Energy- and Space-Saving Hollow Fiber Membrane Module Unit for Water Treatment

Keiichi IKEDA*, Tomoyuki YONEDA, Shinsuke KAWABE, Hiroko MIKI, and Toru MORITA

We have developed and marketed a new POREFLON membrane module unit for water treatment. It has a smaller footprint and is more energy saving than conventional products. In addition to the features of the conventional POREFLON hollow fiber membrane such as fouling resistance, high strength, and bending resistance, the module unit features the cassette type module structure, increased effective membrane length, enhanced packing density, and newly developed air diffusers that generate large air bubbles to prevent fouling. In a pilot test for municipal wastewater treatment jointly conducted with Japan Sewage Works Agency and others, we achieved a power consumption per unit of 0.4 kWh/m^3 or lower, which was the target point for the popularization of membrane treatment. The module unit passed another several field trials and was currently commercialized. This report introduces the development process, product specifications, and case studies regarding the new membrane module unit.

Keywords: PTFE, hollow fiber membrane, energy-efficient, space-saving, submerged type

1. Introduction

For the treatment of wastewater containing organic pollutants (e.g., sewage or factory wastewater), many membrane bioreactors (MBRs*[1]) have been put to practical use when it is required to reuse water, meet tighter regulations on effluent quality, or meet the site restrictions. An MBR is a combination of membrane separation, which is space-saving and ensures high quality for treated water, with conventional biological treatment.

Previously, Sumitomo Electric Industries, Ltd. commercialized a water treatment membrane made from the polytetrafluoroethylene (PTFE) composite hollow fiber membrane developed using its proprietary technology. We have developed a membrane module unit product that is more energy-efficient and space-saving than conventional products.

This paper introduces the product specifications, performance, and application examples, in particular.

2. Features of the POREFLON Hollow Fiber Membrane Module

POREFLON, which is a trademark of Sumitomo Electric for the membrane material, refers to a porous material made of 100% PTFE. It has superb heat resistance and chemical resistance, which are characteristics of fluororesins.

Using it as the base technology, we developed a composite hollow fiber membrane for water treatment. A two-layer structure suitable for water treatment was designed. The inner support layer is characterized by a large pore diameter (2 μm) to attain low water permeation resistance. The outer filtration layer has pores whose diameter is smaller than that of the inner support layer (0.1 μm). A hydrophilic polymer is chemically fixed onto the surface of the membrane, which is bundled in large numbers to create a module. The module product has been commercialized (Photo 1, Fig. 1).

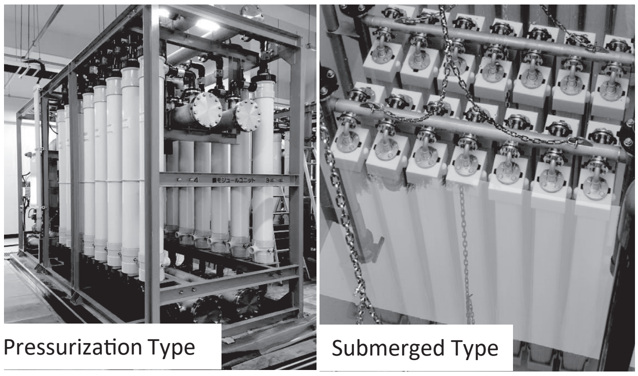


Photo 1. Appearance of a Membrane Module Unit

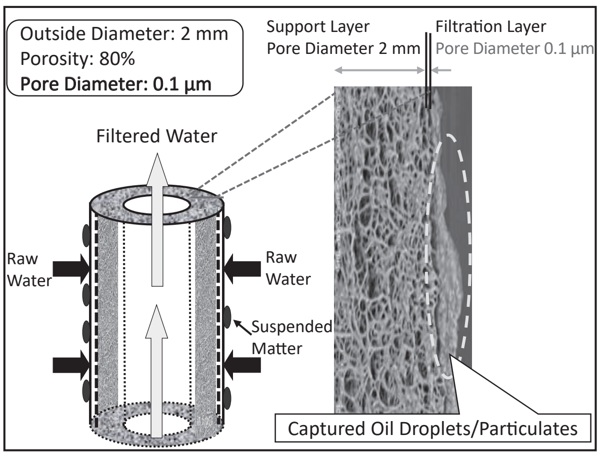


Fig. 1. Structure of the PTFE Composite Hollow Fiber Membrane

The product has three main features. First, it is resistant to contamination and clogging caused by organic matter, oil, and other substances contained in wastewater.

