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Development of a robust bench-scale testing unit for low-pressure membranes used in water treatment

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Abstract. A bench-scale test has recently been proposed as a predictive tool to minimize the scope of pilot-scale testing or to optimize the operation of full-scale membrane filtration systems. Consequently, a bench-scale testing unit was developed for this purpose and systematically evaluated in this study. This unit was capable of accommodating commercially available, low pressure, hollow fiber (LPHF) membranes with various configurations for testing under conditions comparable to real-world applications. Reproducibility of this unit in assessing membrane fouling and microbial removal efficiency of LPHF membranes was tested and statistically comparable results were obtained. This unit serves as a useful apparatus for academic researchers and utilities to evaluate the performance of LPHF membranes used for water treatment.

Keywords: bench scale membrane testing unit; low pressure; hollow fiber membrane; membrane fouling; membrane integrity; virus removal.

1. Introduction

Bench-scale treatment testing has been a key part of water treatment technology since the widespread development of large-scale facilities for water supply. Water treatment is primarily achieved with the so-called "conventional" treatment process, encompassing complete or part of a standard train (coagulation, sedimentation, filtration, and chlorine disinfection). This process is only effective under optimized chemical conditions because it relies upon sufficient and cost-effective functioning of different chemicals (*e.g.*, alum and chlorine) to remove aquatic contaminants. Adjustments of chemical conditions are often required due to the changes in raw water quality and temperature. Without an appropriate bench-scale testing apparatus, suitable chemical conditions have to be determined empirically at plant scale or by costly and time-consuming pilot-scale trials (Fuller 1898). This was changed with the employment of a simple laboratory stirring device, the jar tester. The history of jar tester is difficult to find, but a classical book published fifty years ago has detailed descriptions of a jar tester and its operational method, where the jar tester was introduced as "one of the most needed pieces of equipment in a water works laboratory" for "use in coagulation, color removal, water softening reactions, and taste elimination studies, and for determining minimum quantities of coagulants required for treatment" (Riehl 1957). The scalability of jar test results is a result of the similarity of chemical processes occurring at bench- and full-scale water treatment processes (Shin, Spinette *et al*. 2008). Today, jar tests are widely employed by water industries worldwide as a predictive

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tool for the design and operation of conventional water treatment plants.

Since the first microfiltration (MF) plant started operation in 1988 (Laine, Vial *et al*. 2000), low pressure membranes have been employed at accelerating rates by water industries, with a total global capacity of almost 3,500 mgd by the end of 2006, as compared to less than 1,000 mgd in 2000 (Furukawa 2008). Forty-four percent of them were installed in the Americas and 82% were for drinking water and wastewater treatment. Application of low pressure membranes to small water systems has also drawn increasing attention (Anderson and Sakaji 2007; Peter-Varbanets, Zurbrügg *et al*. 2009). Despite the presence of various configurations, a 2005 survey found that tubular and hollow fiber membranes were preferred over other configurations due to the capability of performing backwashing (Adham, Chiu *et al*. 2005). Further surveys of the installed capacity showed that hollow fiber membranes contributed to a majority of the total capacity (Adham, Chiu *et al*. 2005; Furukawa 2008), indicating the dominant role of LPHF membranes in water treatment and reuse. Therefore, assessing and optimizing the performance of LPHF membranes has become very important for the water community in order to implement this technology. Relevant information is currently obtained in the design phase of a treatment plant through pilot-scale testing; similar situations occur in the early stages of conventional treatment process as discussed previously. Pilot-scale testing of LPHF membranes is often costly and observing the impacts of varying operational conditions can require a considerable period of time.

Alternatively, employing a bench-scale test to predict the performance of full-scale low pressure membrane filtration has been proposed (Choi, Dempsey *et al*. 2005; Huang, Young *et al*. 2008). Similar to conventional water treatment processes, understanding the chemical aspects of the technology and identifying suitable chemical conditions are important tasks for bench-scale testing of LPHF membranes. For these systems, the major chemical conditions are related to physico-chemical interactions between aquatic substances and LPHF membranes (Jacangelo, Adham *et al*. 1995; Huang, Lee *et al*. 2007; Lee, Kim *et al*. 2007), which is specific to the membrane and the water of interest. Bench-scale testing under real world conditions can provide direct assessment of the performance of commercially available membranes. For membrane plants designed with chemical addition, pretreatment can alter the mutual interactions of aquatic substances and their interactions with membranes, thereby affecting membrane fouling and the removal of substances in the pretreated water (Escobar, Hoek *et al*. 2005). Suitable chemical doses or exposure for feedwater pretreatment may be rapidly determined by bench-scale membrane testing, which may also be used to optimize the chemical conditions employed in membrane cleaning. Therefore, a proper "membrane tester" is needed for all the purposes discussed above.

Although several bench-scale systems have been reported in the literature (Lee, Amy *et al*. 2004; Choi, Dempsey *et al*. 2005; Howe, Marwah *et al*. 2007), a robust, universal testing unit for commercially available LPHF membranes (one comparable to a jar tester) has not yet been developed. Some bench-scale systems are small pilot-scale filtration systems designed for specific types of LPHF membranes and required large quantity of feedwater to operate due to use of full-size membrane modules. In comparison, some bench-scale systems are modified stirred-cell filtration devices that are only capable of testing laboratory flat-sheet membranes with chemical compositions similar to LPHF membranes. However, as a result of proprietary surface modification conducted by membrane manufacturers, it is difficult to find surrogate laboratory membranes that are representative of full-scale membranes. Therefore, the objectives of this study were to: 1) design and construct a compact bench-scale testing unit for low pressure, hollow fiber (LPHF) membranes employed in water treatment and reuse; 2) examine the application of this unit to the evaluation membrane fouling

potential; and 3) apply this unit to determine the microbial removal efficiency of commercially available LPHF membranes.

