Energy consumption in a baffled membrane bioreactor (B-MBR): estimation based on long-term continuous operation

T. Miyoshi, T. P. Nguyen, T. Tsumuraya, K. Kimura and Y. Watanabe

ABSTRACT

We investigated the operating conditions of a baffled membrane bioreactor (B-MBR) under which long-term stable operation can be achieved through the continuous operation of a pilot-scale B-MBR. Under appropriate operating conditions, the B-MBR was capable of achieving excellent treated water quality in terms of biochemical oxygen demand and concentration of total nitrogen. Excellent removal of total phosphorus was also achieved. In addition, the degree of membrane fouling was acceptable, indicating that stable continuous operation of a B-MBR is possible under the operating conditions adopted in the present study. Estimation of the specific energy consumption in hypothetical full-scale B-MBRs operated under the conditions recommended by the findings was also performed in this study. The results suggest that energy consumption in full-scale B-MBRs would be in the range of 0.20–0.22 kWh/m^3. These results strongly suggest that energy consumption in MBR operation can be significantly reduced by applying the concept of a B-MBR.

Key words | baffled membrane bioreactor, energy saving, nitrogen removal

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INTRODUCTION

Membrane bioreactors (MBRs) have various advantages compared with conventional biological wastewater treatment processes (such as the conventional activated sludge process), including small footprint, superior treated water quality, and ease of operation (automation) (Judd 2006). These features of MBRs are particularly attractive when upgrading an existing wastewater treatment facility with limited available space. MBRs are also a suitable choice when water reclamation and reuse are required, because the treated water from an MBR basically does not contain any suspended solids, and therefore an MBR can serve as an excellent pretreatment for the reverse osmosis (RO) membrane process, which is often utilized for producing reclaimed water to be reused for various purposes.

Despite such important features of MBRs, the widespread application of this technology is mainly hampered by its high operation and maintenance costs. In particular, the cost associated with energy consumption is generally a dominant economic burden in the operation of MBRs (Kraume & Drews 2010). Reduction of energy consumption during MBR operation is clearly important, though the specific energy consumption in operating MBRs has been significantly decreased by recent intensive research and development, especially on reducing the air-flow rate of membrane aeration (the aeration aimed at maintaining membrane permeability) (Krzeminski *et al.* 2017).

MBRs are divided into two categories based on the location of membrane. One type is the side-stream MBR, in which membrane modules are placed outside of a biological reaction tank, and the mixed liquor suspension is recirculated between the reaction tank and membrane module by recirculation pump. The other type is the submerged MBR, in which membranes are directly submerged into the reaction tank and membrane filtration is performed by a suction pump. Although locating membranes outside of the reaction tank is particularly advantageous for membrane cleaning and replacement (Hoque *et al.* 2012), the energy consumption for the operation of side-stream MBRs (typically in the range of 3–6 kWh/m^3 (Ueda *et al.* 1996; Buer & Cumin 2010; Lorain *et al.* 2010; Krzeminski *et al.* 2012)) is generally much higher than that of submerged MBRs (recently less than 0.4 kWh/m^3 (Tao *et al.* 2010; Miyoshi

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et al. 2018a)). Therefore, at least in municipal wastewater treatment, submerged MBRs are generally preferred.

Among the apparatuses used in submerged MBRs, an air-blower used for introducing coarse bubbles aimed at cleaning membranes (membrane aeration) generally accounts for the largest fraction of energy consumption (Gil *et al.* 2010; Verrecht *et al.* 2010; Krzeminski *et al.* 2012). On this basis, there has already been significant research and development to reduce energy consumption associated with membrane aeration (Verrecht *et al.* 2011; Kurita *et al.* 2015; Yan *et al.* 2016). Owing to such intensive efforts, the specific energy consumption in MBR operation has been significantly reduced. Recently, Tao *et al.* (2010) achieved a specific energy consumption of 0.37 kWh/m^3 in a fully optimized MBR treating real municipal wastewater (primary effluent).

We have also developed an energy-saving MBR, which is equipped with a modified hollow-fiber membrane element; in this, both the effective fiber length (from 2 to 3 m) and the packing density (by 20%) were increased compared with the conventional membrane element. This modification is advantageous for effectively utilizing coarse bubbles introduced from the bottom of the membrane element. The results of our estimation strongly suggest that the energy-saving MBR developed can be operated with a specific energy demand of less than 0.37 kWh/m^3 (Miyoshi *et al.* 2018a). However, these values are still higher than the conventional activated sludge method (0.2–0.3 kWh/m^3) (Fenu *et al.* 2010), and therefore, further reduction in specific energy consumption in MBR operation is required for the widespread application of this technology. For further reductions in energy consumption, reducing the energy consumption in apparatuses other than membrane aeration should also be investigated.

In MBRs used for municipal wastewater treatment, complete nitrification is usually achieved. Taking the decrease in pH as a result of complete nitrification into account, denitrification is typically indispensable for satisfying the pH standard for treated water. In typical submerged MBRs, denitrification is achieved by installing an anoxic tank and recirculating the mixed liquor suspension from the aerobic tank to the anoxic tank. For achieving nitrogen removal in such arrangements, a recirculation pump and a mixer installed in the anoxic tank are indispensable. The energy consumption of these apparatuses also account for large fractions in the overall energy consumption of MBRs (Miyoshi *et al.* 2018a).

Based on the background mentioned above, we focused on the application of a baffled MBR (B-MBR). The concept of the B-MBR was originally reported in the 2000s (Kimura & Watanabe 2005; Kimura *et al.* 2007, 2008) and recently further development has been carried out for application to full-scale wastewater treatment plants (Miyoshi *et al.* 2018b). In a B-MBR, baffles are inserted into the biological reaction tank of a submerged MBR and the water level is controlled by the intermittent addition of raw wastewater to the reactor. As a result, a B-MBR is capable of creating both aerobic and anoxic conditions in a single bioreactor without the transport of aerobic mixed liquor containing nitrate-nitrogen into a zone in which anoxic conditions are created (Kimura *et al.* 2008) (details are explained later). B-MBRs can therefore be operated without the installation of a recirculation pump and a mixer in an anoxic tank, and so the energy consumption of these apparatuses can be reduced.