PTFE is hydrophobic, but a hydrophilic polymer is fixed onto the membrane surface in a chemically stable manner by Sumitomo Electric's proprietary hydrophilic treatment. In addition, the special microstructure and high porosity (Fig. 2) minimize clogging of the membrane, achieving stable treatment.

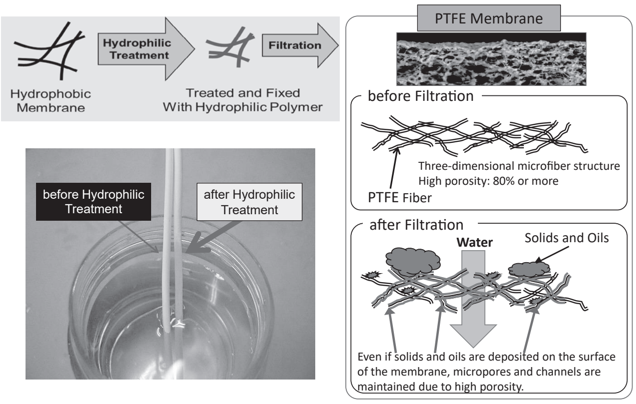
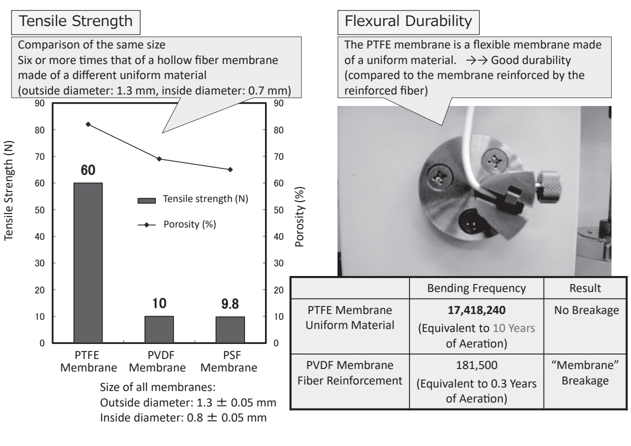


Fig. 2. Hydrophilic Treatment and Special Microstructure of the PTFE Membrane

Second, the product is characterized by high strength and bending resistance. Its tensile strength is six to 10 times that of other organic membranes (uniform membrane materials), and its bending resistance is at least 90 times that of other organic membranes (see Fig. 3). It is highly resistant to vibration stress caused by diffusion during the MBR operation. The risk of membrane breakage is low, enabling long-term operation.

Third, the product is resistant to chemicals. Notably, high-concentration alkali cleaning, which is effective for decomposing, delaminating, and removing organic matter and oil that adhere to the membrane, can be performed. It is easy to recover the performance, leading to long service life of the membrane.



	Bending Frequency	Result
PTFE Membrane Uniform Material	**17,418,240** (Equivalent to 10 Years of Aeration)	No Breakage
PVDF Membrane Fiber Reinforcement	181,500 (Equivalent to 0.3 Years of Aeration)	"Membrane" Breakage

Fig. 3. Tensile Strength and Flexural Durability

3. Improvement and Development of the Membrane Module Unit

In MBR, air is diffused (discharged) from the bottom of membrane modules. The shear energy of the gas-liquid multiphase flow is used to shake the membrane and remove sludge and dirt adhering to the membrane surface, thereby maintaining the flow rate.

It should be noted that the air blower, which serves as the power source, requires high power consumption. The biggest issue in promoting widespread use is developing units comprised of membrane modules and metallic frames that can be efficiently cleaned.

Sumitomo Electric defined three basic solutions to achieve energy-efficient and space-saving membrane modules:

(1) Increasing the effective length and filling rate of the membrane
(2) Increasing the diameter of the diffusion bubbles
(3) Collecting treated water from both ends

3-1 Increasing the effective length and filling rate of the membrane

Regarding diffusion in MBRs, the longer the effective length of the hollow fiber membrane, the deeper the position from which bubbles rise. Bubbles gather and increase the amplitude of shaking, achieving a high cleaning effect.