2. System development and testing protocols

2.1 Fabrication of membrane modules

Fabrication of small membrane modules is an important step in bench-scale membrane testing. Full-length membrane fibers or membrane modules supplied by manufactures are usually more than one meter long. As such, they are difficult to handle in laboratory experiments. For the purpose of bench-scale testing, full-length fibers were cut to approximately 32-cm long fibers. Eight short fibers formed a bundle. One side of the membrane bundle was inserted through a 4-cm long, rigid, translucent polypropylene (PP) tube (outer diameter, OD = 1/4 inch), with approximately 1-cm fiber protruding out of the tube. The void space between the fibers and the internal wall of the tube was filled ("potted") with epoxy glue (Devcon 14270, 5 Minute® Epoxy). The other side of the membrane bundle was inserted approximately 2 cm into a 3-cm long PP tube (OD = 1/4 inch), and the void space inside the tube was also filled with epoxy glue. Unlike the open side, this side of fibers was completely sealed by the glue to form a dead end. The glue inside the tubes hardened in a few minutes and reached the maximum strength in 24 hrs. Afterwards, approximately 1-cm long of the PP tube in the open side of the module was carefully cut with a sharp tubing cutter. The open side of the fibers was then exposed. The openings of the fibers were carefully inspected to ensure that all of them were properly embedded in glue and not closed or deformed by cutting. A membrane module fabricated through these steps had a total length of approximately 31 cm and an effective membrane length of approximately 25 cm. The effective membrane surface area depended on the diameter of the hollow fibers and was approximately 0.005 m^2 for outside-in membranes with an OD of 0.08 cm. An example of a fabricated module is presented in Photo 1.

The number of fibers included in a small module was important to successful membrane potting, and is dependent on the OD of the fibers. Many commercially-available, outside-in membrane fibers have OD of 0.6 mm to 0.8 mm. The thin-wall PP tube is capable of accommodating eight fibers in

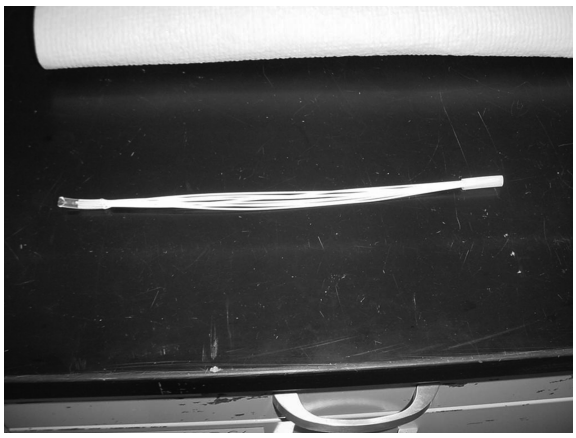

Photo 1 Fabricated hollow fiber membrane module with open side on the right and dead end on the left

this size range. Inserting more fibers in the PP tube made it difficult for glue to completely fill the space in the tube, and therefore, was avoided. For some inside-out membranes with an OD of more than 1 mm, the number of fibers in a module may be reduced to five or fewer. As the number of fibers in a module decreased, however, the module becomes easier to break and more subject to variation in performance. Therefore, the single-fiber module configuration employed in some studies (Howe, Marwah *et al*. 2007) was not adopted in this study.

Proper handling of the epoxy glue was also crucial for module fabrication and several aspects are noted in this regard. Firstly, moisture on the membrane did not affect the performance of the glue. Therefore, wet fibers may be potted in a similar manner. This is beneficial for bench-scale testing of membrane fibers harvested from large-scale systems already in use. Secondly, the epoxy glue sometimes remained soft after 24 hrs, indicating that the two components of the glue were not well mixed or properly reacted with each other. In this case, the modules were discarded. Thirdly, the plastic tube for membrane potting was not made of Teflon materials because they are non-sticky to epoxy glue.

Modules fabricated following the aforementioned steps were not ready for evaluating and a three-step cleaning was required. Commercially available LPHF membranes are often hydrophilized, pre-wetted, or impregnated with polar chemicals (*e.g.*, glycerin). Consequently, modules fabricated with these types of membranes were cleaned in three steps. Firstly, the modules were soaked in 1 to 2 (v/v) mixture of 2-propanol and ultrapure water overnight (ca. 18 hrs) to remove polar chemicals. [It is noteworthy that if hydrophobic membranes were used in the test, this step was conducted by directly filtering the 2-propanol solution until a steady transmembrane pressure was reached; this ensured efficient wetting of the membrane.] As the second step, the modules soaked or rinsed with 2-propanol solution were rinsed thoroughly using high quality water and then soaked in sodium hypochlorite (NaOCl) solution for 30 min. The concentration of NaOCl was chosen as that recommended by the membrane manufacturer for chlorine cleaning of the membrane. This step was conducted to ensure complete removal of the wetting agent on the membrane and prevent abnormally high membrane permeability after chlorine cleaning compared to the virgin membrane. As the third step, the chlorine treated modules were rinsed by filtering ultrapure water continuously until the permeability of membrane module reached a stable level. Permeate of the module was sampled for total organic carbon (TOC) analysis. A TOC level below 0.1 mg/L was achieved following the three steps.

If a large number of modules were fabricated for a series of experiments, the modules were cleaned and then stored in ultrapure water; NaOCl may be added at a low dose of approximately 1 mg/L to prevent biofouling. Alternatively, dry modules were stored without cleaning in air-tight bags to prevent vaporization of hydrophilizing reagent, which can cause irreversible damage to the structure of membrane pores.

