Research on Advanced Energy-Saving Sewage Water Treatment Technology Using Anaerobic Ammonium Oxidation (AMOX) Bacteria

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Abstract

Reducing Greenhouse Gas (GHG) emissions for the realization of a low-carbon society is an urgent issue in the sewage industry sector. Sewage treatment plants are recognized as energy consumers. It has recently been suggested that sewage treatment plants can be turned into an energy producer by saving and creating energy. Such a next-generation type of sewage treatment technology is now attracting global attention.

It has been reported worldwide that energy self-sufficiency in a sewage treatment plant was achieved by an AB process and the use of recently discovered anaerobic ammonium oxidation (AMOX) bacteria.

With the intention of applying these technologies to sewage treatment plants in Japan, we conducted pilot demonstration tests and confirmed energy self-sufficiency.

1 Preface

The amount of electric power consumed in sewage treatment facilities occupies about 0.8% of total power consumption in Japan. Nowadays, it is a general understanding that sewage treatment facilities are high GHG-emitting infrastructures. With the increasing concerns about energy shortage and climate change, reducing power consumption and GHG emissions from sewage treatment plants is a critical issue.

Advanced efforts in saving and creating energy at sewage treatment plants have been made overseas. There is a case where the energy self-sufficiency rate of sewage treatment plants exceeds 100%(1), such as the Strass Wastewater Treatment Plant in Austria. The treatment method used at the Strass Wastewater Treatment Plant is a next-generation sewage treatment process which combines the AB process with anaerobic ammonium oxidation ("AMOX", commonly known as "anammox")(2) reaction. The AMOX reaction was discovered in 1995. The AB process is a treatment method in which organics contained in sewage are efficiently recovered as primary sludge in the A-stage and nutrient removal is subsequently carried out in the B-stage. The removed primary sludge is put into an anaerobic digestion tank. The produced digestion gas containing methane is converted into energy by a digestion gas power generator. After organic substances are decomposed in the digestion tank, residual high-concentration nitrogen is efficiently processed by AMOX. In addition, the nitrogen treatment by AMOX is performed in the B-Stage. In this method, energy saving and cost reduction will be achieved by reducing the amount of oxygen supplied during nitrogen treatment throughout the sewage treatment plant. With this concept, this treatment method can maximize the potential of sewage as biomass energy.

Based on our experience in research and development of methane fermentation and water treatment since the 1980s, we have been searching for further energy-saving technology in sewage treatment as a supplier of heavy electrical machinery. As part of this effort, we developed a nitrogen treatment technology using AMOX, and have conducted demonstration tests for the treatment of dewatering centrate containing high concentrations of nitrogen at a sewage treatment plant. We conducted pilot demonstration tests of the AMOX process called DEMON in Japan and overseas[3], of which we have several installations of full-scale DEMON plant overseas.

Based on these experiences, a pilot demonstration test of an energy-saving advanced sewage treatment technology was conducted for the first time in Japan by combining the AB process and AMOX. This aim was to make the sewage treatment plant energy self-sufficient. It was conducted as joint research at the sewage treatment plant of Kobe City Government. It was additionally adopted by Ministry of Land, Infrastructure, Transport and Tourism (MLIT) as a Sewerage Innovative Technology Demonstration Project (B-DASH Project) during the same research period. This research was also conducted as a Feasibility Study (FS) research under contract research for National Institute for Land and Infrastructure Management (NILIM), MLIT. This paper introduces the test results of the pilot demonstration test.

2 Features of Advanced Sewerage Treatment Technology for Energy-Saving

2.1 Deammonification Process

2.1.1 Outline of AMOX

The AMOX reaction[2] is a denitrification reaction that oxidizes ammonium into dinitrogen gas using a nitrite as the electron acceptor under anoxic conditions indicated by the following stoichiometric equation (1). This reaction is performed by AMOX bacteria, an anaerobic autotrophic bacteria, characterized by preference for a high-temperature and high-concentration nitrogen environment.

$$1.0NH_4^+ + 1.32NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow 1.02N_2 + 0.26NO_3^- + 0.066CH_2O_{0.5}N_{0.15} + 2.03H_2O \quad \cdots\cdots (1)$$