Because our energy-saving MBR technology (Miyoshi *et al.* 2018a) is totally compatible with the B-MBR concept, further reduction in the specific energy consumption of MBR operation is thought to be possible by the combination of the two technologies. However, the specific energy consumption depends heavily on the membrane flux and air-flow rate at which stable operation of MBR can be achieved. This point was not clear for the combination of a B-MBR and our energy-saving MBR. Therefore, we investigated the membrane flux and air-flow rate of membrane aeration under which long-term stable operation of the B-MBR combined with our energy-saving MBR concept could be achieved. Afterwards, the specific energy consumption under the above-mentioned operating condition was also estimated.

MATERIALS AND METHODS

B-MBR concept

Figure 1 shows the schematic description of the concept of the B-MBR. The details of the concept of B-MBR can also be found elsewhere (Kimura *et al.* 2008; Miyoshi *et al.* 2018b). In B-MBRs, baffles inserted into the biological reaction tank of a submerged MBR divide the inside of the tank into two compartments, and a membrane unit is installed at one side of the compartments created by the baffles. Both membrane aeration and biology aeration (the aeration aimed at supplying dissolved oxygen (DO) to the biomass) are performed only in the compartment in which the membrane unit is installed.

Raw water is intermittently added at flow rates higher than that of treated water. When the water level is lower

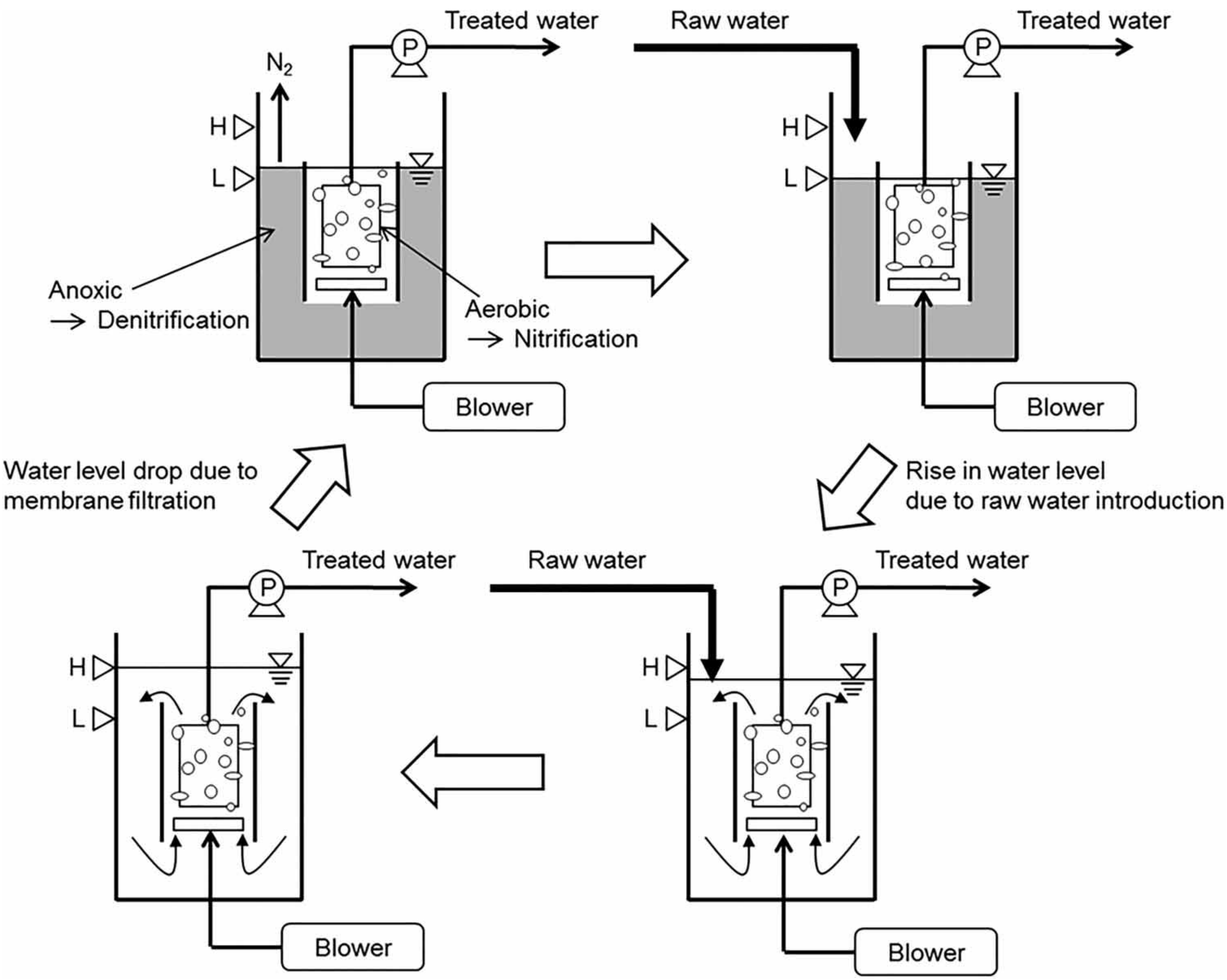

Figure 1 | Schematic description of B-MBR.

