on ultrasound cleaning, greater ultrasound power improves the cleaning effect but it also increases the risk of membrane damage [37].

The ultrasonic attenuation test was conducted by means of an acoustic source (ultrasonic transducer at the bottom of the test system), and an acoustic receiver (hydrophone) placed above test piece of membrane material. Ultrasonic transducer was operated at frequency of 22 kHz and power of 90 W using an ultrasonic generator (International Electric US-1200A). For sound absorption/transmission in/through membrane observatory, a hydrophone (Reson TC4013), with a usable frequency range of 1–170 kHz, was used for acoustic pressure acquisition. The hydrophone was connected to an oscilloscope (Hung Chang Model OS-615S).

2.4. Analyses

FO water flux was determined by measuring the weight changes of the feed as a function of time. Analysis of samples from the feed and draw solutions in the beginning and at the end of an experiment, included pH, conductivity, osmotic pressure, and total dissolved solids (TDS). pH and conductivity were measured using laboratory meters VWR pH100 and VWR EC300, respectively. TDS was determined using a standard method of SFS-EN 15216. Osmotic pressures of solutions were analysed using Vapro 5600XR osmometer from Wescor, Inc. Information of the reverse salt flux was obtained from the conductivity measurement on both feed and draw solutions.

3. Results

Various parameters affecting the performance of ultrasound-assisted forward osmosis process were studied, such as ultrasonic frequency, power, and constant versus pulsed operation. Other variables, such as feed solution as well as membrane structure and material were also tested. In addition, ultrasonic attenuation through membrane at fixed frequency was measured.

3.1. Ultrasonically enhanced FO using deionized water as feed

Using a metallic SEPA module, longitudinal sound waves from the ultrasonic transducer propagate through the steel plate to better distribute the ultrasound more uniformly over wider membrane sur-