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Cleaning Membranes with Focused Ultrasound Beams for Drinking Water Treatment

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Abstract – **Traditional methods for water treatment are not effective to remove micro pollutants such as harmful organics and cannot meet the demand for high-quality drinking water. Membrane technologies are known to produce drinking water of the highest quality. However, membrane fouling is a significant problem, which limits a widespread use of these technologies. Currently, chemical cleaning is used to control fouling, which interrupts the water production process during cleaning, produces secondary pollutants, shortens membrane life due to chemical erosion, adds costs of cleanup, handling, and transporting dangerous chemicals, and waste energy and the cleaned water. Ultrasound has been demonstrated effective for membrane cleaning and does not have the problems of chemical cleaning. However, current ultrasound methods have high energy consumption, require transducers that can handle high power, and are expensive to clean a large membrane area needed for a typical water treatment plant. In this paper, a focused ultrasound beam is used to create a high intensity at focus to produce cavitations for membrane cleaning. This method may save energy and potentially allow inexpensive low-power transducers such as polymeric transducers to be used. Combined with the beamforming technology that is widely used in medical ultrasound, the focused beams can be swept over a large surface area of membranes for cleaning. An experiment was performed and preliminary results show that the method is promising for membrane cleaning.**

Keywords - ***Focused Ultrasound Beam, Membrane Cleaning, Drinking Water Treatment***

I. INTRODUCTION

Water is consumed by humans daily to sustain life and maintain a good health. Therefore, quality of water is of a paramount importance for human beings.

Pollutions of water sources such as surface and ground water by micro pollutants are a global problem. This problem becomes more and more severe due to increased human activities in industry, consumer products, and agriculture. On the other hand, living conditions and living standard of humans are steadily improved due to technological innovations and advancements, which increase the demand of humans for cleaner drinking water. Therefore, we are facing a challenge to produce cleaner water at a time when the water sources become more polluted.

Traditional methods for treatment of drinking water use pretreatment, coagulation/flocculation, clarification, biological treatment, sand filtration, activated carbon adsorption, and ultraviolet and chlorine disinfection [1]. These methods are not very effective for removing micro pollutants such as harmful organics. In addition, these methods produce byproducts that can cause cancers, deformation, and mutation since chlorine or chlorine-related chemicals are used in disinfection. Thus, quality of treated water is difficult to meet the clean water standards. Significant chemical and biological safety issue is becoming a new threat to the drinking water for many cities. The current process for deep treatment of drinking water from water sources contaminated by micro pollutants also has problems in practice.

Pressure-driven membrane technologies such as microfiltration (MF) (0.1-10 micron pore size), ultrafiltration (UF) (2-100 nm pore size), nanofiltration (NF) (0.5-2 nm pore size), and reverse osmosis (RO) (<0.5 nm pore size) are the state-of-the-art technologies that have been demonstrated to produce high-quality drinking water [1-23]. They have many advantages such as they are effective in removing pathogens, easier to be automated, simpler to maintain, compact, requiring less coagulating agents and disinfectors, and capable of producing high-quality drinking water for human consumption. Despite of these advantages, membranes also face many challenges [17]. Among the challenges, membrane fouling is the foremost. Because the pore sizes of membranes such as nanofiltration membranes are small, the surface of the membranes may be electrically charged, and the composition of water sources contaminated by micro pollutants is complex, the surface of such membranes can be fouled very easily in practical uses [1, 17, 23]. The fouling problem has limited a widespread use of the membranes.

To remove foulants and restore membrane functions, membranes need to be cleaned frequently [17, 23]. Currently, backpulse/backwash and chemical cleaning are used to control fouling. Among these methods, chemical cleaning is most common. Chemical cleaning interrupts the water production process during cleaning, produces secondary pollutants, shortens membrane life due to chemical erosion, adds costs of cleanup, handling, and transporting dangerous chemicals, wastes energy by decreasing and then increasing pressures needed for the membrane system to work, and wastes cleaned water.

Ultrasound has been demonstrated effective for membrane cleaning and does not have the problems of chemical cleaning [24-32]. Some advantages of ultrasound cleaning are as follows: (1) the membranes can be cleaned while they are in use, (2) there are no secondary pollutants and problems of transporting and handling of dangerous chemicals as in the chemical cleaning (in addition to the cost of chemicals and their transport, in many cases such as military applications, it has logistic problems to transport, handle, and dispose dangerous cleaning chemicals), and (3) hydrogen peroxide (H_2O_2) and hydroxyl free radical ($^{\cdot}OH$) produced by ultrasound can be used for disinfection of the distribution systems of drinking water, reducing the use of chlorine that produces carcinogenic byproducts and thus is harmful to humans.