However, this increases the stress load that applies to both ends of a membrane and may cause problems such as membrane breakage.

As discussed in Section 2, Sumitomo Electric's hollow fiber membrane is more physically durable than competitors' membranes. Thus, the effective length of the membrane was extended from 2 m to 3 m.

Meanwhile, the improvement in the bonding resin (e.g., epoxy resin) injection technology for the sealing part of the hollow fiber membrane led to an increased effective membrane filtration area of the hollow fiber membrane. The hollow fiber membrane filling rate per installation area was also increased from 343 m^2/m^2 to 750 m^2/m^2. Thus, the diffusion energy per membrane area (water treatment volume) was reduced by about 40%.

3-2 Increasing the diameter of diffusion bubbles

In general, the larger the bubbles for diffusion, the higher the effect of shaking the hollow fiber membrane, helping reduce the air volume.

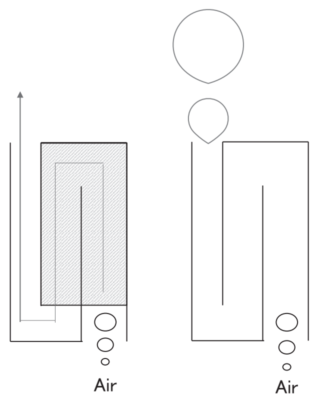


Fig. 4. Mechanism to Feed Coarse Bubbles

The conventional porous pipes are characterized by a simple structure (only pores provided in pipes). An increased pore diameter to create coarse bubbles causes differences in the air volume from each pore. Thus, we provided a mechanism to generate coarse bubbles, as shown in Fig. 4, above the porous pipe.

Air is fed into a container in which a certain amount of air is already accumulated. This causes air to gush out, making it possible to supply coarse bubbles intermittently.

3-3 Collecting treated water from both ends

In this product, raw water flows from the outer surface to the inside of the hollow fiber membrane to achieve filtration. Treated water flows through the hollow fiber membrane and is collected in the end part.

In the conventional product, water was collected only from one end (top). The new structure is designed to collect water from both ends (top and bottom). This has made it possible to reduce the pressure loss in the hollow fiber membrane and the transmembrane pressure (TMP).

Figure 5 shows a demonstration example. An experiment was conducted to compare the water permeability between the one-end water collection type and the both-ends water collection type with different membrane effective lengths (suction filtration pressure: −10 kPa, water temperature: 15°C).

The figure shows that, the greater the effective length, the larger the difference of the water permeation volume between the one-end water collection type and the both-ends water collection type.

We also conducted a demonstration on a pilot-scale MBR using actual raw water (domestic wastewater generated by Sumitomo Electric Fine Polymer, Ltd.). The results are shown in Fig. 6.

The settings were established to attain the same flow rate for concurrent evaluation. The increase in the TMP of the both-ends water collection type was slow compared to that of the one-end water collection type.

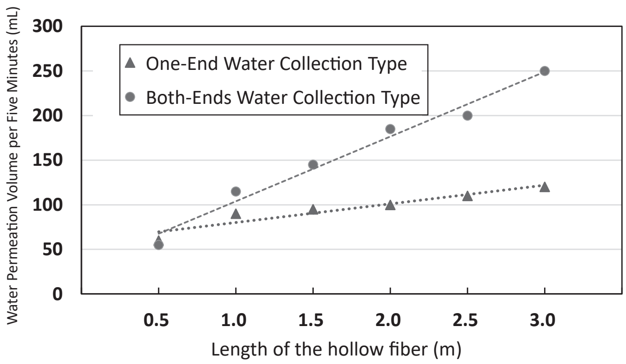


Fig. 5. Comparison of Water Permeability between the One-End and Both-Ends Water Collection Types

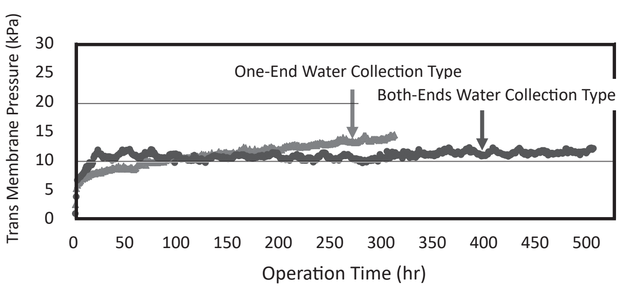


Fig. 6. Comparison of the TMP between One-End and Both-Ends Water Collection Types