than the top of the baffles (i.e., in the separation phase), aerobic conditions are created in the compartment in which the membrane unit is installed (the interior zone of the baffles in the case of the schematic description provided in Figure 1 and denoted as the aerobic zone hereafter). DO in the compartment in which the membrane unit is not installed (the exterior zone of the baffles in the case of the schematic description provided in Figure 1 and denoted as the anoxic zone hereafter) is depleted because no aeration is performed in this compartment. As a result, denitrification is promoted in the anoxic zone. Due to the fact that raw water is not added, the water level in the reactor gradually drops and eventually reaches the predetermined lowest level. At this moment, raw water starts to be added to the bioreactor and the water level is allowed to rise. The water level eventually exceeds the top of the baffles, and from this moment, the entire bioreactor is intensively mixed by the aeration performed in the aerobic zone (i.e., in the recirculation phase). In the recirculation phase, material is exchanged between the interior and exterior zones, and therefore, some of the nitrate-nitrogen formed as a result of nitrification in the aerobic zone is transferred from the aerobic zone to the anoxic zone. The addition of raw water stops when the water level reaches the predetermined highest level. Then the water level goes down due to membrane filtration and eventually the inside of the bioreactor is separated by the baffles again. By repeating such cycles, the B-MBR is capable of removing nitrogen by nitrification and denitrification reactions without installing an anoxic tank and a recirculation pump for transporting mixed liquor suspension from the aerobic tank to the anoxic tank. When the entire reaction tank is sufficiently mixed during the recirculation phase, a mixer, which is indispensable for the anoxic tank, can also be omitted. Therefore, the energy consumption associated with these apparatuses can be reduced in the operation of B-MBRs.

In the operation of B-MBRs, the biomass involved in biological treatment is repeatedly exposed to both aerobic and anoxic conditions. Although the frequency of alternation between these two conditions in B-MBR operation tends to be higher than that in a conventional MBR with nitrification and denitrification functions (e.g., an MBR using a modified Ludzack–Ettinger (MLE) process), the basic biological characteristics in the B-MBR are thought to be similar to conventional MBRs that include nitrogen removal. Taking the operational features of the B-MBR into consideration, the flow rate of the added raw water should be temporarily higher than the flow rate of the membrane permeate. The concept of the B-MBR is thought to be widely applicable as long as the requirement mentioned above is satisfied. At least, superior treatment performances in terms of organic matter and nitrogen removal have been reported in the treatment of real municipal wastewater in hydraulic retention times (HRTs) of 4.7 hr and 5.9 hr (Kimura *et al.* 2008; Miyoshi *et al.* 2018b).

Continuous operation of pilot-scale B-MBR

A pilot-scale B-MBR installed at an existing municipal wastewater treatment plant connected to a combined sewer system (Soseigawa Wastewater Treatment Center, Sapporo, Japan) was continuously operated using the influent from the primary sedimentation basin as raw water. Figure 2 shows the flow diagram of the pilot-scale experimental apparatus used in this study. The continuous operation of the pilot-scale B-MBR was performed from 18th January 2018 to 27th July 2018. There was a temporary interruption from 31st January 2018 to 14th February 2018. The operational period of this temporary interruption was not included in the elapsed time of the continuous operation. The membrane used in this study was the same as the one used in our energy-saving MBR (Miyoshi *et al.* 2018a), though the effective length of membrane fiber used in this study (0.8 m) was much shorter than that used in our previous investigation (3 m). The membrane element comprised a vertically aligned hollow-fiber membrane made of polytetrafluoroethylene (PTFE) with a nominal pore size of 0.2 μm. Because the specific air demand per membrane surface area (SAD_m) required for the stable operation of an MBR is thought to be reduced by increasing the effective length of the membrane fiber in an MBR equipped with vertically aligned hollow fiber membranes, the SAD_m value adopted in the continuous operation in this study was higher than that used in our previous investigation (Miyoshi *et al.* 2018a). As explained in detail later, this difference was corrected in the evaluation of specific energy consumption of the B-MBR.

In the pilot-scale MBR apparatus used in this study, two membrane units (Units A and B) were installed side by side, and operated in parallel. Intermittent membrane filtration (9-min filtration and 1-min relaxation) was carried out in both membrane units. Unit A was used for evaluating the development of membrane fouling under the operating conditions, which are expected to be standard in B-MBR operation. The other membrane unit was used for the adjustment of flow rate and subsequently the HRT during the continuous operation of the B-MBR. The HRT was set at 5.9 hr. Mixed liquor suspended solids (MLSS) concentration during the continuous operation was in the range of 6.5–14.5 g/L. In this paper, the development of membrane fouling is discussed only for the results obtained from Unit A.

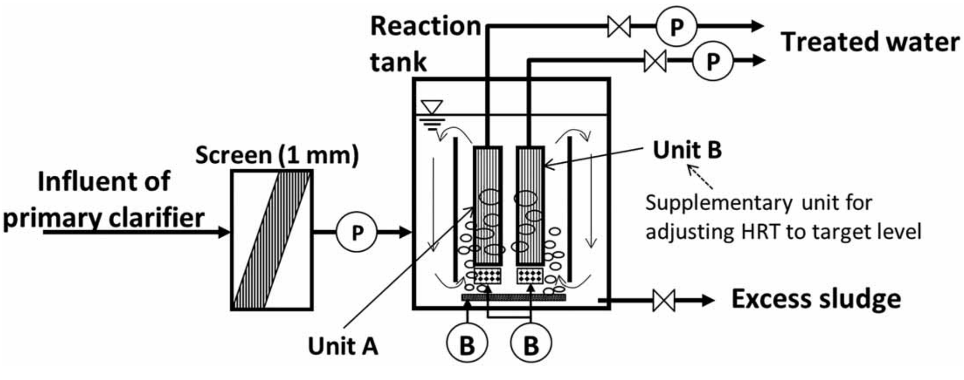

Figure 2 | Flow diagram of pilot-scale experimental apparatus used in this study.