A combination of the nitritation process and AMOX process is called the deammonification process. Comparison between the deammonification process and conventional nitrification and denitrification process is shown in Fig. 1. Compared with conventional nitrification and denitrification process, the deammonification process has been featured for (1) the amount of air that can be reduced, (2) no organic substances are needed during denitrification, and (3) waste activated sludge production is minimal. This process is, therefore, expected to be a low-cost nitrogen removal process. Types of wastewater suitable for application to this process are digestion sludge dewatering centrate, livestock wastewater, landfill leachate, and wastewater containing a high-concentration of ammonium nitrogen. An introduction of this process has already begun in Japan for a side-stream treatment of public sewerage systems.

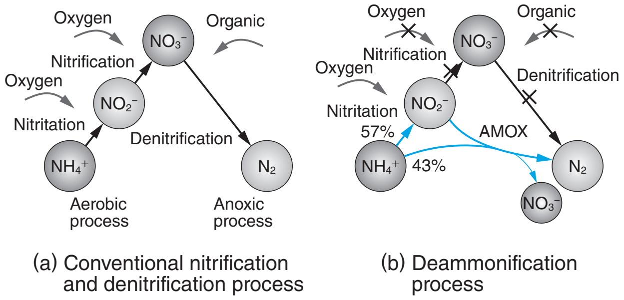

Fig. 1 Comparison between Nitrification and Denitrification Process and Deammonification Process

The metabolic pathway is shown for (a) conventional nitrification and denitrification process and (b) deammonification process.

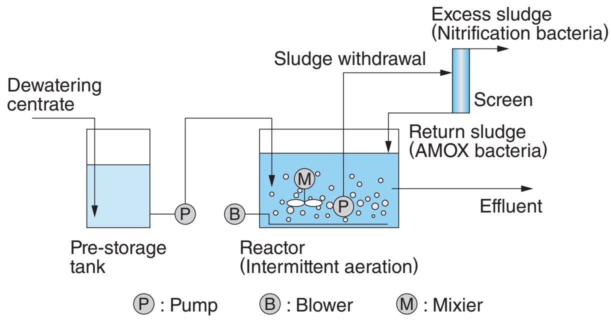

Fig. 2 Flowchart of DEMON Process

A flowchart of the DEMON process is shown. For the DEMON, both nitritation and AMOX are simultaneously performed in a single stage. Aeration is performed in the intermittent mode.

2.1.2 DEMON[4]

The most popular process of deammonification globally is the single-stage deammonification process known as the DEMON. Fig. 2 shows a flowchart of the DEMON process. The DEMON system was developed by NEWport GmbH, in Austria. This system is realized by utilizing suspended sludge in a completely mixed state in a single stage.

The DEMON was initially proposed in a style of a sequencing batch mode. It is now improved into a continuous mode, a more efficient processing system. The sequencing batch mode is composed of the intermittent aeration phase, sedimentation phase and discharge phase. Influent is intermittently introduced into the reactor in the intermittent aeration phase, followed by sludge settling and separation in the sedimentation phase, and finally the supernatant is discharged during the discharge phase. The aeration is intermittently supplied to the reactor under pH control and nitritation and AMOX are simultaneously performed at a single stage. The sludge consists of nitrifying bacteria in flocculated sludge and AMOX bacteria in red granular sludge. Sludge is separated by a screen based on the particle diameter so that the AMOX bacteria with slow growth rate can remain in the tank.

Compared with the two-stage deammonification process, the features of the DEMON system are summed up below. The number of equipment and control parameters can be reduced. Sludge control is easily carried out. In the continuous mode, influent is continuously introduced into the reactor. Sludge is continuously separated, and the supernatant is discharged in the solid-liquid separation zone. Since there is no sedimentation phase, there is an advantage of increasing the nitrogen load and reducing equipment.

2.2 AB Process

The AB process[5] was proposed in the 1970s and this sewerage system was utilized in the 1980s, mainly in sewage water treatment facilities in Europe. This process is composed of an A-stage where organic substances are recovered at a high loading rate and the B-stage where residual organic substances and nutrients such as nitrogen and phosphorus are removed. Since this process can realize high loading rate, the reactor volume can be compact. This is an advantageous process when the site area is limited. **Fig. 3** shows a flowchart of this process.

