Design and operating experiences of full-scale municipal membrane bioreactors in Japan

H. Itokawa, K. Tsuji, K. Yamashita and T. Hashimoto

ABSTRACT

In Japan, membrane bioreactor (MBRs) have been installed in 17 small-scale municipal wastewater treatment plants (WWTPs) in the past 8 years, together with two recently installed MBRs for larger-scale WWTPs. In this study, design and operating data were collected from 17 of them as part of a follow-up survey, and aspects including system design, biological treatment, membrane operation, problems and costs were overviewed. Because most of the MBRs were designed according to standardized guidance, system configuration of the plants was similar; pre-denitrification using the Modified Ludzack-Ettinger (MLE) process with membrane units submerged in aerobic tanks, following a fine screen and flow equalization tank. This led to effluent quality with biochemical oxygen demand and T-N of less than 3.5 and 7.4 mg/L, respectively, for nine plants on an annual average basis. It was a common practice in extremely under-loaded plants to operate the membrane systems intermittently. Frequency of recovery cleaning events was plant-specific, mostly ranging from 1 to 5 times/year. Cost evaluation revealed that specific construction costs for the small-scale MBRs were no more than for oxidation ditch plants. Although specific energy consumption values tended to be high in the under-loaded plants, the demonstration MBR, where several energy reducing measures had been incorporated, attained specific energy consumption of 0.39 kWh/m^3 under full-capacity operation.

Key words | design and operation, MBR, membrane bioreactor, municipal wastewater treatment

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INTRODUCTION

The membrane bioreactor (MBR) has been shown to be a promising wastewater treatment technology, achieving excellent effluent quality with a smaller footprint compared with conventional activated sludge (CAS) systems. The number of full-scale MBR installations has been increasing worldwide, from small-scale onsite plants to larger-scale municipal wastewater treatment plants (WWTPs). In Japan, more than 3,000 full-scale MBRs have been operated since the 1980s, principally for small-scale onsite industrial/household wastewater treatment. In contrast, the application to municipal WWTPs is relatively new, the first full-scale plant being commissioned in March 2005 (Judd & Judd 2011). Since then, one to three municipal MBR plants have been constructed every year, and 19 full-scale plants were operating at the end of March 2013. Most of them were designed according to the 'Japan Sewage Works Agency (JS) MBR Design Recommendations' (later referred to as 'JS Recommendations') prepared by JS for small-scale municipal MBRs. This growth of the number of municipal MBR installations led to intensive design and operating data collection from these plants in 2009–2011, for the purpose of making the current state of our municipal MBRs clear, thereby identifying critical operating problems.

In this paper, a part of this 'follow-up' survey, targeting full-scale municipal MBRs in Japan, is described. In addition, some results are reported of a government-aided demonstration project, in which one wastewater treatment lane in a WWTP was retrofitted to a demonstration MBR with a special focus on operating energy reduction.

METHODS

Table 1 is a full listing of municipal MBRs in Japan, where full-scale MBRs were operating in 19 municipal WWTPs at the end of March 2013. Except for plant Nos 11 and 15, these are newly constructed small-scale MBRs with a capacity ranging from 125 to 6,060 m^3/d. As is usual with new sewerage systems

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Table 1 | Full-scale municipal MBR plants operated in Japan (as at the end of March 2013)

No.	Commissioning	Capacity[a] [m^3/d]	Membrane[b]	MBR type	Biological process[c]
1	March 2005	4,200	FS-01	Integrated	MLE
2	April 2005	240	FS-01	Integrated	MLE
3	December 2005	800	FS-01	Integrated	MLE
4	March 2006	600	HF-02	Integrated	MLE
5	September 2006	1,000	FS-01	Integrated	MLE
6	March 2007	125	FS-01	Integrated	MLE
7	April 2007	230	HF-01	Integrated	MLE
8	March 2008	1,375	HF-03	Integrated	MLE
9	March 2008	2,140	FS-02	Integrated	MLE
10	March 2009	2,150	FS-01	Integrated	MLE
11[d]	January 2010	5,000	FS-01	Integrated	UCT
12	March 2010	300	HF-03	Integrated	MLE
13	March 2010	6,060	FS-01	Integrated	MLE
14	February 2011	150	HF-02	Integrated	MLE
15[e]	March 2011	60,000[f]	FS-01	Integrated	MLE
16	March 2011	450	HF-01	Integrated	MLE
17	April 2011	620	HF-03	Integrated	MLE
18	March 2012	2,500	HF-01	Integrated	MLE
19	April 2012	500	HF-02	Integrated	MLE