Although it has been demonstrated in various laboratory-scale studies that ultrasound can be used very effectively to clean membranes, so far, there are no ultrasound technologies that are used in a large-scale drinking water treatment [28, 29]. There are two main reasons for this: (1) The cost of energy needed by ultrasound cleaner would be high. Based on [28], it is estimated that 8,501,760 watts of power is needed to process 4.5 millions of gallons of drinking water per day with the DOW Chemical Filmtec NF270-4040 spiral wound nanofiltration membrane, adding about 0.45 cents energy cost per gallon of water produced if each kilowatt-hour of electricity costs about $0.1 US dollars. (2) Ultrasound transducers such as lead zirconate titanate (PZT) ceramics that could handle a high power to produce cavitations would be very costly, bulky, and brittle. In addition, the acoustical impedance of these transducers is much larger than that of water, making the coupling of the acoustic energy from the transducer to water difficult due to the impedance mismatch. When made into array transducers to steer beams, there will be high cross talk among elements if the transducers are not diced into thin elements. Dicing ceramics would be too costly to be practical for transducers of a large area (for example, membrane area needed can be 21,254,400 square inches for a water treatment plant that produces 4.5 million gallons of water per day). For such a large area, even the cost of PZT material alone would be very high.

To overcome problems of current ultrasound methods, in this paper, we study the efficacy of a focused ultrasound beam on membrane cleaning. This study is significant since ultrasound intensity is increased greatly at the focus to create cavitation that is the main mechanism for membrane cleaning [29] without the need of high power transducers, potentially saving energy and allowing polymer-based (such as homopolymer or copolymer) transducers to be used [33]. Compared to PZT ceramic types of transducers, polymer-based transducers have low transmission efficiency but they are flexible, non-brittle, have a better acoustical impedance matching with water, and have a low cost. The flexibility of the polymer-based materials is necessary for integrating transducers into the spacer structures of existing commercial membrane units such as spiral wound membrane systems with minimal modifications. In addition, with polymeric phased array transducers that are formed by printing electrode patterns on polymer surfaces, beamforming techniques that are widely used in medical ultrasound [33-34] can be used to both focus ultrasound beams into a high intensity at focus and steer the focused beams over the surfaces of membranes for cleaning.

II. EXPERIMENT AND RESULTS

To show the efficacy of focused ultrasound beam in membrane cleaning, an experiment was performed (Figs. 1 and 2). In the experiment, an ultrafiltration (molecular weight cutoff: 15,000-30,000 Da (or g/mol)) was used. The membrane was made by Osmonics with cellulose acetate. The membranes are nominally neutral (uncharged). The surface potential was not determined. To reduce the time for ultrasound cleaning, the membrane was masked with tapes on the feed side except for an area of 1 square inch. Before fouling, a filtration rate of 3.47 milliliters/minute (mL/min) was measured with a GE Sepa CF II filtration test system. After fouling with a 10% of yeast (Fig. 3) solution that was cooked in microwave until boiling, the filtration rate was reduced to 0.128 mL/min in 15 minutes. The fouled membrane (Fig. 4) was then cleaned with an ultrasound beam of about 2.7 MPa (peak) pressure at focus and 671 KHz frequency (Figs. 5 and 6). The beam has 300 cycles per burst with about 50 Hz pulse repetition rate for the bursts to avoid damaging to the transducer (V301-SU, Panametrics, Inc.). The transducer had a one inch diameter and was focused with a plastic lens of 37.5 mm geometrical focal length. The beam was scanned over the uncovered membrane surface at 1 mm/s speed in a raster format with a table-top scanning system under computer control (Fig. 7) to clean the membrane. After the cleaning, the filtration rate of the membrane was restored partially to about 1.67 mL/min (Fig. 8).

Figure 1. An ultrafiltration membrane (white piece of sheet near the center of the photo) is mounted in a GE Sepa CF II filtration test system for testing.

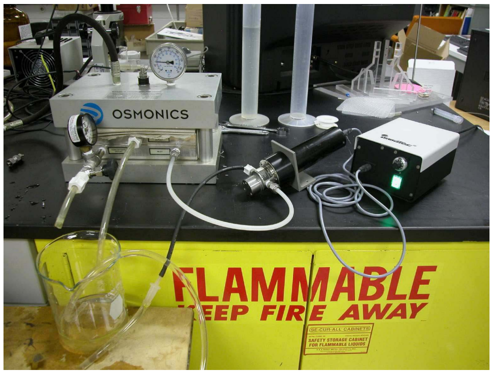

Figure 2. The membrane mounted in the GE Sepa CF II filtration test system is connected to a high-pressure pump (the black cylinder near the center of the photo).