2.2 Bench-scale LPHF membrane testing unit

As shown in Fig. 1, the bench-scale membrane testing unit was set up in three configurations to accommodate different LPHF membranes. It consisted of four major components [feedwater column, peristaltic pump(s), pressure gauge, membrane module] and accessories (tubings, and fittings). This unit was designed to operate in direct-flow, constant-flux mode, similar to most full-scale LPHF membrane systems.

The feedwater columns were fabricated with transparent polycarbonate (PC) hollow rods with a tube size of 1/2 inch and a length of 32 cm. The internal diameter of the column was 3/8 inch and was mounted vertically. Only one peristaltic pump (filtration pump) was needed for membranes operated

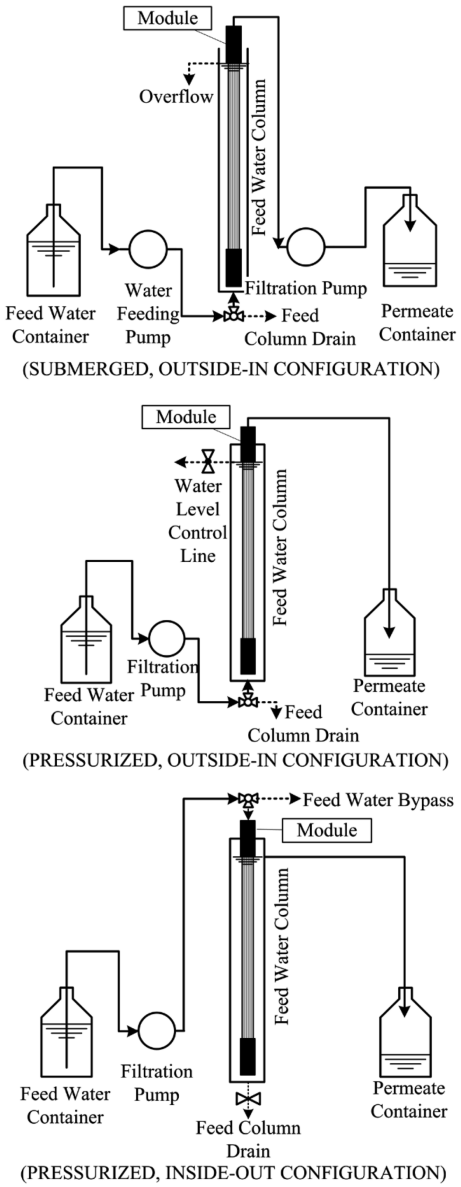

Fig. 1 Schematic of the bench-scale membrane testing unit in three configurations

in pressurized modes, while two pumps (a filtration pump and a water-feeding pump) were needed for submerged membranes. The filtration pump used in this study was a Masterflex™ L/S digital economy drive (Cole Parmer Company) equipped with dual Easy-Load II pump heads (for dual channel operation). This pump can be operated in reverse flow, which eliminated the need for a separate backwash pump and simplified the operation of the testing unit. The water-feeding pump was a Masterflex™ L/S economy drive with dual Easy-Load II pump heads. This single direction pump was employed to transfer water to the feedwater columns. Platinum-cured silicone tubing (Masterflex™ Size 13, Cole Parmer Company) was used as the pump tubing for both pumps, which yielded flow

ranges from 1 to 24 mL/min. Two compound digital pressure gauges (Cecomp Electronics Incorporate, DPG 1000BG +/- 15 PSIG-5) were installed in the permeate lines to measure membrane operating pressure. These gauges had a working range of -15 psig to +15 psig, which was suitable for both submerged (vacuum-driven) and pressurized (pressure-driven) LPHF membranes in either filtration or backwash mode.

Instant fittings made of glass-filled nylon (Legris Incorporate) were purchased from McMaster Co. and adopted in the unit. The utilization of instant fitting provided convenience in assembling and dissembling of any part of the unit. The tubings were fabricated of translucent Teflon and had an outer diameter of 1/4 inch. The Teflon tubing employed had low binding and good chemical tolerance during chemical cleaning of fouled membranes. In order to hold the small module in the test unit, house-made assemblies of fittings and tubings were developed as shown in Photo 2; the installations of submerged and pressurized membrane modules are explained in the caption. Automation of this testing unit was achievable by adding a pressure transmitter, solenoid valves, data logger, computer interface for the pumps and valves, and a personal computer.

An important issue in the construction of the bench-scale membrane testing unit was to minimize the dead air space in the unit that cannot be filled by water. Unlike pilot-scale or full-scale systems, the peristaltic pump used in the bench-scale unit was operated in a relatively low flow range, typically 1 to 10 mL/min for filtration. Presence of air bubbles in the system may significantly extend the time required for depressurization or pressurization of the system. This, in turn, causes a sharp pressure change at the beginning of the filtration experiment which impedes the determination of initial permeate flux employed in further calculation of fouling indices. The presence of air bubbles also deteriorates the efficacy of hydraulic backwash as system pressure cannot reach the maximum level within the short time for backwash. Places most likely to introduce extra air space to the bench-scale