Table 1 | Operating conditions of pilot-scale B-MBR in each sub-period

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Date	Days 0–12	Days 13–27	Days 28–59	Days 60–131	Days 132–160	Days 161–175
Volume ratio	1:2	1:1	1:1	1:1	1:1	1:2
Air-flow rate (Nm^3/hr)	5.3 ± 0.7	10.7 ± 2.7	2.3 ± 2.5	5.4 ± 0.8	8.7 ± 3.4	3.6 ± 0.9
DO concentration (mg/L)	0.9 ± 0.4	1.2 ± 0.6	3.2 ± 1.0	0.6 ± 0.5	1.6 ± 0.7	1.7 ± 0.7
Temperature (°C)	13.6 ± 0.2	13.5 ± 0.7	10.9 ± 1.7	17.5 ± 2.3	20.3 ± 0.9	22.5 ± 0.7
pH	6.91 ± 0.08	6.72 ± 0.21	6.54 ± 0.19	6.76 ± 0.17	6.54 ± 0.15	6.74 ± 0.12

Volume ratios are expressed as interior:exterior zones. Air-flow rate indicates the average air-flow rates of biology aeration. DO concentration presented here is average DO concentration in interior zone of baffles.

Unit A had an effective membrane surface area of 15 m^2 and membrane filtration was performed with a membrane flux (net flux) of 0.5 m^3/m^2/day (approximately 25 L/m^2/hr). Unit A was also equipped with a dummy membrane element (a membrane element which was not used in membrane filtration) with an identical structure. Membrane aeration in Unit A was evenly distributed between the two membrane elements, with an air-flow rate of 9 m^3/hr. Therefore, the SAD_m in the membrane filtration in Unit A was 0.30 m^3/m^2/hr. Unit B had an effective membrane surface area of 30 m^2, and membrane filtration and membrane aeration were performed with a membrane flux of 0.25 m^3/m^2/day (approximately 12.5 L/m^2/hr) and an SAD_m of 0.30 m^3/m^2/hr, respectively.

During the continuous operation, cleaning in place (CIP) with alkaline solution (NaClO 500 mg/L, NaOH 0.02%) and acid solution (H_2SO_4 0.2%) was performed every week and every alternate week, respectively. The continuous operation of the pilot-scale B-MBR was divided into six sub-periods. Table 1 lists the operating conditions of the pilot-scale B-MBR in each sub-period. In this study, to investigate the effect of volume ratio between the aerobic and anoxic zones on the treatment performance of the B-MBR, the pilot-scale apparatus was operated with two different interior (aerobic) to exterior (anoxic) zone volume ratios, namely 1:2 and 1:1 (expressed as interior:exterior volumes). Because the interior to exterior zone volume ratio may also affect the oxygen demand required for biological treatment, the B-MBR operation under different air-flow rates of biology aeration was also examined in this study.

Estimation of energy consumption

Based on the results obtained in the continuous operation of the pilot-scale B-MBR, we estimated energy consumption in hypothetical full-scale B-MBRs assuming typical wastewater treatment plants in both Thailand and Japan. Specifications assumed in the estimation are summarized in Table 2. Figure 3 shows the apparatuses considered in the estimation. The membrane elements utilized in the pilot-scale B-MBR operated in this study (effective length of 0.8 m) was considerably shorter than the one used in full-scale B-MBRs (effective length of 3 m). The SAD_m adopted in the continuous operation of the pilot-scale B-MBR was corrected to the

Table 2 | Specifications used for the estimation of energy consumption

	Thailand	Japan
Daily average flow rate (m^3/day)	10,000	10,000
Daily maximum flow rate (m^3/day)	14,000	12,000
Net flux (m^3/m^2/day) (B-MBR and C-MBR-1)	0.5	0.5
SAD_m (m^3/m^2/hr) (B-MBR and C-MBR-1)	0.08	0.08
Net flux (m^3/m^2/day) (C-MBR-2)	0.6	0.6
SAD_m (m^3/m^2/hr) (C-MBR-2)	0.20	0.20
HRT (hr)	6	6
MLSS concentration (mg/L)	8,000	8,000
MLVSS concentration (mg/L)	6,400	6,400
Average DO concentration in aerobic zone (mg/L)	1.5	1.5
Minimum temperature (°C)	25	13
Oxygen transfer efficiency (membrane aeration) (%)	8	8
Oxygen transfer efficiency (biology aeration) (%)	28	28
α factor	0.65	0.65
BOD (raw water) (mg/L)	50	120
SS concentration (raw water) (mg/L)	40	100
TN concentration (raw water) (mg/L)	15	30
BOD (treated water) (mg/L)	3	3
SS concentration (treated water) (mg/L)	N.D.	N.D.
TN concentration (treated water) (mg/L)	5	5

The water qualities of raw water in Japan were selected based on typical primary effluent qualities. N.D. = not detected.