Figure 3. Microwave cooked baking yeast solution used as a foulant in the experiment.

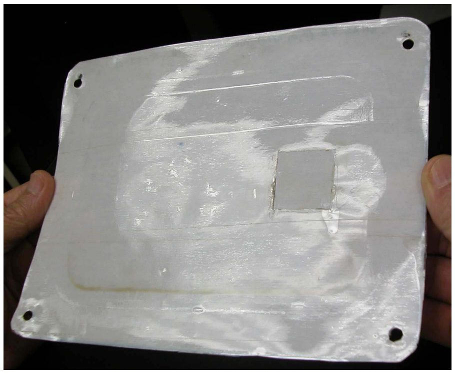

Figure 4. An ultrafiltration membrane (the uncovered area is about 1 square inch) fouled by the yeast. The use of a small uncovered area is to reduce the time in the cleaning experiment.

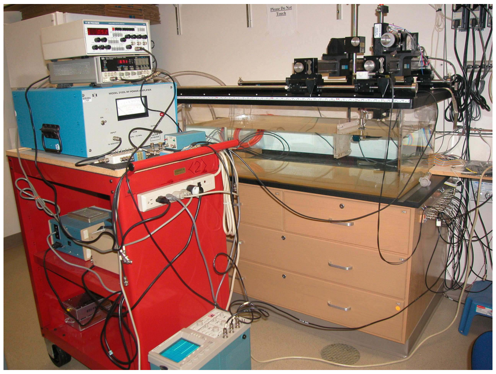

Figure 5. Setup of the ultrasound cleaning experiment. It consists of function generators, 100W ENI 2100L power amplifier (Electronics & Innovation Ltd.), oscilloscope, multi-axis computer-controlled scanning system, Panametrics transducer (Panametrics, Inc.) of 1 inch diameter and 0.5 MHz nominal center frequency, and a plexiglass lens of 37.5 mm geometrical focal length.

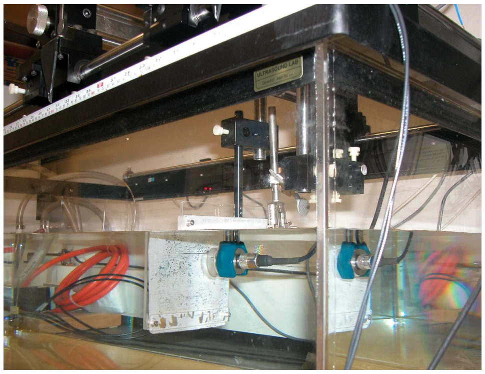

Figure 6. A close view of the focused transducer, lens, and the membrane.

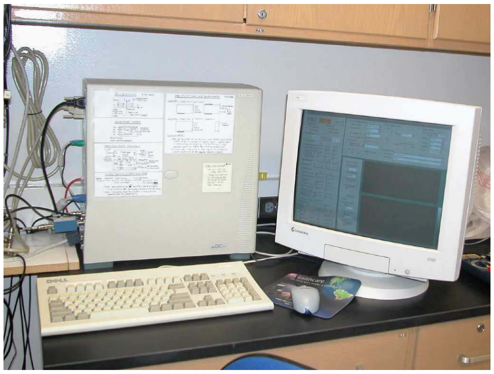

Figure 7. Computer program used to control the scanning pattern of the focused transducer.

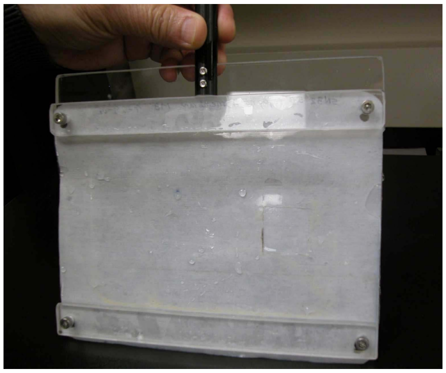

Figure 8. The membrane cleaned and to be tested with the GE Sepa CF II filtration test system in Figs. 1 and 2.

III. CONCLUSION

This study shows the efficacy of focused ultrasound beams for membrane cleaning, potentially reducing energy consumption and allowing transducers of relatively low power rating to be used.

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