Methane Fermentation System with Membrane Bioreactor

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Abstract:

The objective of this study is to improve the organic decomposition of food waste by applying microfiltration membranes for methane fermentation systems. JFE Engineering conducted experiments of the developed system in a laboratory scale. When digestion sludge concentration was doubled, organic decomposition rate was enhanced up to 98%, methane production was increased by 21% and sludge production was decreased by 75% compared with conventional systems, even though hydraulic retention time was reduced by half. Next, JFE Engineering applied this system to the Garbage Electric Generation Center in Nagaoka City as a demonstration test. The digestion sludge was concentrated from 1.5% to 4%, methane production rate was increased by 22% and the sludge production was decreased by 64% compared with conventional systems. In addition, electric power generation of the entire facility was increased by 27% compared to the average in 2017 before this system was installed.

1. Introduction

Methane fermentation technologies for sewage sludge, food waste and other streams of organic waste have increasingly attracted attention in the push toward circular economy and the achievement of Sustainable Development Goals(SDGs). Methane fermentation is a process that produces biogas (containing approximately 60% methane) from organic materials through microbial reactions under anaerobic conditions. One of the applications of such biogas is its usage for power generation, especially when electricity sales can command attractive rates per kWh in a Feed-In Tariff (FIT) system such as the one launched in Japan in July 2012. In such cases, it is desirable to enhance the production of methane contained in the biogas in order to generate more electricity. In addition, methane fermentation also produces fermentation sludge, which contains undecomposed organic residue. Given that fermentation sludge requires post-treatment (e.g., incineration, drying, carbonization, etc.) prior to is disposal, it is also desirable to reduce the generation of sludge to reduce the cost of such post-treatment. To achieve these targets, organic decomposition rate improvement is required. Previous studies have found that the organic decomposition rate increases as the sludge retention time in the digester increases[1)].

Therefore, JFE Engineering has developed a methane fermentation system (hereinafter, the Developed System) with membrane bioreactor by combining the fermentation process with a membrane separation process which makes it possible to retain the organic matter in the digester for an extended time. This report describes a laboratory-scale test which was carried out under a joint research collaboration with Tohoku University, and the results of a demonstration test conducted at The Garbage Biogas Electric Generation Center in Nagaoka City.

2. Features of Developed System

Table 1 shows the concept of the methane fermentation system with membrane bioreactor. Total solids is an index of the digestion sludge concentration and CODcr (Chemical Oxygen Demand) is an index of the concentration of organic matter. In the Developed System, a membrane device for the separation of the fermentation sludge into solid and liquid fractions is combined with a digester. Solid matter, which has a large content of undecomposed organic matter, is returned to the digester by this solid-liquid separation process

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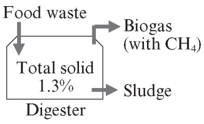
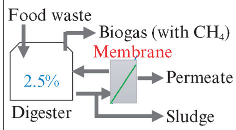
Table 1 Concept of methane fermentation system with membrane bioreactor

	Conventional system	Developed System
Outline process flow		
Total solids (%)	1.3	2.5
Digester volume※1 (–)	100	50
CODcr removal (%)	83	90
Methane production rate (m^3/t※2)	82	94
Sludge production (kg/t※2)	52	31
Ammonium (mg/L)	<2 000	<2 000

※1 100 means the same volume as conventional, ※2 As weight of food waste

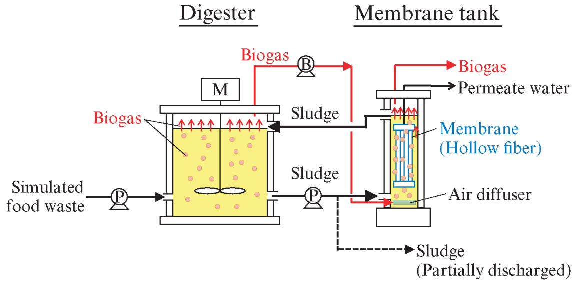


Fig. 1 Schematic diagrams of lab-scale test

Table 2 Specifications of membrane in lab-scale test

Type	Hollow fiber
Membrane material	PTFE
Membrane area	0.1 m^2
Pore size	0.1 µm

Table 3 Results of lab-scale test

	Conventional system	Developed System	
		Result	Target value
Total solids (%)	1.3	2.5	2.5
Hydraulic retention time (L/(L/day))	30	15 (△50%)	15 (△50%)
CODcr removal (%)	83	98	90
Methane production rate (m^3/t)	82	99 (+21%)	94 (+15%)
Sludge production (kg/t)	52	13 (△75%)	31 (△40%)
Ammonium (mg/L)	880	730	≦880

while the permeate water, which contains almost no organic matter, is discharged from the system. As shown in Table 1, the Developed System has the following benefit.