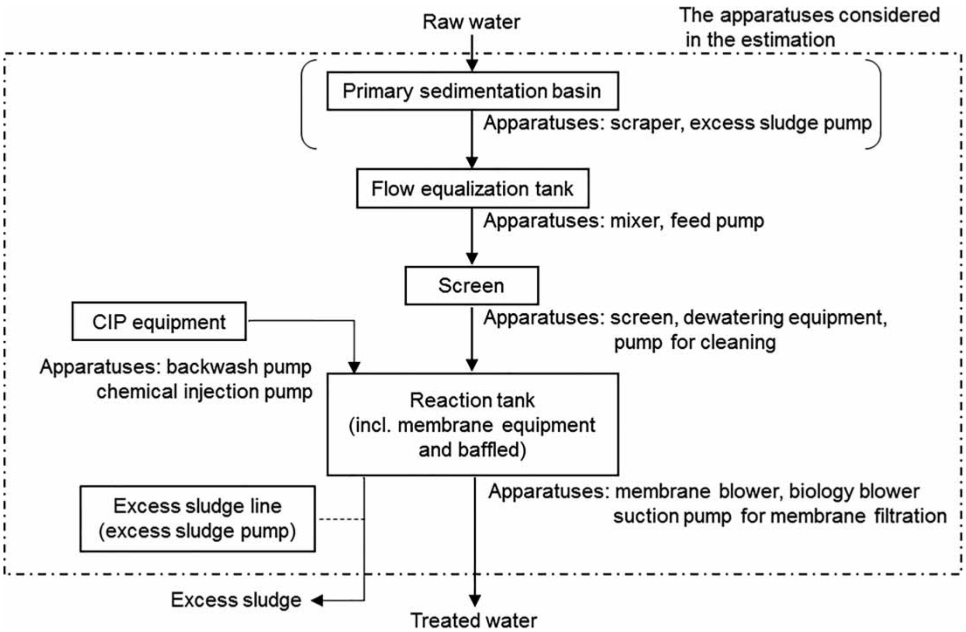

Figure 3 | Apparatuses considered in cost estimation. Primary sedimentation was not involved in the cost estimation for the wastewater treatment plant in Thailand.

one used in full-scale B-MBRs, assuming that the difference in the vertical length does not affect the demand of membrane aeration: the corresponding SAD_m in hypothetical full-scale B-MBRs used for the estimation of energy consumption was $0.08\ m^3/m^2/hr$. Although a primary sedimentation basin was included in the estimation of energy consumption for the hypothetical wastewater treatment plant in Japan, this facility was not considered in the estimation of energy consumption for the one in Thailand. This difference is associated with the difference in raw water quality. Due to the low value of biochemical oxygen demand (BOD) in the raw water assumed for the hypothetical wastewater treatment plant in Thailand (Table 2), installation of a primary sedimentation basin may result in insufficient denitrification associated with limited availability of electron donors required in the denitrification reaction. In the estimation, the membrane areas required for operating each hypothetical full-scale MBR were determined from the daily maximum flow rate and membrane flux. After that the air-flow rates of membrane aeration were automatically determined as the values of SAD_m in each hypothetical full-scale MBR were fixed.

The air-flow rates of biology aeration were determined based on oxygen demand during the operation of each hypothetical full-scale MBR. The BOD and the total nitrogen (TN) concentration of both the raw water and the treated water, the MLSS concentration in the bioreactor, and the average DO concentration in the aerobic zone were taken into consideration in the calculation of the oxygen demand. The air-flow rates of biology aeration were determined by subtracting the DO supplied by membrane aeration from the entire oxygen demand calculated by the procedures mentioned above. The membrane area and the air-flow rates of both membrane and biology aeration are provided in Table S1 in the Supporting information.

In addition to the estimations for hypothetical full-scale B-MBRs, specific energy consumption in operating conventional MBRs using the MLE process operated under the same specifications as the B-MBRs examined in this study (i.e., a net flux of $0.5\ m^3/m^2/day$ and an SAD_m of $m^3/m^2/hr$) (denoted as conventional MBR-1 or C-MBR-1 hereafter) and those adopted in an existing full-scale MBR (a net flux of $0.6\ m^3/m^2/hr$ and an SAD_m of $0.20\ m^3/m^2/hr$) (Krzeminski *et al.* 2012) (denoted as conventional MBR-2 or C-MBR-2 hereafter) were also estimated. The specifications of the C-MBR-2 were selected because the operating conditions reported by Krzeminski *et al.* (2012) were the least energy intensive among the publications summarized in the recently published review paper on MBRs (Meng *et al.* 2017). In all of the hypothetical MBRs considered in the estimation, the phosphorus removal process was not included. Therefore, the information relating to the phosphorus content was not considered in the estimation as it does not affect the overall energy consumption during operation. As indicated in Figure 3, the apparatuses considered in the estimation of energy consumption were limited to the water treatment process, and other functions of wastewater treatment facilities such as lifting pumps or sludge treatment were not involved in the estimation performed in this study.

Analytical methods

During the continuous operation, samples of feed and treated water were corrected and analysed. BOD and concentrations of suspended solids (SS), ammonium-nitrogen, total nitrogen (TN), total phosphorus (TP), MLSS, and mixed liquor volatile suspended solids (MLVSS) were determined in accordance with Japanese standard methods (Japan Sewage Works Association 2012).

RESULTS AND DISCUSSION

Water quality

Figure 4 shows the changes in water quality indices in the raw water and treated water during the continuous operation of the pilot-scale B-MBR. As mentioned above, the operating conditions of the pilot-scale B-MBR were changed several times. Nevertheless, BOD was effectively removed by the B-MBR irrespective of the operating conditions. This result indicates that the B-MBR operated in this study was capable of removing BOD under a wide range of operating conditions. By contrast, the removal efficiency of TN was partially affected by the operating conditions. At the beginning of the continuous operation (Periods 1 and 2), the BOD and TN concentration in the raw water were higher than those in the other periods. Although TN was effectively removed during Period 1, the concentration of ammonium-nitrogen in the treated water slightly increased during this period. This tiny deterioration in the nitrification may be explained by low temperatures (this operating period corresponded to a winter period) or insufficient oxygen supply.