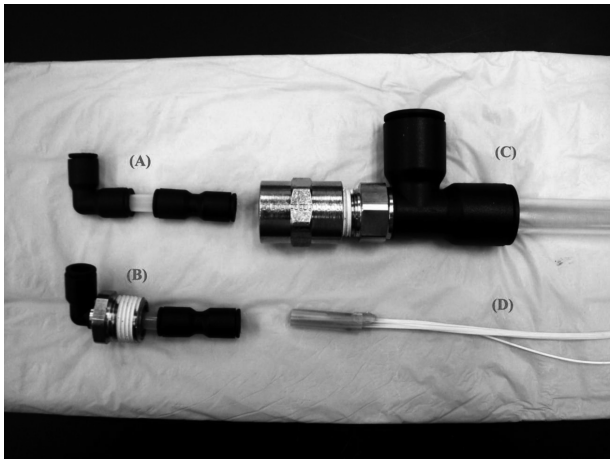

Photo 2 Assemblies constructed for the installation of the membrane module on the Low Pressure Membrane Testing Unit. (A) Submerged membrane assembly, (B) Pressurized membrane assembly (constructed by gluing a 1/4 inch PP tubing in the threaded end of a 1/4 inch tube to 3/8 inch NPT male pipe elbow), (C) top part of the feedwater column, and (D) the open side of a membrane module. For submerged membranes, the left side of (D) is inserted in the right side of (A) and put in (C) with the left side of (C) connecting to the atmosphere. For pressurized membranes, the left side of (D) is inserted in the right side of (B) and the threaded part of (B) is then screwed onto the left side of (C) to form an airtight connection

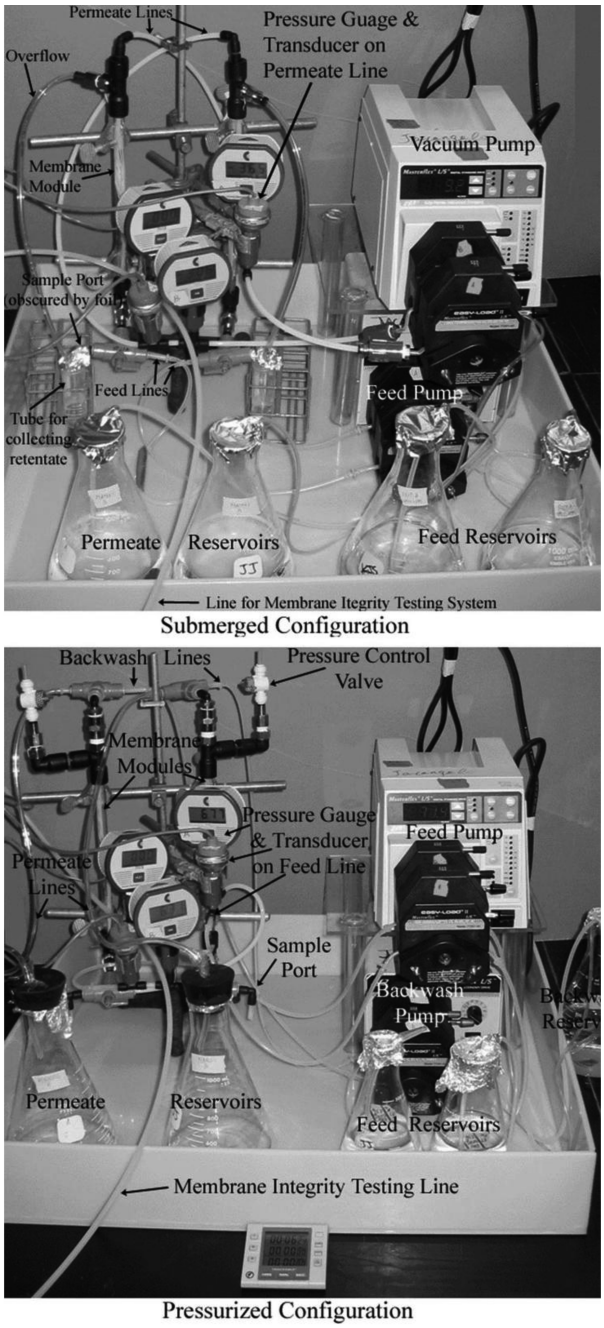

Photo 3 Bench-scale membrane testing unit in submerged (upper) and pressurized (lower) configurations

system included the lines connecting the pressure gauges and the head space inside the column when the system was operated in pressurized configurations. The former was minimized by shortening the connecting line, and the latter was reduced by controlling the water level in the feedwater columns with side pressure control lines (Photo 3, lower photo).

2.3 System Integrity test

A system integrity test was conducted after installing the membrane module and filling up the feedwater column with ultrapure water. This was performed by introducing pressurized nitrogen gas to the line connecting to the inside of the membrane (Photo 3) at a pressure of 1 bar (14.5 psi). Once the applied pressure became stable, the nitrogen gas was turned off. If the held pressure decreased slowly in the lines connecting to the outside of the membrane, generally less than 0.07 bar every 5 min, the system was considered to pass the test. Otherwise, the system was re-assembled or the membrane module replaced.

2.4 Membrane fouling protocol and parameter

A single-cycle filtration protocol for membrane fouling study is shown in Fig. 2. This testing protocol began with filtration of a clean water (ultrapure water) to reach a permeate throughout of V_{s1} to determine the clean membrane baseline permeability. Less than 10% variation was observed for modules fabricated with similar membranes and cleaned according to the method described previously. Next, the feedwater of interest was filtered in order to foul the membrane to a preset condition of a normalized specific flux (J_s/J_{s0}) of 0.5 or a predetermined permeate throughput of V_{s2}. A hydraulic backwash was conducted immediately after the previous step under hydraulic conditions comparable to full-scale systems. The unit was switched to filtration mode after draining the backwash water and refilling the feedwater column with the feedwater. The filtration continued for a time of t_3 (5 to 10 min) and the residual fouling (hydraulically irreversible fouling) was determined. Subsequently, a chemical cleaning was conducted using chemicals of interest, and then, the feedwater column was drained again and refilled with the feedwater. Finally, another filtration step was carried out for a period of time, designated as t_4 (5 to 10 min), to determine residual fouling after the chemical cleaning (chemically irreversible fouling). A membrane fouling profile was determined pursuant to this filtration protocol and quantified using Unified Membrane Fouling Indices (UMFIs).