1) Because undecomposed organic matter can be held in the digester, the sludge retention time (organic matter retention time) can be increased, resulting in a higher organic decomposition rate.
2) The concentration of the microorganisms that contribute to methane fermentation in the sludge can be increased, making it possible to downsize the digester.
3) The ammonium ion, which is known to be an inhibitor for methane fermentation, is discharged from the system together with the permeate water. This feature prevents the concentration of the ammonium ion during sludge thickening, contributing to stable digester performance.

3. Lab-scale Test for Preliminary Study of Fermentation Characteristics

The fermentation characteristics of the Developed System were compared to those of a conventional system during a lab-scale test carried out through joint research with Tohoku University.

3.1 Experimental Method

Figure 1 shows a schematic diagram of the lab-scale equipment of the Developed System. The digester was designed with an effective capacity of 12 L, and the water temperature was controlled to 35±1°C. **Table 2** shows the specifications of the membrane module. The separation membrane was a hollow fiber membrane module for use in small-scale experiments manufactured by Sumitomo Electric Industries, Ltd. To prevent membrane fouling, air-scouring was performed on the membrane using biogas suctioned from the gas phase of the digester with an air pump. The simulated food waste fed to this methane fermentation system was prepared based on a previous study[1] and was diluted with tap water to a total solid concentration of 4.8%.

3.2 Results of Lab-Scale Test

Table 3 shows the results of the lab-scale test. The Developed System was operated for 80 days with a digestion sludge concentration 2 times larger than that of the conventional system, and the hydraulic retention time in the digester was reduced by half. Under these examination conditions, the CODcr removal rate increased to 98%. As a result, methane production increased by 21% while sludge production decreased by 75%. The results also confirmed that the ammonium

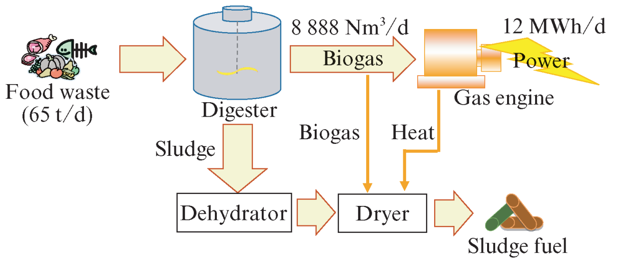


Fig. 2 Process flow of the Garbage Biogas Electric Generation Center in Nagaoka City

ion was not concentrated. Thus, the target values of all items were achieved.

4. Demonstration Test at The Garbage Biogas Electric Generation Center in Nagaoka City

Since the target values were achieved at lab-scale test, a further demonstration test was carried out at The Garbage Biogas Electric Generation Center in Nagaoka City (hereinafter, the Nagaoka Facility) using a separation membrane unit (hereinafter, Large-Scale Membrane Unit) similar in scale as those used in actual Membrane Bio-Reactor (MBR) plants.

4.1 Overview of the Nagaoka Facility

The Nagaoka Facility was planned with a food waste treatment capacity of 65 t/d and was designed with an electric power generation capacity of 12 300 kWh/d [2)]. Two digesters (Digester No. 1, Digester No. 2), each with a tank capacity of 1 800 m^3, were installed. **Figure 2** shows the general process flow of the Nagaoka Facility. The raw material, which is stored in a mix and storage tank, is charged in equal amounts to the two digesters, and the produced methane gas is supplied both to a gas engine for power generation and a dryer used to dry the sludge. The dry sludge is further utilized as fuel by a third party outside the Nagaoka Facility.