On day 13, the ratio between interior and exterior zones of the pilot-scale B-MBR was changed from 1:2 to 1:1 (expressed as interior:exterior zones). This change resulted in a significant increase in oxygen consumption in the interior zone of the baffles, and DO concentration in the interior zone did not reach a high-enough level for promoting nitrification in an entire cycle of B-MBR operation. It is strongly suggested that the oxygen demand during B-MBR

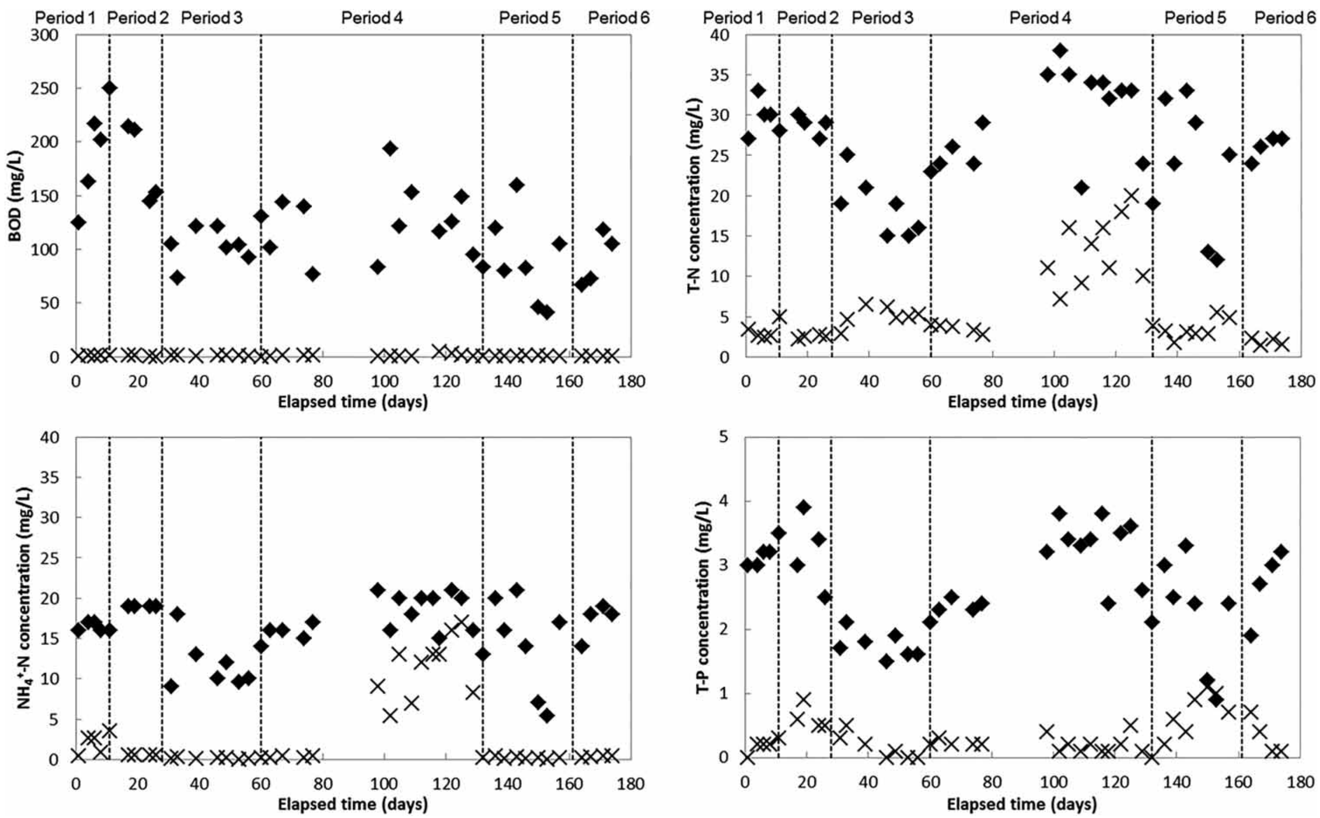

Figure 4 | Changes in water quality indices during continuous operation of pilot-scale B-MBR. Diamonds: raw water, crosses: treated water.

operation increases by increasing the fraction of the interior (aerobic) zone in the entire volume of the reaction tank of the B-MBR. On this basis, we changed the setting of the biology aeration control protocol to increase the oxygen supply. This change resulted in an increase in the air-flow rate of biology aeration (Table 1). As a result, sufficient oxygen was supplied to the biomass and the TN removal during this period was sufficient. The experimental results mentioned above suggest that oxygen demand during B-MBR operation decreases when operated with a smaller fraction of the aerobic zone relative to that of anoxic zone. This was further confirmed at the end of the continuous operation as described later. The operating conditions in Period 3 were identical to those in Period 2. In this period, however, due to the addition of snow runoff, the water temperature in the biological reaction tank of the B-MBR suddenly decreased. The oxygen consumption in this period was likely to be lower and the air-flow rate of biology aeration was also lower than in the other periods.

Taking the sufficient removal of TN during Periods 2 and 3 into consideration, we changed the settings of the biology aeration control protocol to the original one (i.e., identical to the protocol adopted in Period 1) at the beginning of Period 4 (corresponding to the beginning of April). Although TN was effectively removed at the very beginning of Period 4, the removal rate decreased greatly after around day 100 (corresponding to the end of April). Because the ammonium-nitrogen concentration in the treated water also significantly increased at the same time, this deterioration in nitrogen removal was thought to be mainly attributed to the decrease in nitrification. During this experimental period, DO concentration in the interior zone of the baffle was clearly lower than the other experimental periods (Table 1). The oxygen consumption in this period was likely to exceed the oxygen supply capacity of the operating conditions adopted in this period. This result also supports the previous discussion based on the results obtained in Periods 1 and 2, which suggest that more intensive biology aeration is required for achieving sufficient nitrogen removal by increasing the volume fraction of the aerobic zone in the biological reaction tank the of B-MBR. Thus insufficient nitrification can be avoided by either increasing the air-flow rate of biology aeration (Period 5) or decreasing the volume fraction of the aerobic zone in the biological reaction tank of B-MBR (Period 6). Except in the period during which nitrification was insufficient, as mentioned above, nitrate-nitrogen was the predominant nitrogen species and only trace levels of nitrite-nitrogen were detected (generally less than 0.1 mg-N/L and at a maximum of 0.15 mg-N/L) in the treated water.