The definition and principles of UMFI have been presented in details elsewhere (Huang, Young *et al*. 2008). Basically, UMFIs are measures of membrane fouling rates observed within a certain timeframe of interest and calculated using the following equation:

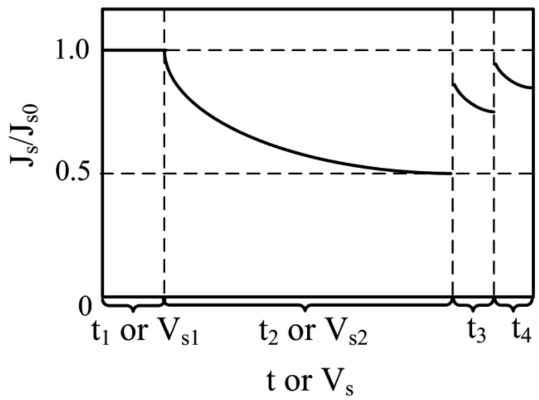

Fig. 2 A schematic diagram of the bench-scale membrane fouling test protocol

$$\frac{J_{s0}}{J_s}=(1+(\mathrm{UMFI})V_s) \quad (1)$$

Based on Eq. (1), UMFI describes the rate of fouling accumulation per unit permeate throughput and is calculated either by linear regression of multiple sets of data or by a two-point (the start and the end points) method. When J_{s0}/J_s and V_s values plugged into Eq. (1) are measured immediately after hydraulic backwashing or chemical cleaning of fouled membranes, UMFI values for hydraulically irreversible and chemically irreversible fouling can be determined; these values have been termed $UMFI_R$ and $UMFI_C$, respectively. In comparison, UMFI values determined immediately before hydraulic cleaning represent total fouling of the membranes, and therefore, are termed $UMFI_T$. As an example, if J_s/J_{s0} decreased to 0.50 after filtration of 0.5 L of feedwater (V_{s2} = 100 L/m^2, given an effective membrane area of 0.005 m^2), the corresponding UMFI value is calculated as 0.01 m^2/L using the two-point method. If the unit is operated at a flux of 50 L/m^2-hr (lmh), the duration of the fouling experiment (t_2) is approximately 2 hrs. Meanwhile, accuracy of the determined UMFI values depends primarily on the determination of J_s, especially J_{s0}. For a constant-flux filtration system, this is to a great extent determined by the accuracy of transmembrane pressure measurement. The pressure gauge used in this study had an accuracy of approximately ±0.01 psi, which led to a potential variation of $\pm 5 \times 10^{-5}$ m^2/L in UMFI value assuming a clean membrane transmembrane pressure of 2 psi and a V_{s2} of 100 L/m^2. This variation is usually negligible for UMFI values representing total fouling and hydraulically irreversible fouling, but can be significant for UMFI values representing chemically irreversible fouling. In comparison, many pressure gauges/transducers have accuracies of ± 0.1 psi or worse; it will increased the uncertainty to UMFI calculation if those gauges/transducers are installed on the membrane testing system.

2.5 Microbial removal test protocol

The microbial removal efficacy of commercially available membranes was determined with the bench-scale unit developed in this study. For this purpose, the bench-scale unit was carefully disinfected before each test by autoclaving the dissembled parts with saturated steam at 121°C and pumping 10 mg/L NaOCl solution through the installed system for 30 min, followed by chlorine quenching using NaS_2O_3 solution and ultrapure water flushing. Afterwards, feedwater containing the microorganism of interest was filtered through the testing unit; the feedwater and the permeate were also sampled for measurement of microbial concentration.

MS2 bacteriophage was used in this study as a surrogate human virus and was assayed using the double agar layer procedure described in EPA Method 1602 (United States Environmental Protection Agency 2001). Briefly, samples were mixed with log phase F+ ampicillin competent host *Escherichia coli* in 0.7% tryptic soy broth top agar containing 1.5 mg/mL of both ampicillin and streptomycin, and plated on 1.5% tryptic soy broth bottom agar. Duplicate inverted plates were incubated at 37°C over night, before counting plaques on the host bacteria lawn. Sample dilutions with between 30 and 300 plaques were considered quantitative, and were used for calculations of plaque forming units per mL (PFU/mL).

Cryptosporidium parvum (*C. parvum*) oocysts used in this study were originated from experimental infection of a calf. Sample tubes for assays were centrifuged (5,000 g, 10 min), the supernatant was discarded and the pellet resuspended in 100 µl of sterile PBS. The suspension was transferred onto a lysine-coated well (10-mm-diameter) on a teflon-coated glass slide (Carlson Scientific, Inc., Peotone,

IL). The slide well was air-dried and fixed with methanol (Graczyk, Cranfield *et al*. 1997; Graczyk, Fayer *et al*. 1997). The well was processed with FITC-conjugated monoclonal antibodies (mAb) against the cell wall antigens of *Cryptosporidium* using the MERIFLUORTM *Cryptosporidium* test kit (Meridian Diagnostic, Inc., Cincinnati, OH) (United States Environmental Protection Agency 1999). The entire well was examined for *C. parvum* oocysts with an Olympus BH2-RFL epifluorescent microscope, dry 60X objective and BP-490 exciter filter.