2.2.1 A-stage

The A-stage is installed after the grit chamber. It consists of a high-load aeration tank and intermediate sedimentation tank. The sewage is aerated before settling, which is very different from the conventional primary sedimentation tank. **Fig. 4** shows a series of processes from adhesion to absorption of organic substances caused by bacteria and successive hydrolysis and cell division. At the A-stage, the reaction is suspended at the biosorption stage. Primary sludge is extracted subsequently, while suppressing excessive decomposition of organic substances. The method of biosorption control comes in the following two approaches: (1) Hydraulic Retention Time (HRT) in the high-load aeration tank is set at about 30 minutes for the contact and absorption reaction of organic substances to bacteria. (2) Sludge Retention Time (SRT) is set at about half a day to suppress decomposition of organic substances. In the biosorption process as shown in **Fig. 4**, not only particulate, but colloidal and soluble substances can also be absorbed by bacteria. Previous research[6] reported that the average partition of the organic matter of the wastewaters between particulate, colloidal and soluble fractions was 45%, 31 and 24%, respectively. The proportion of organic composition other than particulate is not very low and this can be recovered as a primary sludge by biosorption. This is the outstanding feature of the A-stage.

2.2.2 B-stage

The B-stage is intended for the activated sludge treatment. It is installed to remove low-load residual organic substances as well as nitrogen and phosphorus as the latter part of the A-stage. It is composed of an aeration tank and a final sedimentation tank. Since a large amount of organic substances are removed at the A-stage, organic substances for denitrification become insufficient and the nitrogen removal rate is restricted at the B-stage. The generated waste activated sludge consists of

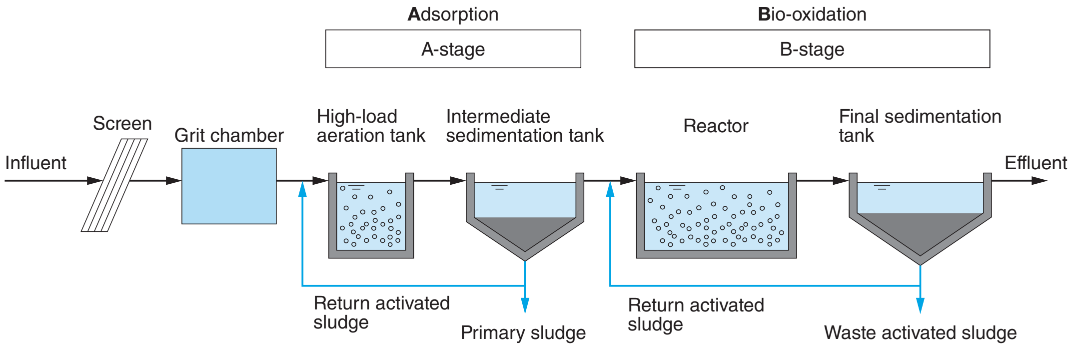

Fig. 3 Flowchart of AB Process

A flowchart of the AB process is shown. There are two steps in this process. The former is called A-stage and the latter is called B-stage.

activated sludge microbes and decomposition is more difficult compared with primary sludge.

Because of such difficulty and features, the B-stage in combination with AMOX was invented at the Strass Wastewater Treatment Plant. Due to the introduction of AMOX, nitrogen removal without organic substances can be partly realized. Since the growth rate of AMOX bacteria is extremely slow, it is additionally possible to suppress the generation of waste activated sludge. At the B-stage, however, the water temperature and nitrogen concentration are low so that it is difficult to sustain AMOX bacteria with high activity. For this reason, it is almost impossible for AMOX bacteria to proliferate at the B-stage and is, therefore, necessary to supply AMOX bacteria continually. Hence, this problem can be solved as the deammonification process is introduced for side-stream treatment.

