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Integrity of hollow-fiber membranes in a pilot-scale anaerobic fluidized membrane bioreactor (AFMBR) after two-years of operation

Chungheon Shin [a], Kihyun Kim [a,b], Perry L. McCarty [a,c], Jeonghwan Kim [a], Jaeho Bae [a,*]

[a] Dept. of Environ. Eng., Inha University, Namgu, Inharo 100, Incheon, Republic of Korea
[b] Samsung SDI, 56, Gosan-ro, Uiwang-si, Gyeonggi-do 437-711, Republic of Korea
[c] Dept. of Civil and Environ. Eng., Stanford University, Stanford, CA 94305, USA

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ABSTRACT

Membrane integrity was evaluated for a pilot scale anaerobic fluidized bed membrane bioreactor (AFMBR) after operation for 765 days. Permeability and bubble point tests results for membrane specimens taken from the top of the membrane modules were similar to those of virgin membranes, thus no significant membrane damage was found at the top. On the other hand, membrane specimens taken from the middle and bottom sections were damaged severely by the continuous contact with fluidized 0.8–4 mm granular activated carbon particles as evidenced through scanning electron microscopy, as well as by permeability and bubble point tests. The occurrence of such significant membrane damage after only 2 years of operation indicates that membranes with a higher resistance to abrasion are desirable for use in the AFMBR.

1. Introduction

Anaerobic membrane bioreactor (AnMBR) treatment of domestic wastewater with its low energy requirement and secondary sludge production has been suggested as an alternative to aerobic MBR treatment [1,2]. Although inclusion of membranes not only enhances effluent quality through increase in solid retention time (SRT) and reduction in effluent suspended solids [3,4], an operational concern is membrane fouling caused by the deposition of foulant materials on membrane surfaces and/or within membrane pores [5]. Several methods to reduce fouling, such as backwashing, chemical cleaning, and biogas sparging, have been practiced.

GAC scouring is an alternative approach for fouling control in the anaerobic fluidized membrane bioreactor (AFMBR) [6], which combines an anaerobic fluidized bed bioreactor (AFBR) with submerged membrane technology. Unlike other fouling-control approaches, the fluidization of GAC particles by bulk liquid recirculation through the AFMBR results in scouring of the membrane surfaces via direct contact between GAC and the membranes. Our previous studies indicated the effectiveness of the AFMBR for domestic wastewater treatment. Shin et al. [7] applied a pilot scale staged anaerobic fluidized membrane bioreactor (SAF-MBR) system for the treatment of domestic primary clarified wastewater at ambient temperatures of 8–30 °C. With flux maintained between 7.5 and 6.1 L/m^2/h, the transmembrane pressure (TMP) generally remained below 0.5 bar without chemical cleaning for 765 days. Periodic relaxation (keeping GAC fluidizing without permeation) was helpful in reducing membrane fouling. Membrane fouling control with GAC scouring was successful over long-term operation and at low wastewater temperatures.

The AFMBR displayed at least a 50% lower energy requirement for membrane fouling control than an AnMBR using gas sparging. Reported energy consumption for the sparging method is 0.5–5.7 kW h/m^3 [8]. In contrast, the energy requirement for fouling control in the SAF-MBR pilot study was only 0.21 kW h/m^3, a value that could be lowered further by improved hydraulic design [7].

Despite the advantages of AFMBR treatment, membrane integrity under GAC fluidization was a concern. Smith et al. [5] suggested that GAC scouring of polymeric membranes might be harmful, causing substantial cost for membrane replacements. Wu et al. [9] found that vigorous rotation of GAC particles in a simple dead-end filtration cell was beneficial for fouling reduction, but caused a negative impact on membrane integrity. Because of these concerns, this investigation of the membrane integrity of the pilot-scale AFMBR after long-term operation was instigated. Membrane integrity was evaluated by comparing the changes in permeability and bubble point test results of the virgin membrane and the used membrane. In addition, scanning electron microscope (SEM) observations of membranes were made.

* Corresponding author.
E-mail address: jhb@inha.ac.kr (J. Bae).

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2. Materials and methods

2.1. Description of the pilot-scale AFMBR

The pilot-scale AFMBR was a second stage reactor that treated the effluent from an AFBR, which in turn was partially treating primary clarified domestic wastewater [7]. About 60% of the effective volume of the AFMBR (0.7 m^3) was occupied by 264 kg (dry weight) of GAC (Filtrasorb 300, Calgon GAC, USA). Prior to addition of the GAC to the reactor, the GAC was shaken on an 0.8 mm mesh screen to remove fine particles. The GAC sizes after screening ranged from 0.8 to 4.0 mm (Table 1). The GAC was fluidized using an upflow velocity of 75 m/h in the reactor as achieved with a recirculation flow rate of 0.53 m^3/min using a PIN-5001H, Wilo inline staged pump (Korea). The pilot-scale AFMBR was operated continuously with a permeate flux of 6.1–7.5 L/m^2/h without chemical cleaning for a total of 765 d.

