Breathing new life into wastewater treatment

A membrane-aerated biofilm reactor cassette is removed from the side-stream demonstration reactor at the Terrence J. O'Brien Water Reclamation Plant. GE, used with permission

Membrane-aerated biofilm reactor holds promise as a means of removing nutrients cost-effectively while using less energy

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Process intensification at water resource recovery facilities has captured the attention of the wastewater sector. Interest has grown in new approaches to increase wastewater treatment capacity and capability within existing infrastructure. Working toward energy neutrality represents one approach by which utilities are defining and measuring their goals in this area.

The Metropolitan Water Reclamation District of Greater Chicago (MWRD) knows firsthand about the pathway to energy neutrality. Comprising seven treatment facilities and serving millions of customers, MWRD is focused on becoming an energy-neutral wastewater treatment leader by the year 2023. The strategy involves harnessing the energy naturally present in wastewater and using it in a reliable, efficient, and cost-effective manner.

In the pursuit of energy neutrality, utilities must continue their day-to-day responsibility of protecting public health and the environment. For MWRD, this means adapting its facilities to meet more stringent treatment requirements, such as the removal of total phosphorous.

MWRD partnered with GE Water & Process Technologies (Trevose, Pa.) to test an innovative membrane-aerated biofilm reactor (MABR). (See Figure 1, p. 33.) The technology potentially could enable enhanced biological phosphorous removal (EBPR) in existing tank volumes, obviating the need for additional infrastructure. MABR's other benefits include improving treatment performance for total suspended solids (TSS) as well as ammonia removal during stressed conditions – specifically, cold-temperature peak-flow periods – and reducing energy requirements for aeration.

Table 1. O'Brien Water Reclamation Plant influent characteristics and effluent requirements (mg/L)

	Primary effluent (2015)	Current limit (summer/winter)	Assumed future limit (summer/winter)
Biochemical oxygen demand, average day	62	10 / 10	10 / 10
Total suspended solids, average day	77	12 / 12	12 / 12
Ammonia, monthly average	11	2.5 / 4.0	2.5 / 4.0
Ammonia, daily maximum	18	5.0 / 8.0	5.0 / 8.0
Total phosphorus	2.7	n/a	1.0 / 1.0

Deploying the demonstration system

MWRD installed a demonstration system at its Terrence J. O'Brien Water Reclamation Plant (WRP) in Skokie, Ill., for a yearlong study. The goal was to evaluate the technology's ability to increase the existing aeration tank capacity by providing nitrification in a much smaller tank volume than that required by conventional activated sludge. This change effectively would expand the capacity of existing aeration tanks, enabling the addition of an anaerobic zone for EBPR without requiring additional infrastructure. MWRD also wanted to assess MABR's ability to improve removal of TSS and ammonia, benefits afforded by the system's ability to operate at a lower concentration of mixed liquor suspended solids. The last evaluation centered around MABR's potential to reduce the energy requirements of aeration by up to 40% compared to the current mode of operation.

The O'Brien WRP employs primary clarification and conventional activated sludge for the removal of TSS, biochemical oxygen demand (BOD), and ammonia. The facility comprises four secondary treatment batteries, each of which processes approximately one-quarter of the flow in dedicated bioreactors and secondary clarifiers. Table 1 (above) lists the current and future effluent requirements for the facility.

A full-scale cassette was installed at the facility in a side-stream configuration and tested from June 2015 to June

Table 2. 12-month results of the membrane-aerated biofilm reactor demonstration unit at the O'Brien Water Reclamation Plant

	Number of analyses	Feed, (mg/L)	Reactor or effluent	Removal (%)
Mixed liquor suspended solids (mg/L) in reactor	218	–	2100	–
Dissolved oxygen (mg/L) in reactor	237	–	0.5	–
Temperature (°C) in effluent	232	–	16.7	–
Ammonia (mg/L) in effluent	229	9.2	6.6	–28
Nitrate + nitrite (mg/L) in effluent	89	2.1	2.8	–35
Filtered biochemical oxygen demand (mg/L) in effluent	55	6.2	3.6	–42