2.3 Combination Effect

Fig. 5 shows a conceptual diagram for a combination of the AB process and DEMON. The ener-

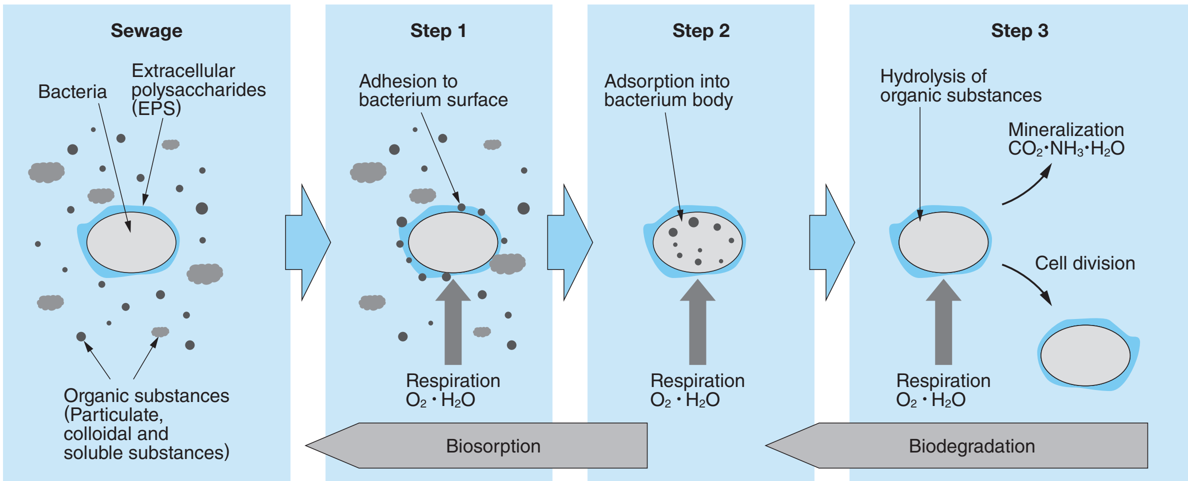

Fig. 4 Organic Metabolism by Bacteria

Schematic diagram is shown regarding adsorption and metabolism of organic substances (particulate, colloidal, and soluble substances) by bacteria. The EPS plays an important role. In the A-stage, the organic metabolism is stopped at the biosorption stage.

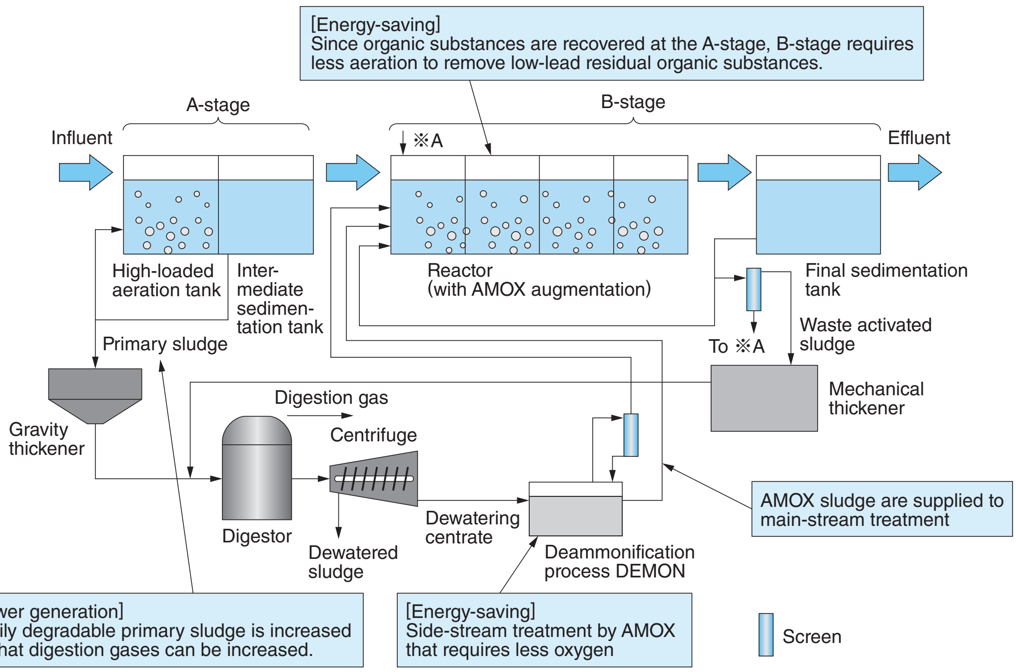

Fig. 5 Conceptual Diagram for Combination of AB Process and DEMON

When the AB process and DEMON are combined, both energy-saving and energy production can be realized at the same time.

gy self-sufficient sewerage treatment system is intended to cover all electric power consumption at the wastewater treatment by utilizing these systems. For this purpose, electric power consumption needed for the B-stage is reduced by using the AMOX reaction, and organic substances are maximally recovered at the A-stage as the primary sludge to be transferred to the digester so that the generation of digestion gas increases. The increased digestion gas can be used for electric power generation. Even though nitrogen concentration should be increased in dewatering centrate, nitrogen treatment is possible using the DEMON without any negative effect.