[a] Design maximum daily flow, not including allocation for future expansion.
[b] FS-01: Kubota, FS-02: Hitachi, HF-01: Mitsubishi, HF-02: GE, HF-03: Asahi Kasei.
[c] MLE: Modified Ludzack-Ettinger process, UCT: University of Cape Town process.
[d] One CAS lane was upgraded to a demonstration MBR.
[e] A part of CAS lanes was upgraded to the temporary MBR lanes.
[f] Design maximum wet weather flow is 94,000 m^3/d.

in Japan, all these small-scale plants principally receive domestic wastewater collected by a separate sewer system. All the plants use an integrated submerged MBR with either flat sheet (FS) or hollow fibre (HF) membrane units which are submerged in aerobic tanks. The number of these two membrane systems is comparable; eight plants use FS membranes from Kubota or Hitachi, while nine plants use HF membranes from Mitsubishi, GE or Asahi Kasei. In contrast to these small-scale installations, plant Nos 11 and 15 are retrofitted MBRs from CAS lanes, for the purpose of R&D and demonstration (No. 11) and for temporary use ensuring treatment capacity during construction works (No. 15). The two plants also use an integrated submerged MBR system, both with an FS membrane from Kubota. Plant No. 15 is the largest MBR in Japan at the moment with an hydraulic capacity of 60,000 m^3/d for daily average dry weather flow and 94,000 m^3/d for wet weather flow conditions.

From these plants, design and operating data were collected from 17 plants (Nos 1–17), which had been commissioned at the time of the survey, by questionnaire or interview with the plant operators, as well as from design materials and published documents. Unfortunately, insufficient data were obtained from some of the plants. For operating data evaluation, the authors selected 9 small-scale plants (Nos 1–9), which had been operated for more than one year before the survey. Data for the largest plant (No. 15) are presented elsewhere (Tsuji *et al.* 2013), therefore not included in this paper. For plant No. 11, only limited project data including system configuration and energy consumption are presented.

RESULTS AND DISCUSSION

System design

With regard to the small-scale MBRs (excluding Nos 11 and 15 in Table 1), 15 out of 17 plants were designed according to the JS Recommendations and because they proposed standardized process configuration and 'typical' design parameters, these MBRs are quite similar (Figure 1). For biological treatment, all the plants used the Modified Ludzack-Ettinger (MLE) process (an anoxic-aerobic process with internal circulation of nitrified mixed liquor), where membrane units were submerged in aerobic tanks. Thus one lane of the MBR consisted of one anoxic tank and one aerobic tank with 3 hrs of design hydraulic retention time (HRT) each, with mixed liquor circulation pumps with a typical capacity of 2Q (2 times the maximum daily average inflow). This incorporation of anoxic tanks is, in the JS Recommendations, considered to be universal irrespective of the necessity of carrying out nitrogen removal from a viewpoint of conserving alkalinity. This is a common practice in Japan for the design of low-loaded (=long SRT) activated sludge processes. If phosphorus removal was necessary, simultaneous precipitation was incorporated. In addition, all these plants were equipped with flow equalization tanks ahead of bioreactors, as per the JS Recommendations. The capacity of the equalization tank was typically 4–5 hrs, determined so that a completely constant flow operation was possible in the MBR against the projected diurnal inflow fluctuation. All the plants were equipped with influent fine screens, typically with a 1 mm bar (slit) type, except for a few HF plants where 0.5 mm bar screens were installed. Nutrient removal was required at a limited number of plants, and external effluent reuse was employed at only one plant, where a post ozonation process was installed.