4. Pilot Demonstration Experiment

4-1 Experiment conditions

An MBR pilot plant that employed the improved small membrane module unit (incorporating the newly developed elements explained in Section 3) was installed on the premises of the R&TD Experiment Center of the Japan Sewage Works Agency in Moka City, Tochigi Prefecture (Photo 2) to conduct demonstration experiments. The flow of the experiment equipment is shown in Fig. 7.

Photo 2. Demonstration Plant jointly with the Japan Sewage Works Agency and Maezawa Industries, Inc.

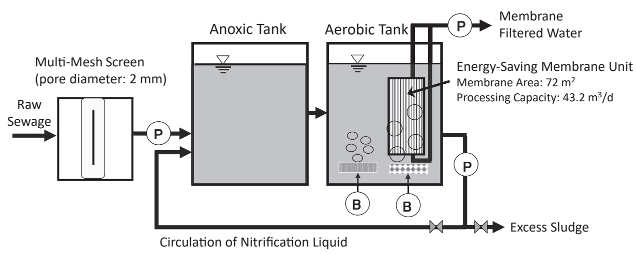


Fig. 7. Flow of the Experiment Equipment

The equipment was a circulation type nitrification-denitrification system. Screenings were removed from the raw sewage using the mesh screen equipment in the former stage. The aerobic tank in the latter stage was designed to return the nitrification liquid (nitrified ammonia) to the anoxic tank for denitrification. The membrane unit shown in Photo 3 was immersed in the aerobic tank in the latter stage. A large bubble diffuser (Fig. 8) was installed under the membrane unit.

In this demonstration experiment, two operations were switched and performed depending on the period: constant flow rate operation, in which raw water was supplied at a

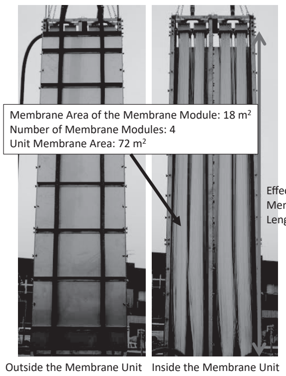


Photo 3. Membrane Unit

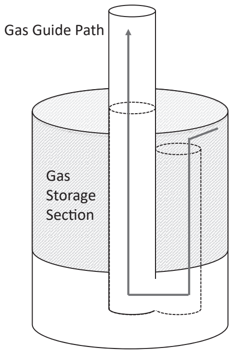


Fig. 8. Large Bubble Diffuser Equipment

constant rate, and variable flow rate operation, which was based on the increased sewage influent flow rate in the morning and evening.

The basic membrane filtration operation cycle consisted of nine minutes of filtration and one minute of suspension. The membrane was subject to chemical cleaning: low-concentration inline cleaning by using NaOCl (500 mg/L) + NaOH (250 mg/L) once a week and high-concentration inline cleaning by using NaOCl (2,000 mg/L) + NaOH (250 mg/L) once every several months. Table 1 shows the details of the operation conditions.

Table 1. Operation Conditions

Item	Constant Flow Rate Operation	Variable Flow Rate Operation
Period	RUN1 : 2014/4/1~2014/5/30 RUN3 : 2014/8/8~2014/12/8 RUN5 : 2015/1/5~2015/2/16	RUN2 : 2014/5/30~2014/8/8 RUN4 : 2014/12/8~2015/1/5
Water Treatment Flow Rate	43.2 m³/d	36.0 m³/d
Average Flux	0.6 m/d	0.5 m/d
Membrane Area	18 m²/Module × 4 units = 72 m²	
Retention Time	3 h (aerobic) + 3 h (anoxic) = 6 h	3.6 h (aerobic) + 3.6 h (anoxic) = 7.2 h
MLSS	7,000~13,000 mg/L	5,000~10,000 mg/L
Circulation Ratio	300%	
Air Flow Rate for cleaning the membrane (Coarse Bubbles)	40 L/min/module × 4 = 160 L/unit	
Auxiliary Diffusion Air Flow Rate (Microbubbles)	50~180 L/min	

4-2 Results of the experiment

(1) Treated water quality

Table 2 shows the mean water quality of the membrane-filtered water. The organic matter and nitrogen were removed effectively during both the constant flow rate operation period and the variable flow rate operation period. The target water quality (BOD: 3 mg/L or less, T-N: 10 mg/L or less) was attained. No coliform bacteria, colon bacillus, coliphage, or norovirus were detected in the membrane-filtered water. The results were good.