With regard to phosphorus removal, the pilot-scale B-MBR operated in this study generally exhibited an excellent phosphorus removal performance, except Period 5. In Period 5, the average air-flow rate of biology aeration was relatively high, though the values of BOD were slightly lower than during the other operating periods. This situation was likely to result in difficulties in creating anaerobic conditions in a part of the B-MBR tank. Such situations are not conducive to biological phosphorus removal. The decrease in phosphorus removal in Period 5 might be explained by the phenomenon mentioned above. This speculation is in accordance with previous findings, suggesting that biological phosphorus removal is one of the dominant mechanisms involved in the excellent phosphorus removal in B-MBRs (Kimura *et al.* 2008).

As mentioned above, BOD, TN and TP were effectively removed at reduced air-flow rates of biology aeration in Period 6. On this basis, it can be said that the operating conditions adopted in this operating period are the optimum of those examined in the present study.

Membrane fouling

The change in transmembrane pressure (TMP) during the continuous operation of the pilot-scale B-MBR is shown in Figure 5. Data presented in Figure 5 were corrected to 20 °C equivalent values, taking the influence of water viscosity on TMP required for achieving the designated flux into consideration. Any chemical recovery cleaning (e.g., chemical membrane cleaning by submerging a fouled membrane into a chemical cleaning solution after taking it out of the bioreactor) were not performed throughout the continuous operation described in Figure 5. The rate of increase in

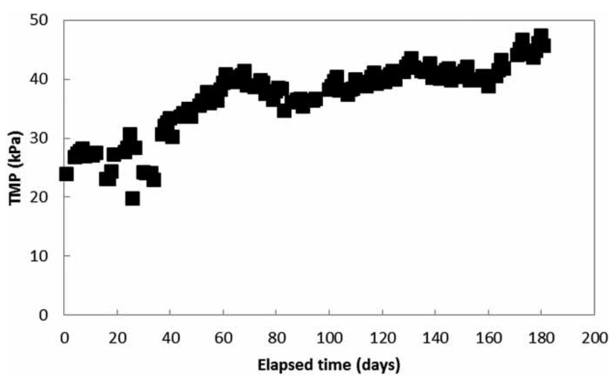

Figure 5 | Change in TMP during continuous operation of pilot-scale B-MBR.

TMP slightly increased in the period between around day 30 and day 60 (corresponding to the period between the middle of February and the end of March). This increase in the rate of increase in TMP was attributed to a decrease in water temperature (Table 1) associated with the addition of snow runoff. In the present study, we operated the pilot-scale B-MBR with regular CIP. Because TMP decreased from around day 60, at which time snowmelt was likely to be complete, it can be said that the membrane fouling during this period was reversible by the CIP performed in this study.

Except for the temporary increase in the rate of increase in TMP associated with the unusual decrease in temperature mentioned above, the continuous operation of the pilot-scale B-MBR was quite stable and the increase in the rate of increase in TMP was fairly moderate throughout the continuous operation. The overall fouling rate, expressed as the rate of increase in TMP determined for the entire period of continuous operation, was 0.12 kPa/day. This value was acceptable for achieving long-term stable operation. The continuous operation could continue without being interrupted by chemical recovery cleaning. This result indicates that, despite the irregular event associated with snow melting, the maintenance cleaning protocol adopted in the continuous operation (i.e., the combination of membrane aeration and CIP) was sufficient for stably operating the B-MBR. Therefore, estimating the energy consumption under the operating conditions adopted in this continuous operation was thought to be valid. The details of the estimation of energy consumption will be given in the following section. Taking the effective elimination of membrane fouling by the regularly performed CIP into consideration, the rapid increase in TMP during the experimental period with extremely low water temperatures could be mitigated by increasing the frequency or chemical concentration in the CIP protocol.

Estimation of energy consumption in B-MBR operation

The results obtained in the continuous operation of the pilot-scale B-MBR strongly suggest that B-MBR can be stably operated under an SAD_m of 0.30 $m^3/m^2/hr$. As explained in the methods for estimating energy consumption, an SAD_m of 0.30 $m^3/m^2/hr$ in the pilot-scale B-MBR operated in this study corresponds to an SAD_m of 0.08 $m^3/m^2/hr$, taking the difference in effective length of the membrane fiber in the membrane element into account. Therefore, we estimated the energy consumption in operating hypothetical B-MBRs operated with an SAD_m of 0.08 $m^3/m^2/hr$. The estimation was performed for two different situations, namely wastewater treatment plants in Thailand and Japan. BOD and TN concentration in the raw wastewater in wastewater treatment plants in Thailand were generally lower than in Japan. In addition to the estimation of energy consumption in hypothetical full-scale B-MBRs, those of conventional MBRs operated with the same specifications as the B-MBR examined in this study (a net flux of 0.5 m^3/m^2/day and an SAD_m of 0.08 $m^3/m^2/hr$, denoted as C-MBR-1) and with the operating conditions reported in a previous publication (a net flux of 0.6 m^3/m^2/day and an SAD_m of 0.20 $m^3/m^2/hr$, denoted as C-MBR-2) were estimated.