2.2. Membrane sampling

Five membrane modules (Samsung SDI, Korea) were installed vertically in the pilot AFMBR in a cassette having a 0.9 m by 0.43 m cross section and a 2.27 m depth, as illustrated in Fig. 1. Each membrane module contained 630 polyvinylidenefluoride (PVDF) hollow-fiber membranes with nominal pore size of 0.03 μm and effective fiber length of 1.85 m. The effective surface area of each membrane module was 7.9 m^2. Both ends of the membranes were fixed in the membrane modules.

After 765 d of AFMBR operation, nine membrane specimens for evaluation were taken from the reactor at the locations indicated in Fig. 1b. From membrane module #1, membrane specimens were taken from five equally-spaced positions. From modules #2 and #3 membrane specimens were taken from only two different locations, one near the edge and the other at the center of the module. Each membrane specimen was then cut into three 61.7 cm samples representing the top, middle and bottom sections of each membrane as illustrated in Fig. 1a (front view). For membrane integrity testing, a 30 cm section was cut from the middle of each 61.7 cm specimen and these fiber specimens were used for fiber testing. Thus, the total number of fiber specimens was 27. Each fiber was then cleaned chemically by soaking for one day each in a 1000 mg/L NaOCl solution followed by a 5000 mg/L citric acid solution. Then, the fiber specimens were stored for about a day in DI water at room temperature prior to membrane integrity testing.

2.3. Fiber integrity test

Permeability of the fiber specimens was measured to determine changes that might have occurred through two years of AFMBR operation. Initially, DI water was drawn through a fiber specimen for 5–10 min to reach a steady TMP as determined with a digital pressure meter (Type 2089, Ashcraft, USA). Then, permeate flow rate was increased incrementally until the TMP reached 1.0 bar, and was held constant for 0.5–2 min to measure and record flowrate (L/h) and TMP. The permeability (L/m^2/h/bar) was calculated by dividing the permeate volume obtained by the time interval, the measured TMP, and the fiber surface area. Repeated tests in triplicate indicated that the permeability measurement gave good consistency for a given fiber specimen with a standard deviation of ±2%, and so a single permeability measurement for each fiber specimen was then considered to be adequate. The permeate flux determined at other than 20 °C was normalized to a temperature of 20 °C as follows Eq. (1) [10]:

$$J_{20} = J_T \times 1.024^{(20-T)} \quad (1)$$

where J_T is the average permeate flux (L/m^2/h) at the measured temperature T (°C).

The permeability obtained for each fiber after pilot operation was compared with that of the fiber before pilot operation. An increase in permeability, which may occur during pilot operation, would indicate that the membrane resistance (R_m) at the location of the fiber had decreased during operation, an indication that membrane damage had occurred.

Membrane integrity was also evaluated by performing bubble point tests on fiber specimens. The bubble point is defined as the minimum air pressure (bar) that when applied to a specimen immersed in water causes bubbles to start forming [11]. Bubble emission from fibers results at lower pressures with damaged fibers as a result of increased pore size. For this test, air was initially applied to a submerged fiber at 0.1 bar, and then the pressure was increased gradually until air bubble formation on the outside of the specimen was observed. Gas pressure was measured using a digital pressure meter (Type 2089, Ashcraft, USA).

SEM views of specimens was obtained with a Hitachi SEM s-4800 (Hitachi, Japan) with acceleration voltage of 5 kV and a working distance of about 8.5–9.2 mm. Membrane segments were cut from each membrane fiber and coated with platinum. Magnifications of about 40×, 400×, and 2000× were used to find the appropriate resolution for good examination of a segment's plain and cross-sectional views.

Table 1
Reactor GAC particle size mass distribution.

Size (mm)	Distribution (mass%)
0.80–0.85	3
0.85–1.00	5
1.00–1.18	5
1.18–1.40	29
1.40–1.70	2
1.70–2.00	19
2.00–4.00	38

3. Results and discussions

Fig. 2 illustrates the measured permeabilities for the membrane fibers. The permeabilities varied considerably, and tended to be dependent largely upon the vertical location along the membrane, but variation in the cross-sectional (horizontal) location of the membranes was also noted. The average permeability for all nine top-section fibers was 749 ± 78 L/m^2/h/bar, which compares well with that for the virgin hollow-fiber membrane of 700–800 L/m^2/h/bar (provided by the membrane manufacturer), indicating no significant damage had occurred to the upper portions of the membranes. However, the fibers taken from the middle section of the membrane showed a wide range of permeabilities, varying from a low of 811 to a high of 1406 L/m^2/h/bar, all of which (except for one case) are higher than that of the virgin membranes. The average and standard deviation here was 1030 ± 250 L/m^2/h/bar. Most damage here was in location ⑤, with permeabilities for all three modules at this location being higher than 1300 L/m^2/h/bar.

Interesting is that the bottom portion of the membranes displayed the largest permeability variation from a low of 461 L/m^2/h/bar in the center of module #1 to a high of 2075 L/m^2/h/bar at the rear of module #3. All permeabilities in the three center sections (461–633 L/m^2/h/bar) were lower than that of virgin materials. This suggests that here, pore clogging by foulants that were not removed by chemical cleaning occurred. In contrast, very high bottom permeabilities (1131–2075 L/m^2/h/bar), well above that of virgin material, were present in the rear membranes of modules #2 and #3. This suggests that extensive damage had resulted in these