Table 2. Results of Permeated Water Quality

Item	Unit	Average of constant flow rate operation		Average of variable flow rate operation		Target water quality
		Influent Water	Permeated Water	Influent Water	Permeated Water	
BOD	mg/L	138	0.5	102.0	0.4	3
T-N	mg/L	26.6	6.9	19.8	7.5	10
NH_4-N	mg/L	17.6	1.5	13.2	1.1	—
SS	mg/L	152	ND	124	ND	ND
Coliform Bacteria	CFU/mL	1.6×10^5	ND	2.0×10^5	ND	—
Colon Bacillus	CFU/mL	3.5×10^4	ND	2.6×10^4	ND	—
Coli Phage	PFU/mL	—	—	5.1×10^3	ND	—
Norovirus GI	Copies/L	—	—	2.4×10^6	ND	—
Norovirus GII	Copies/L	—	—	5.6×10^7	ND	—

* ND for SS is less than 0.4 mg/L.
* Viruses are measured once when the water temperature is low during the variable flow rate operation.
* ND for coli phage is less than 1 PFU/100 mL. ND for norovirus is less than 9.6 × 10 copies/L.

(2) Operability (flow rate, TMP)

The changes over time in the TMP and flux*2 are shown in Fig. 9. The constant flow rate operation was performed in RUN1, RUN3, and RUN5. The TMP was stable at 10 to 20 kPa during the high water temperature period (20°C or more) (RUN1, RUN3).

During the low water temperature period (20°C or less) (RUN5), the TMP was high at 17 to 25 kPa, but no rapid increase was observed.

In RUN2 and RUN4, the variable flow rate operation was performed. During the high water temperature period (RUN2), the predetermined diffusion could not be performed due to the failure of the air blower. The TMP shot up temporarily but decreased to the normal level due to low-concentration inline cleaning. It was stable at roughly 20 kPa or less. Even during the low water temperature period (RUN4), the TMP was stable at 20 kPa or less.

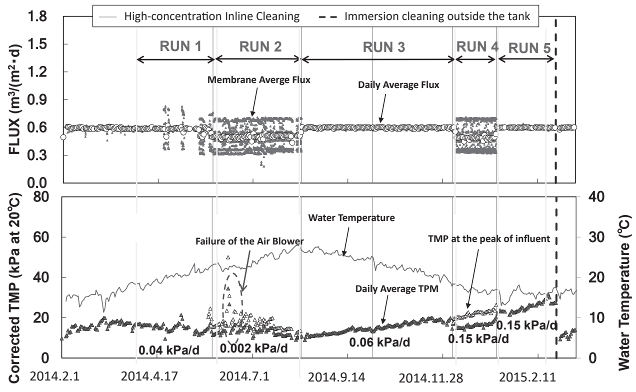


Fig. 9. Change over time of TMP and Flux

4-3 Trial calculation of energy conservation

We performed trial calculation of the power consumption basic unit based on the assumption that this MBR system was introduced for a project with a treatment capacity of 5,000 m^3/day. The conditions for trial calculation are shown in Table 3. The time change ratio of the influent water flow rate was set to 1.4.

This trial calculation was also based on the assumption that an inflow regulation tank would be used. Thus, the agitator and raw water supply pump for the tank were also included in the calculation.

The equipment specifications were determined under these conditions, and the electricity consumption basic unit was calculated based on the assumption that a water flow rate equivalent to the daily average water flow rate would be treated.