Since the amount of produced gas is increased, electric power generation is coincidentally increased, and the power self-sufficiency rate is raised at the sewage treatment plant. If surplus power is generated, it can be sold to the power utility company. The sewage treatment plant can be a power plant for regional power distribution.

Table 1 Target Values for Each Elemental Technology of Pilot Experiment

Target values for the A-stage, B-stage, DEMON and combination techniques are shown.

Technology	Evaluation item	Target values
A-stage	Organic removal rate	Sludge COD_{Cr} conversion rate: ≧50% (T-COD_{Cr} removal rate: ≧60%, S-COD_{Cr} removal rate: ≧25%)
B-stage	Effluent quality	Advanced water quality shown below shall be met. BOD: ≦10 mg/L Total nitrogen: ≦10 mg/L Total phosphorus: ≦0.5～1.0 mg/L
DEMON	Nitrogen removal rate	Nitrogen removal rate: ≧80%
Combination techniques	Energy creation	Digestion gas generation: 15% increase

Note. COD_{Cr}: Chemical oxygen demand by potassium dichromate,
T-COD_{Cr}: Total COD_{Cr}, S-COD_{Cr}: Soluble COD_{Cr},
BOD: Biochemical oxygen demand

3 Demonstration Test of Energy Self-sufficient Sewage Treatment in Japan

3.1 Purpose and Target

To investigate the possibility of energy self-sufficiency at a sewage treatment plant combining the AB Process and DEMON, we implemented a pilot experiment at the Tarumi Sewage Treatment Plant in Nishi Water Environmental Center of the Kobe City Government. **Table 1** shows the target values for each elemental technology of the pilot experiment.

3.2 Methods

Fig. 6 shows the processing flow of the pilot plant. The raw sewage flow rate was 24 m^3/day, simulating the diurnal fluctuation. **Table 2** shows the water quality results of the raw sewage and the B-stage effluent during the test period.

The A-stage consisted of a high-load aeration tank with an effective volume of 0.5 m^3 and an intermediate sedimentation tank with an effective volume of 1.5 m^3. By adjusting the HRT of the aeration tank to 30 minutes and the SRT to 0.5 days, the primary sludge was extracted at the biosorption stage before biodegradation started. For the aeration control to the high-load aeration tank, either constant dissolved oxygen control or constant air volume control was used. In addition, we conducted a test in which excess sludge from the B-stage was introduced to the A-stage in order to further improve the biosorption capacity.

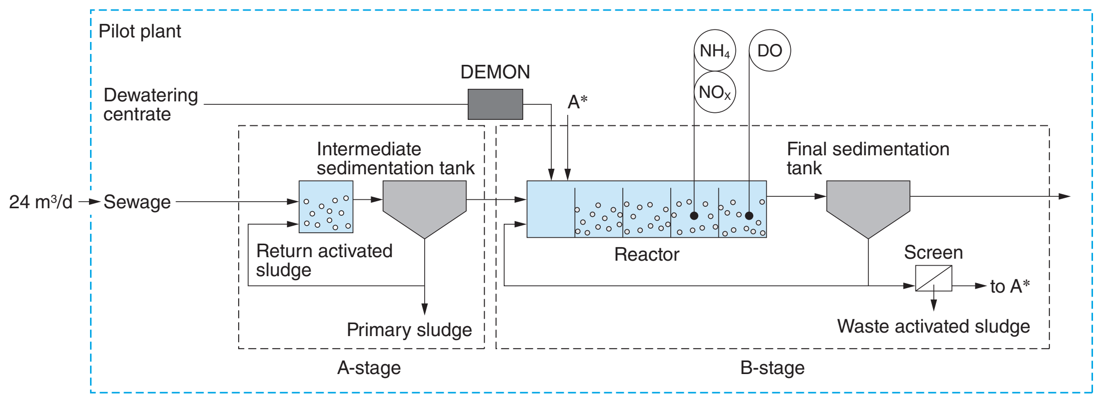

Fig. 6 Processing Flow of Pilot Plant

A flowchart of the pilot plant process is shown. The pilot plant is composed of the A-stage, B-stage, and DEMON. The NH_4 and NO_X sensors of the B-stage are installed in the later part of the reactor.