Plant No. 11 (in Table 1) is a demonstration plant installed in 2009 by a national R&D project 'A-JUMP' funded by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT 2011). In this project, a lane of an existing CAS in a municipal WWTP was retrofitted to a MBR with a capacity of 5,000 m^3/d. The plant was intended to remove nitrogen and phosphorus by UCT configuration with primary sedimentation and FS membrane units submerged in an aerobic tank. It was designed with a special focus on operating energy reduction by incorporating a series of measures including: (i) newly developed larger membrane units, (ii) siphon filtration, (iii) mixed liquor circulation with air-lift pumps, and (iv) low-energy mixers.

Biological treatment

Operating conditions for the selected nine plants (Nos 1–9 in Table 1) are summarized in Table 2. Because all these plants were newly constructed, most of them were underloaded; the inflow/capacity ratio (a ratio of daily average inflow to design hydraulic capacity of operating lanes) exceeded 50% only at three plants. Thus, depending on the plant-specific situation on sewer connection, the actual bioreactor HRT showed a wide range from 10 to more than 40 hrs. Similarly, operating sludge concentration in the bioreactors was quite plant-specific. Generally, the operators were inclined to operate their plants with higher mixed liquor suspended solids (MLSS) concentration than the design value (typically 10 g/L in the aerobic tank). Simultaneous precipitation with polyaluminium chloride (PAC) addition in the aerobic tank was employed at two plants.

For these nine plants, annual average and standard deviation values for influent and effluent biochemical oxygen demand (BOD), T-N, NH_4^+-N and T-P concentrations are summarized in Table 3. The annual average BOD was less than 3.5 mg/L at all the plants. While nitrogen removal was mandatory at only a few plants, the annual average effluent T-N was less than 7.4 mg/L, mostly less than 6 mg/L, since MLE configuration was employed at all the plants. As for effluent NH_4^+-N concentration, almost full nitrification was carried out at these plants except for plant No. 3. Surprisingly, six plants had experienced occasional suspended solids detection in the effluent (data not shown), possibly due to contamination in the permeate lines.

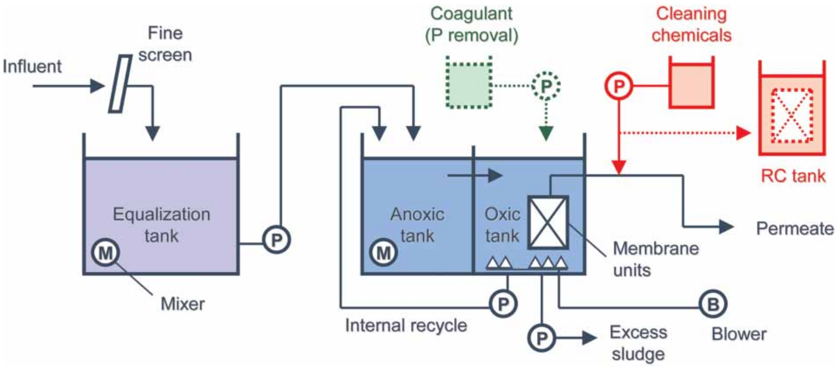


Figure 1 | Standardized process configuration for small-scale municipal MBR in Japan.