Figure 1. The basic principle of membrane-aerated biofilm reactor technology

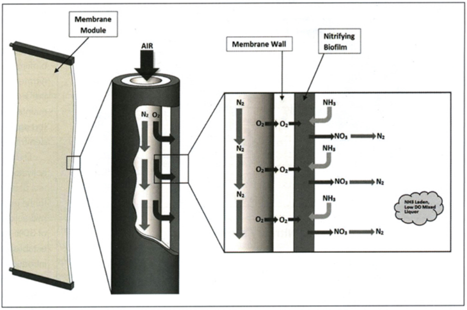


Figure 2. The membrane-aerated biofilm reactor (MABR) demonstration unit at the O'Brien Water Reclamation Plant

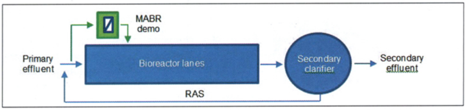
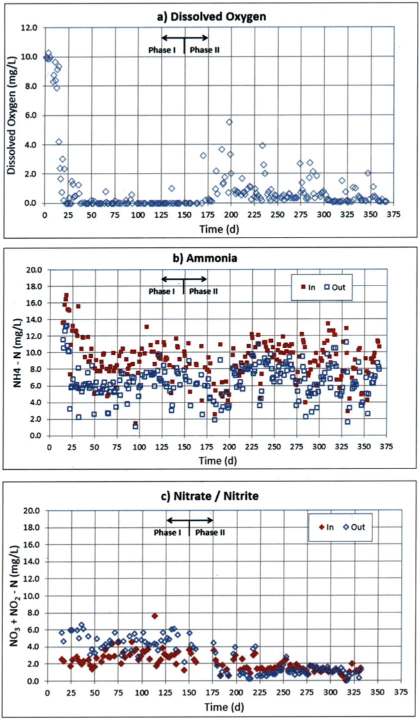


Table 3. Oxygen transfer rate and nitrification rate performance of membrane-aerated biofilm reactor demonstration unit at the O'Brien Water Reclamation Plant

	Range	Average
Oxygen transfer rate*	8 to 12 g $O_2/m^2 \cdot d$	10.5 g $O_2/m^2 \cdot d$
Nitrification rate	1.0 to 3.0 g $N/m^2 \cdot d$	1.6 g $N/m^2 \cdot d$

* Excludes three short periods: 21 days for biofilm establishment, 7 days for reduced process air flow rate, and 10 days due to oxygen measurement issues.

Figure 3. Chronological results for dissolved oxygen, ammonia, and nitrate + nitrate concentrations



2016. The side-stream approach ensured that the pilot test would not affect the performance of the O'Brien WRP. The study was complemented with a process modeling exercise to optimize operational parameters, because the side-stream configuration did not enable verification of all process parameters. Rather than being immersed in the bioreactor, the demonstration unit was housed in a separate container. This allowed for reasonable scale and facilitated monitoring performance through a mass balance on the liquid side. Figure 2 (see p. 33) shows a process flow diagram of the O'Brien WRP test system.

The cassette was fed with ambient air through the lumen of the hollow fibers, and mixing air was directed to a coarse-bubble grid located at the bottom of the cassette to mimic a continuous stirred-tank reactor. The oxygen supplied by the membrane created an aerobic environment within the biofilm, facilitating nitrification. The resulting nitrate then underwent denitrification within the surrounding mixed liquor, which was maintained in anoxic conditions. Essentially, the reactor conducts nitrification–denitrification simultaneously.

Blended primary effluent and return activated sludge were pumped through the unit at a flow rate of 65 m³/h and discharged back to the existing bioreactor, corresponding to a hydraulic retention time of 16 minutes. A target of 30% removal of ammonia by the biofilm was established, as that amount would enable the introduction of a suspended growth anaerobic zone for EBPR without having to establish new infrastructure. (See explanation of EBPR on p. 36.).

