Water reclamation with membrane bioreactors


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Abstract The City of San Diego was awarded a grant from the Bureau of Reclamation to investigate the feasibility of using Membrane Bioreactors (MBRs) for water reclamation. Based on the findings of the first phase of the project (Adham et al., 1998), the project team concluded that a parallel comparison of commercially available MBR systems needed to be evaluated at pilot-scale. Two submerged MBR systems were evaluated at the Aqua 2000 Research Center in Escondido, California. The project was designed to evaluate the MBR performance treating municipal wastewater and the feasibility of using the MBR permeate as a feed source for thin film composite reverse osmosis (RO) membranes. The first part of the project was dedicated to operating both MBRs in a nitrification and denitrification mode. After completion of Part 1 of the project, both MBR systems were retrofitted and operated in a nitrification only mode. Throughout both parts of the study, the effluent from each MBR was fed to two separate, single stage RO pilot systems. Both MBR systems showed high BOD removal with values below the detection limit, and significant TOC reduction. The effluent turbidities from the MBRs were consistently less than 0.1 NTU. Both MBRs also produced a high quality effluent that could be used by thin film composite RO membranes with minimal fouling.

Keywords Bioreactors; membranes; wastewater; water reclamation

Introduction

The increased need for reclaimed water in arid environments has resulted in the emergence of new wastewater reclamation technologies. The membrane bioreactor (MBR) is one of these new technologies that combines activated sludge treatment with a membrane separation process. The reactor is operated in a similar way to conventional activated sludge (CAS), however a clarifier is not needed. Instead, a low-pressure membrane, either a microfiltration (MF) or ultraviolet (UF), is used to perform the sludge separation. The combination of an activated sludge and membrane process produces water that has undergone secondary, tertiary and low-pressure membrane treatment using only one unit operation.

The MBR process has been shown to provide high quality effluent with high BOD removal, complete nitrification and partial denitrification (Cicek et al., 1998; Fan et al., 1996; Kishino et al., 1996). The MBR process has also shown good TOC removal, and complete TSS reduction (Cicek et al., 1998). The MBR effluent also has the added advantage of being low in turbidity and SDI values, making it possible to use as feed water to an RO system. Previous pilot-scale work using MBR effluent as feed water to an RO system has shown moderate success (Lozier et al., 1999).

Because a membrane is performing the separation instead of a clarifier, the MBR can be operated at higher mixed liquor suspended solids (MLSS) concentrations, and longer solids retention times (SRT) (Cote et al., 1997). The removal of the clarifier further eliminates such problems as sludge bulking, pin floc and various other settling problems associated with clarifier operation, (Metcalfe & Eddy, 1991) and the overall footprint of the system is much smaller than a CAS facility.

The sludge separation can be performed in one of two ways. (Adham et al., 1999) The in-
line MBR configuration pumps sludge from a reactor to a pressure-driven membrane where the solids are retained and the water passes through the membrane. The membranes are systematically backwashed in order to remove solids build-up, and are chemically cleaned when operating pressures become too high. Lyonnaise-des-Eaux/Degremont is a French based company that is currently marketing the in-line configuration MBR.

The submerged MBR configuration has a low-pressure membrane submerged in the reactor and operates under vacuum pressure. The membrane is agitated by coarse air that assists in preventing solids build up at the membrane surface. The submerged membranes are also systematically backwashed, and are chemically cleaned when operating pressures become too high. There are currently three companies that are marketing the submerged MBR configuration: Mitsubishi Rayon Corporation (Mitsubishi) from Japan, Zenon Environmental Systems, Inc. (Zenon) from Canada, and Kubota Corporation (Kubota) from Japan.

The MBR process has been implemented at full-scale installations all over the world (Adham et al., 1998). To date, the largest MBR installation operating on municipal wastewater in the United States is a Zenon system in Arapahoe County, Colorado. The system is a retrofitted sequencing batch reactor with a 1-MGD flow capacity (Mourato et al., 1999).