Table 2 | Annual average operating conditions of nine MBR plants

No.	Inflow/capacity ratio[a] [%]	Min temp. [°C]	HRT [hr]	MLSS (aerobic) [mg/L]	Circulation ratio[b] [–]	Precipitation[c]	Net flux[d] [m/d]	Membrane operation[e]
1[f]	75/60	14.4	12	9.2	2.3	PAC	0.49/0.39	C
2	13	8.5	47	13.5	1.7	No	0.07	C
3	49	10.3	14	12.3	1.9	No	0.32	I
4	55	13.2	10	10.8	0	PAC	0.33	n.a.[g]
5	26	11.6	24	13.6	3.8	No	0.17	I
6	34	9.9	45	17.3	n.a.[g]	No	0.24	I
7	50	11.5	15	11.3	0.2	No	0.18	I
8	12	9.7	33	9.5	5.0	No	0.05	I
9	12	15.1	169	8.4	7.8	No	0.09	I

[a] A ratio of daily average inflow to operating hydraulic capacity.
[b] A ratio of internal circulation flow to inflow.
[c] If simultaneous precipitation was employed, a name of coagulant was specified.
[d] Daily average net flux.
[e] C/I: Continuous/intermittent operation of membrane system.
[f] Because one lane was expanded in the course of the year, data before/after the expansion are presented.
[g] n.a.: Data were not available.

Table 3 | Annual average performance of biological treatment at nine MBR plants

	Influent concentrations [mg/L]			Effluent concentrations [mg/L]			
No.	BOD	T-N	T-P	BOD	T-N	NH_4^+-N	T-P
1	244 ± 80	n.a.	n.a.	1.1 ± 0.5	7.4 ± 1.0	n.a.	0.21 ± 0.09
2	80 ± 43	n.a.	n.a.	2.9 ± 5.0	n.a.	n.a.	n.a.
3	n.a.	n.a.	n.a.	3.5 ± 1.4	5.9 ± 2.6	4.6 ± 1.2	0.23 ± 0.25
4	140 ± 59	27 ± 14	2.9 ± 1.6	0.8 ± 0.4	2.5 ± 0.7	0.2 ± 0.4	1.0 ± 0.5
5	229 ± 26	n.a.	n.a.	1.5 ± 0.7	3.6 ± 2.1	0.3 ± 0.1	0.9 ± 0.5
6	324 ± 70	35 ± 6.7	4.1 ± 0.4	1.4 ± 0.5	3.6 ± 0.6	0.3 ± 0.3	1.3 ± 0.4
7	91 ± 25	n.a.	n.a.	1.7 ± 0.4	3.6 ± 0.8	n.a.	1.5 ± 0.3
8	114 ± 36	29 ± 4.2	3.4 ± 0.5	2.0 ± 0.2	6.3 ± 3.3	0.6 ± 0.4	1.7 ± 0.4
9	114 ± 30	23 ± 8.6	2.7 ± 0.8	0.8 ± 0.6	2.4 ± 0.9	0.3 ± 0.6	1.0 ± 0.4

Annual average and standard deviation values are presented.
n.a.: Data were not available.

Of all the surveyed plants, the demonstration MBR (No. 11 in Table 1) was the only one which incorporated enhanced biological phosphorus removal (EBPR) as a design basis. After start-up, however, phosphorus removal was rather unstable when primary effluent was used as the sole influent. As a result, the operator was forced to feed a mixture of raw wastewater and primary effluent, together with the temporary addition of PAC, particularly under wet weather conditions, in order to comply with the effluent T-P target value of 0.66 mg/L. It was also found that the effluent T-P concentration temporarily increased after cleaning in place (CIP) events. This led to the supplementary PAC addition at CIPs. A possible cause for this may be phosphorus release during CIP, in which activated sludge was kept unaerated.

Membrane operation

The membrane surface area installed in the nine small-scale MBRs corresponded to the net flux values of 0.37–0.74 m/d under design maximum daily inflow conditions. In contrast, the actual daily average net flux was in a range of

0.05–0.49 m/d (Table 2), depending on the inflow/capacity ratio. It was a common practice in extremely under-loaded plants to operate membrane systems intermittently, including a filtration pump, scouring aeration and internal circulation, according to diurnal fluctuation of the influent flow. At some such plants, a pre-aeration measure was taken prior to re-start of the membrane system, in order to avoid possible adverse effects caused by direct filtration of unaerated sludge.