Assessing the results

Results cover a 367-day period (June 14, 2015, through June 15, 2016) divided into two phases. Phase I lasted 145 days, during which the cassette contained 64 modules. Phase II lasted 222 days, during which the cassette contained 48 modules. For Phase II, 48 of the original 64 modules were transferred to a 48-module cassette so that testing could continue without having to grow biofilm on new modules.

Table 2 (see p. 33) provides a simple, high-level overview of the 367-day MABR pilot test at the O'Brien WRP. The mixed liquor suspended solids concentrations measured during the pilot test were similar to the values obtained for the overall facility and ranged between 1500 and 3000 mg/L, with an average of 2100 mg/L. Low dissolved oxygen in the mixed liquor around the membranes was maintained most of the time. Initially, the membranes transferred oxygen into the bulk to the point of saturation, but oxygen levels declined to zero within a month (see Figure 3a, p. 34). Under normal operating conditions, the biofilm completely used the oxygen transferred by the membrane. Significant dissolved oxygen levels in the reactor resulted from rain events or snow melt and low organic and ammonia loading.

Figure 4. Nitrification rate versus ammonia loading rate

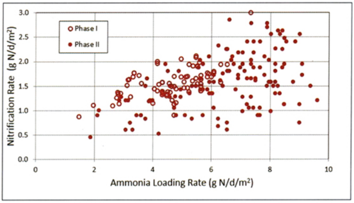
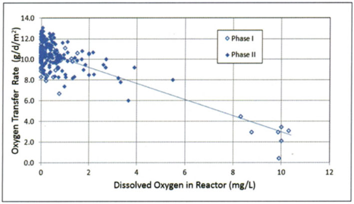


Figure 5. The effect of dissolved oxygen on the oxygen transfer rate



The feed ammonia concentration, after dilution with return activated sludge, averaged 9.2 mg/L. On average, this concentration was reduced by 2.6 mg/L, or 28% of the feed concentration (see Figure 3b, p. 34). The concentration of nitrate plus nitrite increased, on average, by 0.7 mg/L. Because more ammonia was nitrified than nitrate and nitrate were created, denitrification can be assumed to have occurred in the reactor, mostly during Phase II, as evident in Figure 3c (p. 34). On average, the feed contained 6.2 mg/L of filtered BOD, of which the reactor removed 2.6 mg/L, or 42%. The average carbon-to-nitrogen ratio, calculated as filtered BOD divided by ammonia, was 0.7, which is rather low for an optimal biological nutrient removal process.

Evaluating membrane performance

Table 3 (p. 34) provides detailed information on the oxygen transfer rate and nitrification rate throughout the duration of the demonstration. The MABR cassette was removed from the reactor six times during the demonstration for general observation and biofilm sampling. Biofilm grew to 200 µm within a month and

Membrane-aerated biofilm reactor

What is a membrane-aerated biofilm reactor (MABR)?	An innovative gas-transfer membrane that delivers oxygen to a biofilm attached to the membrane surface. Oxygen-permeable hollow-fiber membranes distributed around a reinforcing core create a flexible, yet unbreakable, "cord." Multiple cords are configured into top and bottom headers to create a module. Modules are installed in cassettes, which are placed in biological reactor.
How does it work?	The top header delivers and distributes low-pressure air to the inside of the fiber lumens. As the air travels down the membrane, oxygen diffuses through the membrane, where it is consumed by bacteria that have collected into a biofilm on the membrane's surface. The bacteria in the biofilm metabolize ammonia and organic material in an aerobic environment (see Figure 1, p. 33).
What are the benefits?	Intensification of nutrient removal. Increasing biomass inventory in existing biological reactors improves nutrient removal without requiring new infrastructure. Energy savings increases because diffusion delivers oxygen to the biofilm up to four times more efficiently than conventional bubble aeration. The small footprint of the MABR enables nutrient removal and capacity expansion in existing bioreactor volumes. Simplicity comes during construction because cassettes are installed into existing bioreactor basins with minimal effect on facility hydraulics and use existing air-supply systems.