Methodology

Feed water characteristics

All pilot testing for the project was performed at the Aqua 2000 Research Center at the San Pasqual Water Reclamation Plant (SPWRP) in Escondido, California. The pilot units were operated using the primary effluent wastewater that was treated by the SPWRP. Municipal raw sewage passed through a travelling screen, vortex grit chamber, rotary drum screen, and a rotary disc filter. A portion of the primary effluent waste stream was diverted to the MBR pilot units.

Mitsubishi MBR pilot unit

A Mitsubishi MBR pilot unit with a capacity of 11,700 gpd (44 m³/day) was initially seeded with activated sludge from the North City Water Reclamation Plant (NCWRP). The pilot unit came equipped with a 1,250-gallon (4.73 m³) serpentine anoxic tank and a 1,700-gallon (6.44 m³) aerobic tank (see Figure 1). Two mixers were installed in the anoxic tank during the study in order to keep the tank well mixed. During Part 2 of the testing, the anoxic tank was taken out of service, and the aerobic tank overflow pipe was used to perform the batch wasting. Two membrane banks were submerged in the aerobic tank, where coarse air
diffusers agitated the membranes continuously, and aerated the biomass. Each membrane bank consisted of 50, 1 m² (10.76 ft²) Mitsubishi Sterapore HF microfiltration membranes with a nominal pore size of 0.4 microns, for a total of 100 m² (1,076 ft²) of membrane surface area. The hollow fibers are arranged horizontally and are attached at both ends to two permeate lines. The hollow fiber membranes operated under vacuum pressure. The original membrane that was tested during Part 1 had a design flaw that warranted its replacement. The membrane had plastic support material at the center of the fibers to help support the fibers. However, this support material was thought to cause more frequent fiber breakage. Consequently, an identical membrane was installed that did not have the plastic support material.

**Zenon MBR pilot unit**

A Zenon MBR pilot unit with a capacity of 10,000 gpd (38 m³/day) was initially seeded with activated sludge from the NCWRP. The pilot unit came equipped with a 750-gallon (2.84 m³) anoxic tank, a 1,300-gallon (4.92 m³) aerobic tank and a 185-gallon (0.7 m³) ZenoGem pilot unit (see Figure 1). A submersible pump, placed in the primary effluent break tank, was controlled by the PLC and fed the MBR. During Part 2 of the testing the anoxic tank was taken out of service and the primary effluent was fed directly to the aerobic tank. One membrane cassette, with a surface area of 500 ft² (46.5 m²) was submerged in the ZenoGem tank where it was agitated with coarse air diffusers. During Part 1 the coarse air in the ZenoGem tank ran continuously, however during Part 2 the coarse air in the ZenoGem tank ran for 10 seconds on and 10 seconds off. At the beginning of Part 1 of the study, the Zenon OKC MF was tested, with a nominal pore size of 0.1 microns. However, this membrane did not perform adequately and was replaced by the Zenon OCP UF membrane, with a nominal pore size of 0.035 microns and the same surface area as the MF.

**RO pilot units**

Each RO pilot unit housed two pressure vessels in series, operating in a single stage mode. Each pressure vessel contained 3 spiral wound 4 in by 40 in (10.2 cm × 101.6 cm) TFC RO membranes. Both RO pilot units contained Dow/Filmtec low-pressure polyamide BW30-4040 RO membranes, and were operated at a constant flux, variable pressure mode. The RO influent was initially dosed with a manufacturer recommended 1-ppm dose of King Lee antiscalent, and was then filtered through a 5-micron cartridge filter. A 1-ppm target concentration of chloramines was also maintained in the RO feed. The effluent from the cartridge filter was then passed through a high-pressure pump where it entered the first pressure vessel.

The RO treating Mitsubishi MBR effluent was operated with 6 membrane elements at a 12-gfd (20.4 L/hr-m²) flux for the duration of the study. During Part 1 of the study, the RO downstream of the Zenon MBR operated at a lower flux because of the reduced capacity of the Zenon MBR. For Part 2 of the study, 3 of the RO elements were replaced with 3 dummy elements to reduce the surface area of membrane by half. As a result, the RO pilot unit was operated at a flux of 12 gfd.