Table 2 Water Quality Results of Raw Sewage and B-stage Effluent

This table shows the average water quality of raw sewage and B-stage effluent, target water quality of advanced treatment, and final effluent after chlorine dosing at the Tarumi Sewage Treatment Plant.

Water quality item	Raw sewage	B-stage effluent	Target water quality of advanced treatment	Final effluent from the Tarumi Sewage Treatment Plant
T-COD_{Cr} (mg/L)	330	14	—	—
BOD (mg/L)	150	7	≦10	7.5
C-BOD (mg/L)	130	2	—	2.2
COD_{Mn} (mg/L)	67	7	—	8.4
SS (mg/L)	180	3	—	2
Total nitrogen (mg/L)	31	9.2	≦10	14
Total phosphorus (mg/L)	3.4	0.7	≦0.5~1.0	1.6

Note. C-BOD: nitrification inhibited BOD, COD_{Mn}: Chemical oxygen demand by potassium permanganate, SS: Suspended solids

The B-stage consists of a reactor with an effective volume of 1.25 m^3 × 5 tanks and a final sedimentation tank with an effective volume of 1.5 m^3 × 2 tanks. The first tank of the reaction tank was an anoxic tank, and the last four tanks were intermittent aeration tanks.

The ratio of the anoxic/aerobic time was controlled by a method called Ammonium vs NO_X (AvN) control(7). To maintain sufficient activity of the AMOX bacteria, residual ammonium nitrogen and an anoxic environment are required. AvN control uses an ammonium (NH_4) sensor and an NO_X sensor to adjust the aeration time to keep the NH_4/NO_X ratio constant. The ammonium nitrogen tends to remain even at the end of the reaction tank, and an anoxic environment is likely to be conserved.

The amount of sludge supplied from the DEMON was set at 10 g-SS/day in accordance with the ratio of the amount of the DEMON sludge generated from the average side-stream nitrogen load of sewage treatment plants in Japan. Sludge separation was conducted by a screen to control the difference in growth rate between the AMOX bacteria and other bacteria. The mesh width of the screen was 0.2 mm, and the leakage of the AMOX granules with a particle size of about 0.3 to 0.8 mm was stopped and returned to the reactor. At the end of the reactor, poly-aluminum chloride as a coagulant, was added to remove phosphorus.

In addition to the sequencing batch mode that has been demonstrated so far, the DEMON has also been conducted under continuous mode. A reactor with an effective volume of 0.5 m^3 was used in the batch mode. For the continuous mode, the DEMON consists of a 0.5 m^3 reaction tank and a 0.014 m^3 separation tank that separates the solid-liquid installed outside the reaction tank (external separator type). On the other hand, internal baffle type in which the solid-liquid is separated in a 0.022 m^3 separation zone installed inside a 0.75 m^3 reaction tank is also investigated. For sludge separation, a screen with a mesh width of 0.2 mm was used as in the case of the B-stage.

The amount of digestion gas was evaluated by a batch digestion test using a vial simulating a digestion tank. The digested sludge in the test was originated from the digestion tank operated at the Tarumi Sewage Treatment Plant. The primary sludge and excess sludge collected from the AB process were used as a test sample and those collected from the Honjo train of the Tarumi Sewage Treatment Plant were used as a control sample.