Figure 6 shows the estimated energy consumption in the two cases of hypothetical B-MBRs. The specific energy consumption estimated for C-MBR-2 were slightly lower than 0.4 kWh/m^3. These values are thought to be reasonable, given the recent achievement in energy saving in MBR operation (Tao *et al.* 2010; Miyoshi *et al.* 2018a). The differences in specific energy consumption between C-MBRs −1 and −2 indicate the degree of energy saving which can be achieved by applying the energy-saving MBR technology we proposed previously; energy consumption associated with membrane aeration is reduced by increasing both effective length and packing density of hollow-fiber membranes (Miyoshi *et al.* 2018a). Based on the results obtained in the continuous operation of the pilot-scale B-MBR apparatus performed in this study, a significant reduction in air-flow rate of membrane aeration is thought to be possible. The operating conditions adopted in the continuous operation performed in this study correspond to an SAD_m of 0.08 $m^3/m^2/hr$ in a full-scale MBR utilizing our energy-saving MBR technology. Taking the net flux adopted in the continuous operation (i.e., 0.5 m^3/m^2/day) into account, the B-MBR operation performed in the present study corresponds to a specific air demand per permeate (SAD_p) of 3.84 m^3-air/m^3-permeate. This value of SAD_p is substantially lower than typical MBRs (more than 10 m^3-air/m^3-permeate) (Judd 2008). As indicated in Figure 6, our energy-saving MBR alone also had a significant advantage for reducing energy consumption, though the energy consumption associated with the recirculation pump and mixer in the anoxic tank are inevitable in conventional MBRs utilizing our energy-saving technology mentioned above.

As explained above, a sludge recirculation pump for recirculating mixed liquor suspension from the aerobic tank to the anoxic tank and a mixer installed in the anoxic tank are not required in the operation of a B-MBR. Therefore,

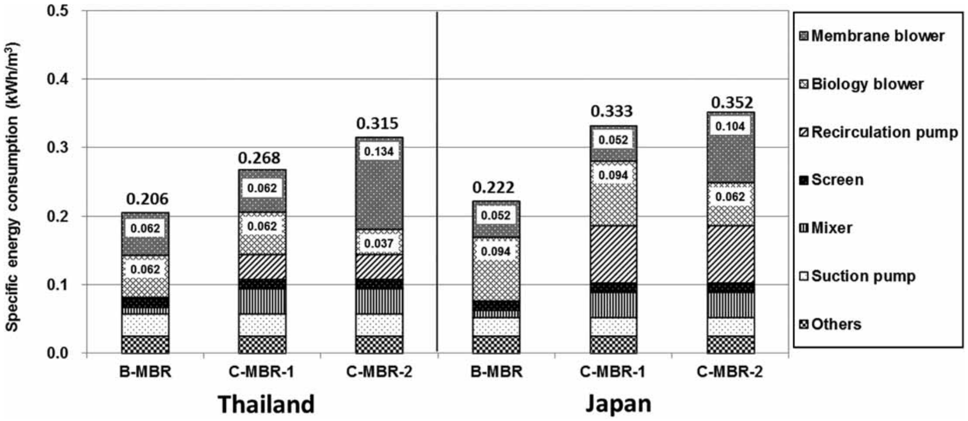

Figure 6 | The results of estimation of energy consumption.

energy consumption associated with these apparatuses can be reduced by utilizing B-MBR technology. The reductions in energy consumption associated with omitting these apparatuses are reflected in the differences between the specific energy consumption estimated for C-MBR-1 and B-MBR. As indicated in Figure 6, applying the B-MBR concept also had a significant effect on reducing specific energy consumption. On the basis of the information mentioned above, it can be said that both reducing air-flow rate of membrane aeration by utilizing our energy-saving MBR technology and omitting a recirculation pump and the mixer by applying the B-MBR concept played important roles in reducing overall energy consumption in the wastewater treatment plant utilizing B-MBR technology.

Although the energy consumption estimated for the wastewater treatment plant in Thailand was slightly lower than that estimated for the one in Japan, the difference between the two situations was not significant. This result suggests that the advantage of a B-MBR in reducing energy consumption can be utilized in a wide range of wastewater treatment plants. The difference in the energy consumption estimated for the two situations was likely to be mainly attributed to the difference in raw water quality: both BOD and TN concentration of raw water in Thailand was substantially lower than that in Japan.

The high energy consumption during MBR operation has been one of the biggest obstacles for its wide-spread application in municipal wastewater. However, the specific energy consumption estimated in the present study were comparable to that of wastewater treatment plants utilizing the conventional activated sludge process (Fenu *et al.* 2010). This fact indicates that the issues associated with high energy consumption of operating MBRs can be almost completely overcome by applying the achievement obtained in this study. Because B-MBRs also have all of the advantages of MBRs (e.g., excellent treated water quality, small footprint, and ease of automation), applying the B-MBR concept would allow us to take advantage of MBRs without any additional expenditure on energy consumption. Therefore, the achievement obtained in this study could be a breakthrough for the widespread application of MBRs.

CONCLUSIONS

In this study, we investigated operating conditions under which long-term stable operation of B-MBRs can be achieved by performing long-term continuous operation of a pilot-scale B-MBR with real municipal wastewater. The specific energy consumption in hypothetical full-scale B-MBRs operated under the operating conditions examined in the pilot-scale experiment were also estimated. The results obtained in the continuous operation revealed that a B-MBR can be operated under an SAD_m of 0.30 m^3/m^2/hr and net flux of 0.5 m^3/m^2/day (the value of the SAD_m examined in the pilot-scale B-MBR corresponds to an SAD_m of 0.08 m^3/m^2/hr in a full-scale B-MBR taking the difference in the effective length of membrane fiber into account). The specific energy consumption in the operation of full-scale B-MBRs under these operating conditions was estimated to be 0.206 and 0.222 kWh/m^3 in wastewater treatment plants in Thailand and Japan, respectively. These values of specific energy consumption are almost comparable to those typically found in the operation of the conventional activated sludge process. The results obtained in this study strongly suggest that application of B-MBR concept allows us to utilize MBR technology without a substantial increase in the energy consumption of a treatment plant.

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SUPPLEMENTARY DATA

The Supplementary Data for this paper are available online at http://dx.doi.org/10.2166/wst.2019.335.

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