**Results and discussion**

**Membrane performance**

The Mitsubishi MBR membrane showed good throughout Parts 1 and 2 of the study. A chemical clean (see Figure 2) was performed once on the original Mitsubishi MBR membrane, and three times on the new membrane during Part 1 of the testing. The chemical cleaning involved slowly backpulsing a 3,700-ppm sodium hypochlorite solution through the membrane in place in the activated sludge tank. The Mitsubishi MBR was operated at a
target flux of 13 gfd for the duration of the study. The first chemical clean was performed after 1652 hours of operation with the original membrane. The vacuum pressure was reduced from 4.27 psi (0.29 bar) to 1.42 psi (0.10 bar). After the new membrane was installed, see Methodology, the system ran for 1986 hours, and a chemical clean was performed. The chemical cleaning reduced the vacuum pressure from 3.98 psi (0.27 bar) to 2.56 psi (0.18 bar). The first two cleanings were performed over a 2-hour period as recommended by the manufacturer. In an attempt to achieve better membrane recovery, all other cleanings were performed for 3 hours. After the initial cleaning of the new membrane, the membrane was cleaned after 864 hours, and again after 823 hours. The second cleaning on the new membrane reduced the vacuum pressure from 4.41 psi (0.30 bar) to 2.13 psi (0.15 bar). The final cleaning for Part 1 reduced the vacuum pressure from 4.27 psi (0.29 bar) to 2.70 psi (0.19 bar).

A chemical cleaning was performed on the Mitsubishi membrane in between Part 1 and Part 2. The membrane soaked in a 1,000-ppm sodium hypochlorite solution overnight. Three chemical cleanings were performed on the Mitsubishi MBR during Part 2 of the testing. A chemical clean was performed during the first week of operation in order to observe any further recovery of the membrane after the full tank soak. The chemical clean did not give any more recovery. After the initial cleaning, the MBR ran for 1337 hours.
before another chemical cleaning was required. The chemical cleaning reduced the vacuum pressure from 4.6 psi (0.3 bar) to 2.6 psi (0.18 bar). After the chemical cleaning was performed, the MBR ran for another 987 hours before another chemical clean was required. The chemical cleaning lowered the vacuum pressure from 4.1 psi (0.28 bar) to 2.9 psi (0.20 bar).

The Zenon MBR membrane performed well over the duration of the study. During the start-up period of the Zenon MBR in Part 1, the system was operated using only the ZenoGem tank. During this time, the membrane did not need to be chemically cleaned (see Figure 3). The system was initially operated at 6 gfd (10.2 L/hr-m²). Upon the installation of the auxiliary reactors, the membrane ran for 185 hours at a flux of 25 gfd (34 L/hr-m²), before it reached a high vacuum alarm. The flux was then lowered to 20 gfd (34 L/hr-m²) until the UF membrane was installed. The UF membrane was initially operated at a flux of 19 gfd (32.3 L/hr-m²), and then at 22 gfd (37.4 L/hr-m²) after 760 hours of operation. The UF membrane ran for a total of 2082 hours before a chemical clean was performed. The chemical clean involved soaking the membrane in a 2,000 mg/L sodium hypochlorite solution over night. The chemical cleaning reduced the vacuum pressure from 8.10 psi (0.56 bar) to 1.47 psi (0.10 bar). During the membrane filter cycle, the manufacturer recommended that the backpulse pressure be turned down. After the chemical clean, the

Figure 3 Membrane performance of the Zenon MBR
membrane began to foul rapidly. It was initially thought that the decreased back pulse pressure was causing the membrane to foul. The back pulse pressure was returned to its initial value, but showed no difference in the fouling trend. Upon further examination, the blower airflow in the ZenoGem tank had decayed due to a blower malfunction. This airflow decrease corresponded to the fouling events.