Basic membrane cleaning was carried out according to the recommendations of the membrane suppliers. As shown in Table 4, frequent maintenance cleaning (MC) was carried out only at one plant (No. 4) where a HF membrane from GE was used. Frequency of recovery cleaning (RC) events was plant-specific, mostly ranging from 1 to 5 times/year. Oxidant (NaOCl) cleaning was quite universal, with only four plants employing additional acid cleaning. On the other hand, far more frequent CIP was carried out in plant No. 11, where NaOCl cleaning was carried out 9–10 times/year, as well as oxalic acid cleaning 2 times/year (data not shown). The relatively intensive cleaning practice at this plant may be as a result of several reasons including: (i) inflow close to design capacity throughout these years, (ii) peak flux operation against diurnal inflow fluctuation, and (iii) temporary drop of influent temperature under wet weather conditions.

Table 4 | Summary of the membrane cleaning events in eight MBR plants in FY 2009

No.	Membrane	Operating duration	Methods of cleaning[a]	Chemicals	Frequency
1	FS	5 year	CIP	NaOCl + oxalic acid	3/year
2	FS	5 year	CIP	NaOCl	2/year
3	FS	5 year	CIP	NaOCl	4 or 8/ year[b]
4	HF	4 year	CIP (MC)	NaOCl + oxalic acid	1/week
			CES	NaOCl	1/year
5	FS	4 year	CIP	NaOCl	1/year
6	FS	3 year	CIP	NaOCl	2/year
7	HF	3 year	CIP	NaOCl	3/year
			CES	Citric acid	1/year
8	HF	2 year	CIP	NaOCl	5/year
			CIP	Oxalic acid	1/year

[a] CIP: cleaning in place, CES: cleaning ex-situ.

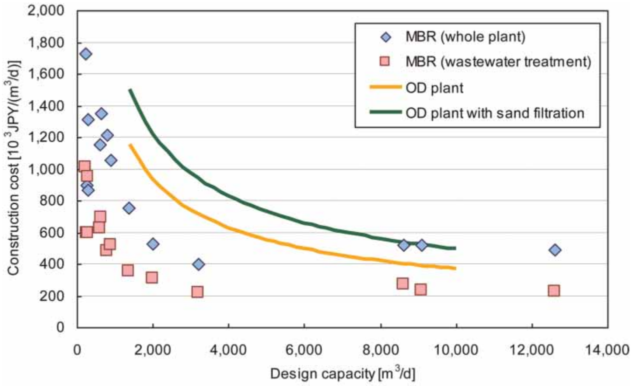
[b] Depended on the lanes.

Operating problems

In the survey, information on the operating problems experienced and countermeasures used was obtained. Problems with the influent fine screen were not very common in the plants. Only one plant experienced screen clogging, possibly caused by reject water from sludge dewatering and was mitigated by controlling the dewatering conditions. Over time, some plants experienced deterioration of nitrification under too high sludge concentration or reduced aeration. Air accumulation in permeate pipes was also observed in some plants, where an air release device was later installed. A few plants experienced the detection of coliform group bacteria in the effluent, due to contamination in the permeate lines/tanks, loosened pipe connections or, in the worst case, damaged membranes.

Costs

In Figure 2, construction costs for the 15 small-scale MBR plants (Nos 1–10, 12–14 and 16–17 in Table 1) were plotted as a function of design hydraulic capacity, together with Japanese cost function values for the oxidation ditch (OD) process, which was quite a common process for small-scale municipal WWTPs in Japan. Specific construction costs in terms of hydraulic capacity for these MBR plants reduced as plant capacity increased up to 3,000 m^3/d. For larger capacity, specific construction costs were rather stable around 0.2 million JPY/(m^3/d), although these values were not more than the costs for the OD process estimated by the cost function.