What is enhanced biological phosphorous removal (EBPR)?

A sustainable method of phosphorus removal, EBPR involves creating an anaerobic zone ahead of the aeration tank to facilitate the release of accumulated phosphorous by phosphorous-accumulating organisms. The phosphorous then is taken up in the aeration tank, where it is removed and recovered as a resource.

With its current process configuration, the O'Brien Water Reclamation Plant would require the construction of a new treatment battery to facilitate the introduction of an anaerobic zone in every aeration battery. However, if a membrane-aerated biofilm reactor can increase nitrification capacity and accommodate 30% removal of ammonia, thus creating an anaerobic zone without adding to the footprint, then, EBPR can be implemented in the existing infrastructure.

consistently stayed in the 200 to 300 μm range.

The nitrification rate is plotted against the ammonia loading rate in Figure 4 (see p. 35). Although variability is significant, the data show a relationship between the two parameters. Different symbols for Phase I and Phase II illustrate the change of cassette from 64 to 48 modules. The data are more scattered through Phase II because of feed variability during winter conditions. On average, the nitrification rate was equal to 27% of the ammonia loading rate.

Figure 5 (see p. 35) shows the effect of dissolved oxygen on the oxygen transfer rate. The buildup of oxygen in the reactor has a strong negative effect, which can result from the absence of a biofilm. Such occurrences are reflected by the Phase I data points for dissolved oxygen in the range of 8 to 10 mg/L, when the membranes first entered service, as well as Phase II data points in the range of 1 to 4 mg/L, resulting from rain events. The MABR process works best when dissolved oxygen is less than 1 mg/L in the reactor.

Assessing energy requirements

The MABR process reduces the energy needed for biological treatment. Energy savings take three forms:

- reduced overall oxygen demand from operating the suspended portion of the biomass at lower solids retention time, without compromising nitrification;
- reduced oxygen demand from simultaneous nitrification/denitrification in an anoxic zone, without the need for recirculation pumping; and
- more efficient oxygen transfer as compared to fine-bubble diffusion.

Of these three forms of energy savings, the MABR demonstration at the O'Brien WRP only showed the improved oxygen transfer. Because of the project's small scale, all the air required by the demonstration unit was supplied by a compressor, rather than a low-pressure blower. Therefore, it was not possible to directly monitor the power draw and use it to validate energy consumption.

Based on optimized process conditions demonstrated in the study, the aeration efficiency of the MABR membranes was 3.6 and 4.0 kg of oxygen per kWh for the 48 and 64 module cassettes, respectively. GE is working on two product improvements that would increase the aeration efficiency to 6.5 and 7.0 kg of oxygen per kWh for the 48 and 64 module cassettes, respectively.

Promising potential

The 1-year study of the MABR technology at the O'Brien WRP demonstrated the technology's potential to intensify nitrogen removal in a small tank volume while also reducing the energy needed for biological treatment.

Incorporating the performance results into a process model showed that full-scale implementation of MABR at the O'Brien WRP would reduce the energy demand of the aeration system by about 30% compared to the current mode of operation. To achieve this, about one-third of the facility's reactors would be converted into anoxic zones in which MABR membranes are immersed to provide supplemental nitrification capacity in the existing reactor volume. This configuration would free up sufficient tank volume to accommodate an anaerobic zone for EBPR without having to build a new battery of tanks.

MABR technology intensifies wastewater treatment by enabling process improvements while reducing energy consumption. It offers a solution for water resource recovery facilities looking to upgrade for nutrient removal or capacity expansion. For MWRD, MABR technology potentially could enable the district to meet its future phosphorous removal targets while obviating the need to build new activated sludge tanks and reducing energy consumption to support the goal of energy neutrality.

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