4.2 Exploring for Stable Operating Condition and Evaluation of Fermentation Characteristics

4.2.1 Demonstration plant and method

Photo 1 shows the appearance of the demonstration plant. A reinforced concrete membrane tank was installed between the digesters and the gas holder. The Large-Scale Membrane Unit was installed in the membrane tank. **Figure 3** shows the flow of the demonstration plant. The red lines in Fig. 3 indicate the equipment that was added for this demonstration test system. Digester No. 1 was operated using the Developed System. Fermentation sludge from Digester No. 1

Photo 1 Appearance of demonstration plant

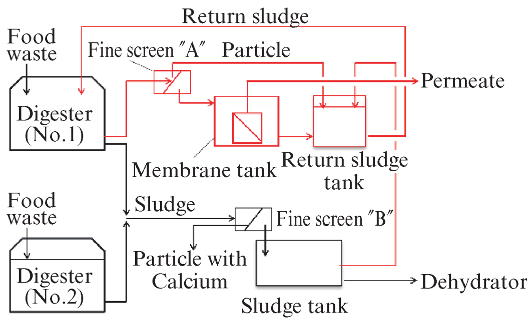


Fig. 3 Schematic diagram of demonstration plant

was supplied to the membrane tank, and concentrated sludge was returned to the digester. Fine screen "A" was installed to prevent physical damage to the membrane caused by coarse suspended solids. Particles removed by screen "A" before the membrane tank were returned to Digester No. 1 together with the concentrated sludge as return sludge. Digester No. 2 was operated by the conventional method as control system. Because the food waste treated by the Nagaoka Facility contains many eggshells, clogging of the piping by calcium scaling was a concern. As a countermeasure for this problem, Fine Screen "B" is used to remove coarse suspended solid particles, including calcium, when the fermentation sludge is discharged to the sludge tank. This countermeasure was also implemented for the return sludge in the demonstration test system.

Table 4 shows the specifications of the membrane tank and the Large-Scale Membrane Unit. The Large-Scale Membrane Unit was a TMR 140J-200D (Toray Industries, Inc.), which is a flat sheet membrane that is less prone to trouble caused by coarse suspended solids. **Table 5** shows the operating conditions of the Large-

Table 4 Specification of membrane tank and module in demonstration plant

Tank volume	88 m^3
Tank size	5 $m^W \times 3.2\ m^L \times 5.5\ m^H$
Type	Flat sheet
Membrane material	PVDF
Membrane area	280 m^2/unit
Pore size	0.1 µm

Table 5 Operating conditions of membrane process

Unit number of membrane	2～4 unit
Area of membrane	560～1 120 m^2
Suction pump operation	7 min (ON) – 2 min (OFF)
Chemical for membrane cleaning	①Acid 1.5 wt% citric acid ②Alkaline 0.5 wt% NaClO

Scale Membrane Unit. The operating conditions were set in accordance with the membrane manufacturer's recommended operating conditions. Chemical cleaning was performed by an in-line method by chemical dosing on the membrane surface from the permeation side via the permeate water piping. The amount of chemical dosed was set at 3.6 L/m^2 of the effective area of the membrane. Acid cleaning was carried out to remove membrane fouling substances of inorganic origin such as calcium, etc., and alkali cleaning was done to remove fouling substances of organic origin. To verify stable operating performance of the membrane separation process, the fluctuation of the transmembrane pressure (TMP), which is an indicator of membrane fouling, was evaluated during the operation period. Although the membrane manufacturer's recommended TMP value is 15 kPa or less, during this demonstration test, operation was conducted using a value of less than 5 kPa as a guideline.

4.2.2 Test results

(1) Stable operation performance

Figure 4 shows the flux, TMP and digestion sludge concentration of Digester No. 1. Operation was started in March 2019 at a flux of 0.04 $m^3/m^2/d$. The frequency of chemical cleaning was once/week for acid cleaning and once/month for alkali cleaning. Studies show that, for membrane treatment process for organic wastewater, the organic content of the wastewater causes biofouling on the membrane[3]. Therefore, alkali cleaning is typically required more frequently than acid cleaning. In this test, however, the reason for the increased frequency of acid cleaning is thought to be due to membrane fouling mainly caused by calcium originating from the eggshells contained in the raw material.

Two Large-Scale Membrane Units were operated at 0.07 $m^3/m^2/d$ starting in June 2019. Three months later, the sludge concentration reached 2.5%. Stable operation was achieved through to December 2019 with no significant rise in TMP during this period. In order to achieve further increase in methane fermentation efficiency, the sludge in Digester No. 1 was further concentrated by increasing the number of Large-Scale Membrane Units from 2 to 4. Under operation at a flux of 0.07 $m^3/m^2/d$, TMP rose sharply when the digestion sludge concentration of 3% in February 2020. Membrane permeation conditions for stable operation at a digestion sludge concentration of 3% were evaluated. It was found that stable operation is possible at a flux of 0.05 $m^3/m^2/d$. Digestion sludge concentration was further increased to 4.0% in April 2020, and stable operation could be achieved through to June 2020. The chemical cleaning conditions and frequency did not change during the entire test period.