The operation of the bench-scale unit for microbial removal test was similar to membrane fouling test discussed previously. Hydraulic backwash and chemical cleaning were not conducted because their effects were not of interest. The bench-scale testing was conducted repeatedly with fresh modules for approximately 30 min, to determine the average and deviation of the microbial removal efficiency of the LPHF membrane.

3. Results and Discussion

3.1 System hydraulic performance

In order to simulate the operation of full-scale LPHF systems, the bench-scale system established in this study was operated in constant-flux mode. Fig. 3 illustrates the TMP versus permeate flux curves for a membrane module before and after being fouled by a natural surface water. The membrane module was fabricated by using Membrane B, a PVDF UF membrane with a tight pore structure as observed under scanning electron microscopy (data not shown) and a nominal pore size of 20 nm. As shown in this figure, linear correlations exist between TMP and flux over the broad flux range employed by full-scale systems for both clean and fouled membranes. Hydraulic resistances of the two modules can be calculated from the slopes of the linear curves using a revised Darcy's law equation:

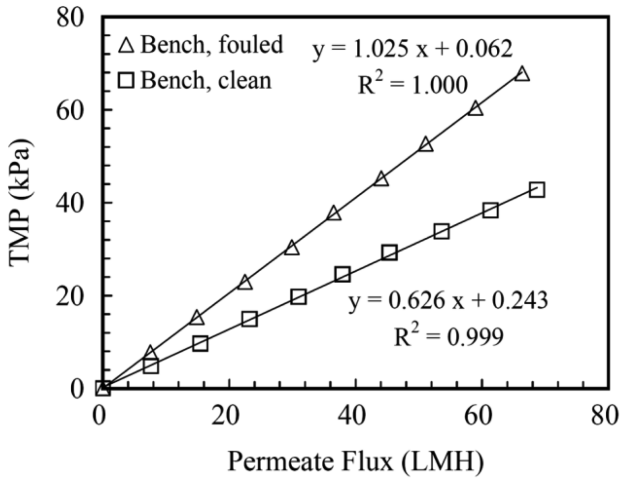

Fig. 3 TMP versus permeate flux obtained with a clean membrane module and a module fouled by a natural surface water in the filtration of purified water

$$R=\frac{3.6\times10^{9}}{\mu}\left(\frac{\mathrm{TMP}}{J}\right) \tag{2}$$

where R (m^{-1}) is the hydraulic resistance of the membrane, μ (Pa·s) is the viscosity of the testing water (purified water in this case), (TMP/*J*) is the ratio of TMP (kPa) and permeate flux (*J*, LMH), and 3.6×10^9 is a coefficient originated from different units used by other parameters of the equation. Given a water temperature of 25°C and corresponding water viscosity of 0.000891 Pa·s, the hydraulic resistances of the clean membrane and the fouled membrane were calculated as 2.53×10^{12} m^{-1} and 4.14×10^{12} m^{-1}, respectively, using Eq. (2). The difference between the hydraulic resistances of the two membrane modules was primarily ascribed to membrane fouling, and appeared to be independent of the operating TMP as indicated by the goodness of the linear fitting (Fig. 3). This suggests that the fouling resistance was not a function of TMP under the studied condition.

3.2 Reproducibility of membrane fouling results

Fig. 4 presents the cumulative distributions of $UMFI_T$, $UMFI_R$, and $UMFI_C$ values as a function of normalized differences of duplicate runs determined with four types of LPMs (Table 1, Membranes A, B, C and D) and 12 types of natural waters or pretreated waters in 19 filtration runs. Hydraulic backwash and/or chemical cleaning were not conducted in some runs due to low levels of total fouling or hydraulically irreversible fouling. Therefore, the numbers of $UMFI_R$ and $UMFI_C$ values are fewer than that of $UMFI_T$ values. As shown in this figure, the normalized difference in $UMFI_T$ and $UMFI_R$ values for duplicate runs varied between 0 to 0.5 with a median value of approximately 0.2. A broader difference was observed for $UMFI_C$ values due to relatively low levels of residual fouling after chemical cleaning. Overall, the normalized differences in UMFI values were within a narrow range of 0 to 0.3 for majority of filtration runs (p = 0.75) despite a broad variation of UMFI values between 0 and 1.97×10^{-2} m^2/L (data not shown).

Multiple filtration runs were conducted with a single membrane and water combination using the bench-scale system to determine the variability of membrane fouling. Fig. 5 illustrates the mean and standard deviation of $UMFI_T$ and $UMFI_R$ values obtained by an operator in 10 replicate filtration

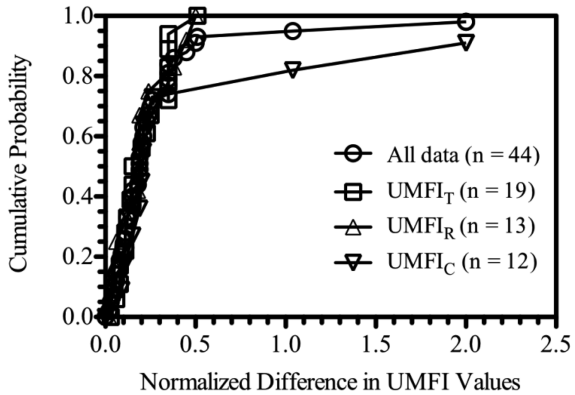

Fig. 4 Cumulative probability of the absolute difference in UMFI values determined in duplicate runs normalized to their mean value, *i.e.*, $(UMFI_1 - UMFI_2)/[(UMFI_1 + UMFI_2)/2]$. Calculation was based on 44 sets of UMFI data, including UMFIT (n = 19), UMFIR (n = 13) and $UMFI_C$ (n = 12)

Table 1 Properties of the LPHF membranes used in this study

LPHF membrane	Material [a]	Nominal pore size (μm) [b]	Outer diameter (mm)	Inner diameter (mm)	Configuration
A	PVDF	0.02	0.8	0.5	Outside-in, pressurized
B	PVDF	0.02	0.8	0.5	Outside-in, submerged
C	PVDF	0.1	0.8	0.5	Outside-in, submerged
D	PES/PVP	0.03	1.1	0.8	Inside-out, pressurized
E	PES	0.025	1.3	0.8	Inside-out, pressurized

Note: [a] PVDF – polyvinylidene fluoride, PES – polyether sulfone, PVP – polyvinylpyrrolidone. [b] manufacturer data.