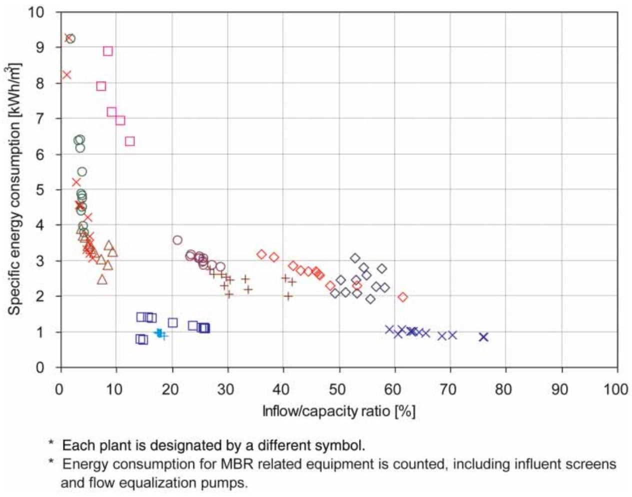


* For MBR plants, costs include estimated future expansion. Costs for purchasing land is not included.

* MBR (wastewater treatment) counts only MBR related facilities/equipment, including fine screen, flow equalization tank and effluent channel.

* Costs of oxidation ditch (OD) plant was estimated by cost function used in Japan.

Figure 2 | Construction costs of 15 small-scale MBR plants in Japan.



* Each plant is designated by a different symbol.
* Energy consumption for MBR related equipment is counted, including influent screens and flow equalization pumps.

Figure 3 | Monthly averaged specific energy consumption at 11 small-scale MBR plants in Japan.

Figure 3 shows monthly averaged specific energy consumption for 11 MBR plants (Nos 1, 2, 4–10, 12 and 13 in Table 1) as a function of the inflow/capacity ratio. Here, only energy consumption regarding MBR trains was taken into account, including fine screens, flow equalization pumps, mixers, circulation pumps, filtration pumps and all the blowers. An overall trend was that, as expected, specific energy consumption became lower as the inflow/capacity ratio increased, both among the plants and within each plant. In addition, there were significant differences in the range of energy consumption among the plants with comparable inflow/capacity ratio. If we exclude the data under extremely low-loaded conditions (inflow/capacity ratio less than 20%), the specific energy consumption values ranged from 0.8 to 3 kWh/m^3. These are in the range of reported values for full-scale municipal MBR plants worldwide (Krzeminski *et al.* 2012). In contrast to these small-scale installations, specific energy consumption in the demonstration plant No. 11 was extremely low, being 0.47 kWh/m^3 on an annual average basis and 0.39 kWh/m^3 under the full-capacity operation, in which aeration for membrane scouring and additional oxygen supply accounted for 72% and 25%, respectively. The use of air-lift pumps significantly reduced energy consumption for two routes of internal circulation to only 1%. These energy consumption values in plant No. 11 are at the lower edge of the reported range (Krzeminski *et al.* 2012).

CONCLUSIONS

The design and operating status of Japanese municipal MBR plants was surveyed. The selected MBRs showed good performance in terms of carbon and nitrogen removal, although incorporation of EBPR seemed to be challenging if primary sedimentation was operated. It was a common practice in extremely under-loaded plants to operate membrane systems intermittently. Frequency of RC events was plant-specific, mostly ranging from 1 to 5 times/year. Cost evaluation revealed that specific construction costs for the small-scale MBRs was not more than for OD during FY2009 plants. Although specific energy consumption values tended to be high in the under-loaded MBRs, the demonstration MBR with several energy reducing measures attained specific energy consumption of 0.39 kWh/m^3 under full-capacity operation.

Taking this achievement of energy consumption into consideration, in 2012 the Japan Sewage Works Agency (JS) launched new (4th-stage) intensive pilot-scale studies with several engineering firms and membrane suppliers, aiming to reduce energy consumption of municipal MBRs to less than 0.4 kWh/m^3. In addition, the Ministry of Land, Infrastructure, Transport and Tourism has commenced the standardization of MBRs, through discussion with a specialist committee established in JS. These projects are to further extend the market of MBRs inside and outside of Japan.

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