Table 3. Trial Calculation Conditions

T-N	mg/L	35	30	10
Kj-N	mg/L	—	—	1
T-P	mg/L	4	3.4	0.5

Daily average water flow rate	5,000	m^3/d
Daily maximum water flow rate	6,650	m^3/d
Hourly maximum water flow rate	7,000	m^3/d
Lowest water temperature in winter	15	°C
Average Flux (constant flow rate)	0.6	m/d
Air volume for cleaning the membrane (coarse bubbles)	40	L/min/module
Oxygen dissolution efficiency of the air diffuser for cleaning the membrane	8	%
Oxygen dissolution efficiency of the auxiliary air diffuser	20	%
Correction coefficient for kLa: α value	0.6	
Correction coefficient for oxygen saturated concentration: β value	0.95	
Sludge generation amount of the raw sewage	0.65	Kg/MLSS/kg-SS

Figure 10 shows the electricity consumption basic unit of each piece of equipment used for the conventional module and the energy-efficient membrane module derived from the trial calculation. The electricity consumption basic unit of the energy-efficient membrane module (raw water: raw sewage) was 0.39 kWh/m^3. Thus, we judged that the development target of 0.4 kWh/m^3 would be attained.

Compared to the results of a full-scale submerged type MBR facility in Japan, the contribution rate of the blower for cleaning the membrane was reduced from 70 or 80% to 30%. The results suggested that the factor that contributed to energy conservation of this MBR was reduction in power consumption of the blower for cleaning the membrane due to the improvement in the membrane module unit discussed in Section 3.

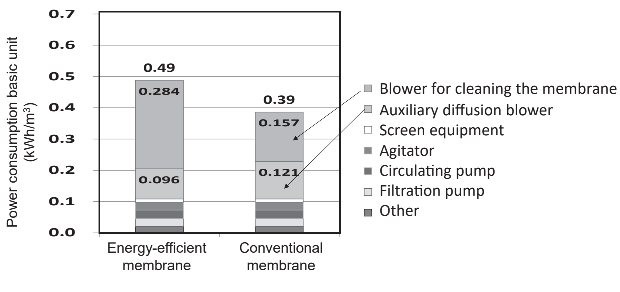


Fig. 10. Electricity consumption basic unit of the conventional and energy-efficient membrane units

It should be noted that this section is part of the results of the joint research by the Japan Sewage Works Agency, Maezawa Industries, Inc., and Sumitomo Electric ("Technology Development toward Promoting Introduction of MBRs—Research on Increasing the Energy Efficiency of MBRs Using PTFE Hollow Fiber Membrane").

5. Cassette Type Membrane Module Unit

We verified the energy conservation effect in the demonstration experiment discussed in Section 4. To cope with large-scale projects, we developed a cassette type module (Fig. 11) and unit and standardized them as products. The specifications in comparison with the conventional product are shown in Table 4.

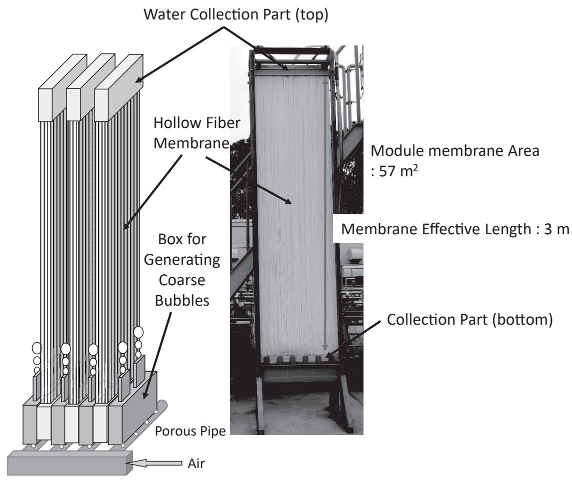


Fig. 11. Cassette type membrane module

Table 4. Comparison of Specifications between the Conventional and Cassette Type

	Conventional	Cassette type (energy-efficient)
Photo of the membrane unit		
Module membrane area (m^2)	12	57
Module dimensions (mm)	154 × 164 × 2410	840 × 50 × 3220
Unit membrane area (m^2)	12 × 20 = 240	57 × 48 = 2736
Unit dimensions (mm)	1768 × 400 × 2920	1750 × 2084 × 4015
Unit projection area (m^2)	0.7	3.65
Unit membrane filling rate (m^2/m^2)	343	750
Diffusion structure	Porous pipe only	Porous pipe + Box for generating coarse bubbles

6. Application Examples

This section introduces application examples of the cassette type module unit described in this paper. In April 2018, the first module unit in Japan was introduced to a food industrial park for wastewater treatment (1,300 m^3/day), as shown in Photo 4.