For Part 2 of the study, the Zenon MBR was operated under intermittent aeration. The blower providing the coarse air to the membrane in the ZenoGem tank was operated for 10 seconds, and was shut off for 10 seconds, and the airflow in the aerobic tank was run continuously. Intermittent aeration gives the advantage of reducing power consumption by the aeration system. The Zenon MBR pilot unit was operated for 1,007 hours at 19 gfd (32.3 L/hr-m²) under continuous aeration in order to observe a fouling trend during Part 2 of the testing. After the initial 1,007-hour run, the unit was operated with intermittent aeration at the same flux. The fouling trend did not appear to be affected by the initiation of the intermittent aeration, and the membrane ran without chemical cleaning for 2,087 hours. The vacuum pressure increased from 1.72 psi (0.12 bar) at the beginning of Part 2, to 3.49 (0.24 bar) psi at the conclusion.

The RO unit following the Mitsubishi MBR ran for a total of 2,345 hours at 12 gfd (20 L/hr-m²) at a recovery of 50% (see Figure 4) before a chemical clean was performed.
The RO pilot unit ran for another 1,143 hours with no sign of fouling during Part 1. The RO unit ran for an additional 1,985 hours without a chemical clean during Part 2 of the testing. The specific flux of the RO unit remained consistent throughout the testing.

The RO unit following the Zenon MBR ran for a total of 3,350 hours (see Figure 5) without a chemical clean and with no signs of fouling during Part 1. The flux was adjusted from 12 gfd (20 L/hr-m²) to 6 gfd (10 L/hr-m²) and finally to 9 gfd (15 L/hr-m²) based on the Zenon MBR flux. The recovery was initially 50%, then 33% and finally 43%, respectively. The RO unit ran for an additional 1,796 hours at 12 gfd, and a recovery of 32%, without a chemical clean during Part 2 of the testing. The specific flux of the RO unit remained consistent throughout the testing.

Organic removal

All BOD samples were analyzed according to Standard Methods for the Examination of Water and Wastewater. Both MBR systems showed good BOD removal throughout the testing. The Mitsubishi MBR produced effluent with BOD values less than 20 mg/L with a majority of samples being below the detection limit. The nitrogenous BOD method was used during the testing, which resulted in increased BOD values corresponding with ammonia presence in the effluent in the Mitsubishi MBR. The Zenon MBR produced efflu-
ent water with BOD values less than 11 mg/L with a majority of the samples below the detection limit.

All TOC samples were analyzed using a Sievers 800 Portable TOC analyzer. Primary effluent DOC grab samples ranged in values from 9 to 20 mg/L. Both the Mitsubishi and Zenon MBRs produced effluent water with consistent TOC values less than 10 mg/L with a majority of samples less than 7 mg/L.

**Particulate removal**

All turbidity samples were analyzed using a Hach 2100N bench top turbidimeter. The MBRs produced water with consistent turbidities less than 0.1 NTU. The Mitsubishi MBR effluent turbidity was higher when the original membrane was in production. However, upon the replacement with the new membrane, all effluent turbidities were less than 0.1 NTU. The Zenon MBR had higher turbidities when the microfilter was in production. The replacement with the ultrafilter resulted in turbidities less than 0.1 NTU.

All SDI analyses were performed using a Chemetek FPA 2000 SDI machine and 0.45 micron filter paper. Upon the installation of the new membrane in the Mitsubishi MBR, the SDI values were consistently less than 2. The Zenon showed SDI values less than 2 after the installation of the ultrafilter, with a majority of values less than 1.

**Inorganic nitrogen removal**

All inorganic nitrogen species were analyzed using a Hach DR/4000 Spectrophotometer. During Part 1 of the testing, each MBR system was operated in a nitrification/denitrification mode. The primary effluent NH$_3$-N values ranged from 20 to 50 mg/L. The NO$_3$-N and NO$_2$-N samples were all less than 1 mg/L.

The Mitsubishi MBR did show complete nitrification at times with NH$_3$-N values less than 1 mg/L during Part 1. However, the nitrification did not occur at all times due to inadequate aeration supplied by the coarse air diffusers. The NO$_3$-N values were between 0.5 and 25 mg/L and all of the NO$_2$-N values were less than 5 mg/L. The dissolved oxygen concentrations (DO) ranged in value from 0.5 to 4 mg/L in the aerobic tank, and 0.3 to 1.3 mg/L in the anoxic tank.