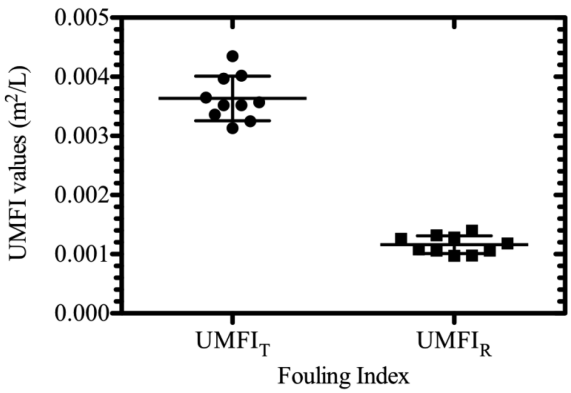

Fig. 5 Mean and standard deviation of $UMFI_T$ and $UMFI_R$ values determined by an operator in 10 filtration runs for one type of LPM and a natural surface water under similar operating conditions. Long and short bars represent the mean values and the standard deviations (n = 10), respectively

experiments. As shown in this figure, a $UMFI_T$ value of $3.68 \pm 0.38 \times 10^{-3}$ m^2/L and a $UMFI_R$ value of $1.16 \pm 0.15 \times 10^{-3}$ m^2/L were obtained based on the results of the replicate runs. Except for two data points for $UMFI_T$ and one data point for $UMFI_R$, the majorities of the UMFI values were within one standard deviation, indicating good reproducibility of the experimental results.

3.3 Reuse of membranes and membrane modules

Although virgin membranes are preferred in the evaluation of membrane fouling potential, bench-scale membrane modules may be reused when virgin membranes are unavailable, given effective cleaning of the membranes. Fig. 6(A) illustrates the decrease of membrane specific flux with cumulative permeate throughput for a PVDF MF membrane during the filtration of a natural surface water. The virgin membrane was effectively cleaned by chlorine cleaning and reused in the second run to filter the same water sample. As a result, the membrane module showed similar fouling profiles in two runs. In comparison, if a membrane was not effectively cleaned after fouling and reused in the bench-scale filtration experiment, substantial deviations in membrane fouling profiles may occur and complicate the interpretation of membrane fouling potential. As shown in Fig. 6(B), the fouled membrane had an initial specific flux of approximately 300 lmh/bar, which was about 70% of that of the virgin membrane. The two membrane modules deviated in their fouling profiles and a faster

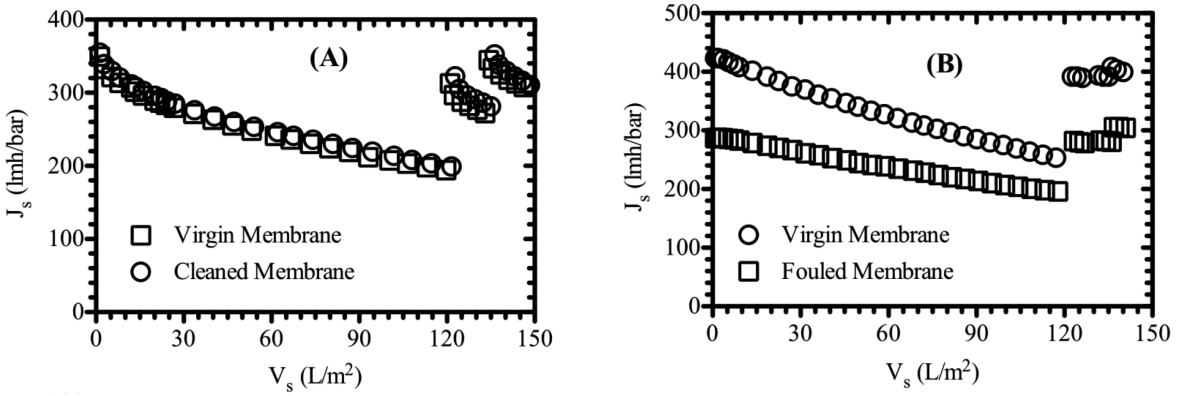

Fig. 6 Comparison of the fouling profiles of (A) virgin and reused cleaned PVDF MF membranes by a natural surface water, and (B) virgin and reused fouled membranes by a natural surface water

decrease in specific flux was observed with the virgin module. On the other hand, permeability of both modules was substantially restored after hydraulic backwash and almost to their initial levels after chlorine cleaning. In this case, reuse of fouled membrane appeared to affect the determination of total fouling, not that of fouling reversibility, which added uncertainties to the resistance of the membrane to fouling. Therefore, effective cleaning of fouled membranes is recommended if reuse of membrane modules is needed.