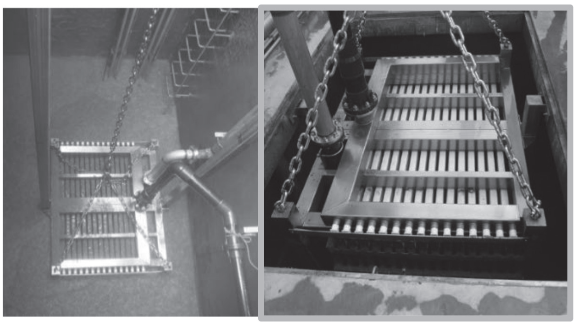


Photo 4. Membrane unit installed in a food factory in Japan

Figure 12 shows the daily change in the membrane differential pressure. The membrane differential pressure exceeded 20 kPa temporarily due to the abnormal raw water quality, but the increase in the membrane differential pressure one year after commencement of operation was approximately 5 kPa. This indicates that stable operation was maintained.

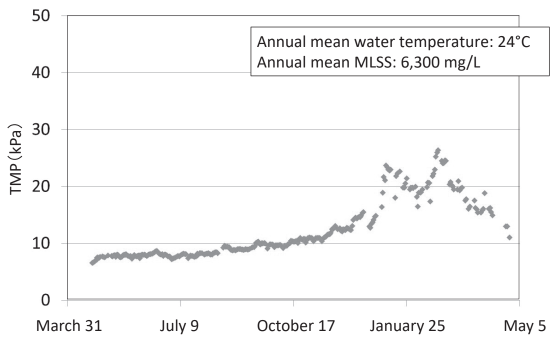


Fig. 12. Daily change in membrane differential pressure

Our module units have also been highly evaluated for their advantages in lifecycle cost and installation area in foreign countries where the demand for water treatment is high. We delivered the module units to an urban sewage treatment plant (35,000 m^3/day) in China, which was the largest treatment capacity for Sumitomo Electric. Photo 5 shows the module units in place. This fiscal year, we received an order for a large project (50,000 m^3/day). In Taiwan, we delivered our module units to a leading semiconductor manufacturer in the world for treatment of organic wastewater in 2018 and 2019, respectively. These module units are in stable operation.

Photo 5. Membrane unit of urban sewage treatment plant in China

7. Conclusion

We developed and marketed energy-efficient cassette type hollow fiber membrane modules and units whose installation area per membrane area is small by taking full advantage of the features of the PTFE hollow fiber membrane, including (1) contamination resistance and clogging resistance, (2) high strength and bending resistance, and (3) chemical resistance.

In the near future, pollution of water resources and water shortage are expected to become more serious due to global population growth mainly in emerging countries. Higher expectations are placed on the evolution of inexpensive and advanced water treatment technologies.

We remain committed to promoting the technological development to deliver water treatment systems that are more energy-efficient, less expensive in terms of membrane cost, and easier to maintain.

• POREFLON is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

Technical Terms

*1 MBR: MBR is an abbreviation for membrane bioreactor. The MBR process is a type of the activated sludge method to purify sewage and factory wastewater. Treated water is separated from activated sludge using a microfiltration (MF) membrane or ultrafiltration (UF) membrane instead of a conventional sedimentation tank.

*2 Flux: Flux refers to the volume of membrane-filtered water per unit time/unit membrane area. The unit $m^3/m^2/d$ or $L/m^2/h$ is often used.

Reference

(1) T. Miyoshi, T. Nguyen, T Tsumuraya, H. Tanaka, T. Morita, H. Itokawa, T. Hashimoto. Energy reduction of a submerged membrane Bioreactor using a polytetrafluoroethylene (PTFE) hollow-fiber membrane. Front. Environ. Sci. Eng. 2018, 12(3)

Contributors The lead author is indicated by an asterisk (*).

K. IKEDA*

- Assistant General Manager, Water Processing Division

T. YONEDA

- Group Manager, Water Processing Division

S. KAWABE

- Department Manager, Zhongshan Sumiden Hybrid Products Co., Ltd.

H. MIKI

- Water Processing Division

T. MORITA

- General Manager, Water Processing Division