In part 2 of the testing, supplemental fine air diffusers were installed to promote nitrification. The effluent NH$_3$-N concentration spikes in Part 2 of the testing correspond to chemical cleanings. The high chlorine solution kills off a significant amount of nitrifiers causing nitrification to decrease. The system did show complete nitrification at times with values less than 1 mg/L. The NO$_3$-N values were between 5 and 25 mg/L and all of the NO$_2$-N values were less than 5 mg/L. The DO concentrations ranged in value from 1 and 5 mg/L. The installation of the fine air diffusers helped in maintaining DO concentrations suitable for nitrification.

The Zenon MBR did show complete nitrification at times with values less than 1 mg/L during Part 1. The majority of NH$_3$-N values were less than 5 mg/L. The NO$_3$-N values were between 2 and 25 mg/L and all of the NO$_2$-N values were less than 5 mg/L. The target DO concentration was above 1 mg/L in order to encourage nitrification. The anoxic tank DO was targeted to be less than 0.5 mg/L. The system did not achieve total denitrification, but did achieve partial denitrification most of the time.

During Part 2, the system did show complete nitrification at times with values less than 1 mg/L. The majority of NH$_3$-N values were less than 5 mg/L. The NO$_3$-N values were between 5 and 25 mg/L and all of the NO$_2$-N values were less than 5 mg/L. The DO was maintained between 1 and 4 mg/L in order to encourage nitrification.

**Microbial removal**

All total and fecal coliform samples were analyzed according to Standard Methods for the
Examination of Water and Wastewater. The total coliphage samples were analyzed using the membrane filtration method. Both MBR systems showed good removal of total coliform and fecal coliform. A majority of the Mitsubishi MBR effluent samples were below the detection limit. The Zenon MBR effluent did show some total coliform during Part 1 of the study. The decrease in total coliforms in Part 2 is probably due to irreversible pore blocking of the membrane, which results in decreased particle breakthrough of the membrane.

There was also an observed decrease in total coliphage in the effluent of both MBR systems, with the majority of the samples below the detection limit. This is unexpected because coliphage is much smaller than the pores of the membranes. This reduction is probably due to virus particles adsorbing to larger particles that are rejected by the membranes.

**Salt rejection**

Conductivity samples were collected as grab samples and were analyzed with a Fisher Scientific Conductivity Meter. The RO pilot unit treating the effluent from the Mitsubishi MBR showed consistent salt rejection of over 98% over the duration of the study. The RO pilot unit treating the effluent from the Zenon MBR also showed consistent salt rejection of over 98% over the duration of the study.

**Conclusions**

**Conclusions from part 1**

- The MBR pilot systems were capable of producing a good quality effluent water suitable for use by an RO system in a nitrification/denitrification mode.
- Both membranes were operated at reasonable cleaning intervals.
- The airflow rate used to agitate the membrane fibers is a critical parameter in respect to membrane fouling rate.
- Both systems showed high removal of total and fecal coliforms and total coliphage.
- The Zenon MBR pilot system achieved complete nitrification and partial denitrification at times, and the Mitsubishi MBR pilot system achieved complete nitrification and significant denitrification at times.
- The RO pilot unit following the Mitsubishi MBR only required one chemical clean during the duration of Part 1.
- The RO pilot unit following the Zenon MBR did not require a chemical clean during the duration of Part 1, however it was operated at a lower flux rate than the RO skid following the Mitsubishi MBR.
- Both RO units achieved high salt rejection over the duration of Part 1.

**Conclusions from part 2**

- The MBR pilot systems were capable of producing a good quality effluent water suitable for use by an RO system in a nitrification only mode.
- Both membranes were operated at reasonable cleaning intervals.
- Both systems showed high removal of total and fecal coliforms and total coliphage.
- Both systems were capable of complete nitrification.
- Neither RO pilot unit required a chemical cleaning throughout the entire Part 2 testing.
- Both RO units achieved high salt rejection over the duration of Part 2.

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