3.4 Scalability of bench-scale UMFI results

An important application of the bench-scale filtration unit was to predict the fouling potential of pilot- or full-scale LPHF membrane systems. Fig. 7 presents matched-pair analysis of the bench- and pilot-scale UMFI values obtained with two membrane-water pairs. Details of the pilot-scale tests have been provided elsewhere (Huang, Young *et al*. 2008; Lozier, Cappucci *et al*. 2008). These results showed that, for both membrane-water pairs, the total and irreversible fouling potentials determined with the bench-scale system were statistically comparable to those observed with the pilot-scale

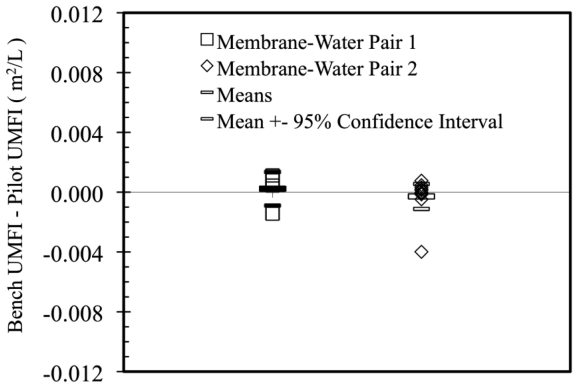

Fig. 7 Matched-pair analysis of the bench- and pilot-scale UMFI values obtained with two membrane-water pairs. Details of the pilot-scale testing have been presented elsewhere (Lozier, Cappucci *et al*. 2008)

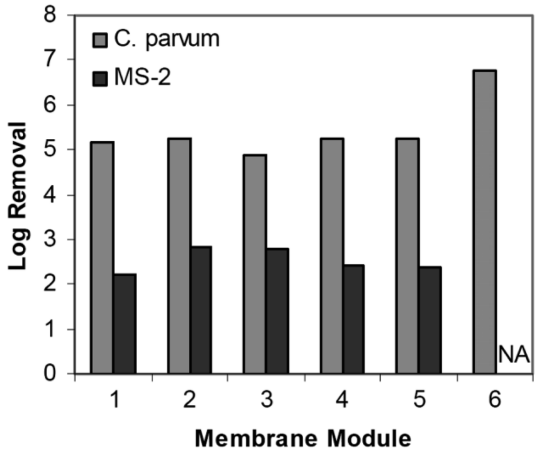

Fig. 8 Removal of Cryptosporidium parvum and MS2 bacteriophage by a commercially available LPMF membrane as obtained with various modules. NA – data not available

systems as the zero line of bench UMFI minus pilot UMFI is within 95% confidence intervals. This consistency in bench- and pilot-scale UMFI values was probably attributable to similar fouling mechanisms as the same membrane and water were used at two testing scales. As such, the bench-scale system developed in this study may serve as a "jar tester" for full-scale LPHF membrane applications.

3.5 Microbial removal by LPHF membranes

This bench-scale system was applied to determine the microbial removal efficacy of various commercially available LPHF membranes. Fig. 8 shows the removal efficiencies of MS2 bacteriophage and *Cryptosporidium parvum* (*C. parvum*) achieved by a pressurized LPHF membrane. As shown in the figure, $\log_{10}$ removal values (LRVs) of approximately 2 and 5 were observed for MS2 and *C. parvum*, respectively; the results were reproducible for different modules fabricated with this membrane. The variations in the LRVs observed for *C. parvum* were caused by variations in initial oocyst concentrations in the feedwater. Overall, the results were consistent to microbial removal efficacy claimed by the manufacturer, suggesting the validity of the bench-scale unit and the operating protocol elucidated previously.

It is noteworthy that LRVs obtained in the bench-scale experiments, in general, reflect the capability of the membrane in removing aquatic microorganisms. The performance of a full-scale LPHF membrane facility may, however, be affected by other factors, such as the imperfections in the construction of full-scale modules, thereby deviating from bench-scale results. Therefore, full-length modules should be used for membrane integrity testing as proposed in other studies (Jacangelo, Brown *et al*. 2006).

4. Conclusion

LPHF membranes have been increasingly employed in water and wastewater treatment both in the United States and around the world. Lack of suitable bench-scale technology, assessment of membrane

performance has to be carried out through costly and time-consuming pilot-scale trial tests during the design phase of full-scale membrane filtration facilities. Development of suitable bench-scale technology for the testing of commercially available LPHF membranes is, therefore, very important for their applications; a central part of this technology is a properly designed bench-scale testing unit.

A robust bench-scale membrane testing unit for LPHF membranes (Photo 3) was developed in this study. This unit is capable of accommodating commercially available LPHF membranes in various configurations (Fig. 1) with special designed fittings (Photo 2) and conducting performance test under conditions comparable for their full-scale applications. Corresponding protocols for the membrane fouling test and contaminant removal test have also been established and employed in the evaluation of representative types of LPHF membranes. The reproducibility of the fouling results obtained with this system was validated by replicate testing of a LPM and natural water pair, as well as duplicate testing of multiple LPM and natural water pairs.

The bench-scale unit developed in this study was also employed to rapidly determine the microbial removal efficacy of commercially available LPHF membranes. The experimental results showed that the LRVs determined with this unit and corresponding protocol were reproducible for different modules fabricated with the same type of membrane and were in good agreement with the values claimed by the membrane manufacturer.

This study established an important research and application tool for academia and water industry. The unit developed in this study may be employed by water utilities and other membrane users to screen candidate membranes for desired applications or by water utilities as a routine test to assess and optimize the operation of full-scale membrane filtration facilities. Further, it also makes it possible for academic researchers to investigate commercially available membranes under experimentally controllable and practically relevant conditions, which is beneficial for bridging the gap between laboratory studies and engineering applications.

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