(2) Fermentation characteristics

Table 6 shows the comparison between the fermentation result of the Developed System and the conventional system. As can be noted, at the digestion sludge concentration of 2.5%, the organic matter (CODcr) removal rate was 97%. When the digestion sludge was

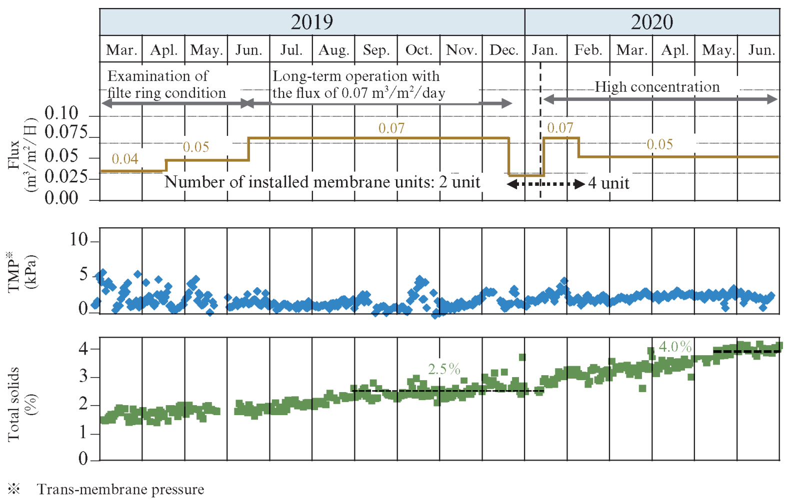


Fig. 4 Long-term operation of membrane process (flux, TMP, Total solids of digestion sludge)

Table 6　Comparison of fermentation characteristics between Developed System and conventional system

	Conventional system (Digester No.2)	Developed System (Digester No.1)	
Total solids (%)	1.5	2.5	4.0
HRT※1 (m^3/(m^3/day※3))	38	38	38
SRT※2 (m^3/(m^3/day※3))	38	165	318
CODcr removal (%)	83	97	98
Methane production rate (Nm^3/t※4)	104	120 (＋15%)	127 (＋22%)
Sludge production (kg/t※4)	60	28 (△53%)	22 (△64%)
Ammonium (mg/L)	1 500	1 500	1 500

※1 Hydraulic retention time, ※2 Sludge retention time,
※3 As volume of food waste, ※4 As weight of food waste

Table 7　Permeate quality

	Developed System	Conventional system
	Permeate	Liquid from dehydrator
pH (－)	7.8	8.3
SS※1 (mg/L)	<1	1 400
BOD_5※2 (mg/L)	30	1 300

※1 Suspended solids, ※2 Biochemical oxygen demand

further thickened to 4.0%, the CODcr removal rate was improved to 98%, the methane production per ton of food waste increased by 22%, and the sludge production decreased by 64%. The higher CODcr removal rate at a digestion sludge concentration of 4.0% was achieved due to the increase of the sludge retention time in the digester from 165 days to 318 days caused by the increase of the digestion sludge concentration. Similarly to the results of the lab-scale test, the results of the demonstration test also confirmed that there was no increase in the ammonium ion concentration. **Table 7** shows the analysis of the water permeated by the Large-Scale Membrane Units and the water filtered by the dehydrator. According to the analysis results, extremely low concentrations were obtained for suspended solids (SS) and biochemical oxygen demand (BOD_5) in the membrane permeate water. Based on this result, it can be concluded that, as expected, undecomposed organic matter was concentrated in the digester as sludge.

(3) Results of introduction of Developed System in the Nagaoka Facility

Table 8 shows the results of the Development System's implementation at the Nagaoka Facility. This table compares the results for the entire facility during the operation of the Developed System as described previously (i.e., applied to only one of the two digesters), and the results of conventional operation during the fiscal year 2017, before the introduction of the Developed System. As a result of the introduction of the Developed System, when the digestion sludge concentration (Total solids) was increased to 4.0%, methane gas production increased by 10%, sludge production decreased by 20% and electric power generation increased by 27% compared to before the implementation. The increase of the digestion sludge concentration to 4.0% had an even higher impact on the facility's methane fermentation efficiency. The main factors contributing towards the increased electric power generation were found to be as follows: i) Increase in methane gas production and ii) Increase in biogas available for electric power generation due to the decrease in biogas consumption by the sludge dryer due to the lower sludge production. The reason for the 4-point decrease in the moisture content of the dewatered cake is due to the increase of inorganic matter content in the fermen-

Table 8　Effect of applying the Developed System

	Before demonstration test	Result of demonstration test No.1: Developed System No.2: Conventional system	
Period	F.Y.2017	'19/Jun.～'20/Jan.	'20/Apl.～'20/May.
Total solids※1 (%)	1.3	2.5	4.0
Methane production rate (Nm^3/t※2)	96	101 (+5%)	105 (+10%)
Sludge production (kg/t※2)	36.4	32.1 (△12%)	29.0 (△20%)
Electric power generation (kWh/t※2)	237	263 (+11%)	300 (+27%)
Polymer usage (g/t※2)	248	189 (△24%)	166 (△32%)
Moisture content of dewatered cake (%)	72	69 (△3points)	68 (△4points)

※1　In digester No.1, ※2　As weight of food waste

Table 9 Economic benefits estimated based on results of demonstration test

(unit; million JPY per a year)

	Economic benefits
Increase in electric power generation	+ 24.9
Reduction of sludge disposal cost	+ 5.1
Reduction of polymer usage cost	+ 0.3
Reduction of power consumption by existing plant equipment	+ 1.4
Chemicals cost for membrane cleaning	▲ 1.5
Power cost consumed by demonstration plant	▲ 0.2
Membrane replacement cost	▲ 1.8
Maintenance cost of demonstration plant	▲ 2.6
Total	25.6

tation sludge caused by the improvement of the organic decomposition rate[4].

(4) Trial calculation of economic benefit

Based on the test results obtained during the period from April 2020 to May 2020(i.e., the operation at a digestion sludge concentration of 4.0%), an estimation of the economic benefit of the Developed System against the baseline year of FY 2017(i.e., before the start of the demonstration test) was carried out. This trial calculation assumed that half of the food waste disposed of at the Nagaoka Facility was treated by the Developed System. **Table 9** shows the results of the trial calculation of the economic benefit in the demonstration test.

The economic benefit included i) Increase in the amount of electricity sales revenue, and ii) Reduction of sludge disposal cost due to the reduction of sludge production. On the other hand, the operating costs of the membrane treatment unit included the cost of chemicals for membrane cleaning, the cost of electric power consumed by the membrane unit, etc. Local unit prices in Nagaoka were used to calculate the revenue from the sales of electricity to grid and the unit cost of sludge disposal. Actual data obtained during the demonstration test was used to calculate the cost of membrane cleaning and power consumption. The membrane replacement cost and maintenance cost were calculated assuming a useful equipment life of 5 years and 10 years, respectively. The results of the trial calculation showed that an additional revenue of ¥25.6 million/year can be expected.

In this study, the economic estimation assumed that the Developed System would process half of the food waste as carried out in this pilot demonstration. Future studies will be carried out to determine the economical and operational benefits of the Developed System when treating 100% of the food waste disposed of at the Nagaoka Facility.

5. Conclusion

JFE Engineering Corporation has successfully developed a high-efficiency methane fermentation system incorporating a membrane bioreactor which improves the organic decomposition rate in methane fermentation of food waste. Following the verification of the concept design during a lab-scale test, a large-scale demonstration test was conducted at The Garbage Biogas Electric Generation Center in Nagaoka City. During the large-scale demonstration test, the following results were obtained when operating at a digestion sludge concentration of 4%.

(1) The CODcr decomposition rate (removal rate) improved to 98% compared with a rate of 83% for a conventional system. Moreover, methane production per ton of food waste increased by 22%, while sludge production decreased by 64%.

(2) The Nagaoka Facility saw an overall, methane gas production increased by 12%, sludge generation decreased by 30% and electric power generation increased by 27% compared to before the test. In addition, the moisture content of the dewatered cake also decreased by 4 points.

(3) As the result of a trial calculation, the introduction of the Developed System to treat 50% of the Nagaoka Facility's total food waste had an overall economic benefit of ¥25.6 million/year.

During future test, fermentation characteristics under even shorter hydraulic retention times using the Developed System will be evaluated with its results aiming at commercialization. Future tests will also study the maximization of the impact of the Developed System in the facility by conducting a demonstration test in which 100% of the food waste is treated by the Developed System.

Acknowledgment

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