3.3 Results and Discussion

At the A-stage, the T-COD_{Cr} removal rate was about 60%, the S-COD_{Cr} removal rate was about 25%, and the sludge COD_{Cr} conversion rate was 55%. In the operation of the primary sedimentation tank mode with the same equipment, the T-COD_{Cr} removal rate was about 54%. The S-COD_{Cr} removal rate, however, was 10% or less, confirming the effectiveness of the A-stage in removing a large amount of soluble organic matter. The SS and total nitrogen concentrations of the sewage inflow to the Tarumi Sewage Treatment Plant were close to the average values of Japanese sewage treatment plants. The organic matter fraction of particulate, colloidal, and soluble was 61%, 19% and 20%, respectively. Since the sewage of this treatment plant contained a large amount of particulate proportion, it was easy to obtain a high removal rate in the conventional primary sedimentation tank. It was, therefore, difficult to observe the effect of improving the removal rate by removing colloidal and soluble proportion obtained by introducing the A-stage. It is considered that a higher adsorption effect can be obtained in sewage with a large amount of colloidal components.

It was confirmed that the quality of the B-stage effluent achieved the target effluent quality required for advanced treatment and was equivalent to the final effluent quality of the Tarumi Sewage Treatment Plant.

Based on the gene analysis results by the next-generation sequencer and activity test, it was confirmed that a certain amount of AMOX bacteria existed in the B-stage due to the continuous supply of the DEMON sludge. Experimental results using stable isotope-labeled nitrogen (^{15}N) indicated that the AMOX reaction mainly contributed to nitrogen removal in the anoxic tank of the B-stage.

In AvN control, an NH_4 sensor and a NO_X sensor were installed in the third tank of the intermittent aeration tank. Even if the influent load fluctuates, the anoxic phase and aerobic phase was automatically adjusted appropriately by indicated NH_4/NO_X ratio.

Due to the contribution of these AMOX reactions and the aeration control by AvN control, the amount of air in the entire pilot, including the A-stage and DEMON, was reduced by approximately 12.5% compared to the Tarumi Sewage Treatment Plant. It was, therefore, confirmed that the use of AMOX in the B-stage can achieve energy saving while preventing deterioration of water quality.

As for the DEMON, we were able to achieve target nitrogen removal rate of 80% or more. Nitrogen volumetric load results are stable at 0.8 kg-N/m^3/day for the sequencing batch mode, at 1.4 kg-N/m^3/day for the continuous mode with external separator type, and at 1.8 kg-N/m^3/day for the continuous mode with internal baffle type. By improving the DEMON from a sequencing batch mode to a continuous mode, the sedimentation and discharge phase can be reduced and the nitrogen load increased. By adopting a continuous mode, the volume of the pre-storage tank can be reduced. Moreover, the effluent tank which is installed in the sequencing batch mode to receive effluent for a short time is unnecessary. Consequently, the number of devices and footprint can be further reduced.

Based on the results of bacterial gene analysis and the investigation of sludge activity, it was confirmed that the AMOX and nitrifying bacteria was efficiently separated by the screen. Screen clogging can be easily prevented by spraying effluent.

By confirming the sludge balance, the amount of sludge generated by the AB process increased by 10% in the primary sludge and decreased by 15% in the excess sludge. In the digestion test, the amount of digestion gas generated per unit sludge increased by 18% with the primary sludge, and remained almost unchanged with the excess sludge. From these results, it can be said that the easily degradable primary sludge was increased, the excess sludge that was difficult to be decomposed was reduced, and the primary sludge became easy to generate digestion gas. Considering the whole of the AB process, digestion gas production resulted in a 24% increase. In addition, due to supplying excess sludge to the A-stage, the adsorption capacity in the A-stage was further improved, resulting in a 31% increase in the amount of digestion gas generated compared to those produced at the Tarumi Sewage Treatment Plant.

Using the above energy-saving and energy-creating effects, the energy recovery rate was calculated for the case where both the AB process and DEMON were introduced to the Tarumi Sewage Treatment Plant. The energy recovery rate was defined as the ratio of the amount of power generated by the contribution from the target train to the amount of power consumed by pump and blower in the same train. As a result, the energy recovery rate was 75% before the introduction, but it was estimated to improve to 111% after the introduction.

4 Postscript

Toward a goal of energy self-sufficient sewage treatment plant, we conducted a series of pilot-test. We confirmed that energy potential from sewage was highly recovered by the A-stage and energy consumption was reduced by the B-stage and DEMON by using AMOX bacteria. The proposed water treatment system verified that both energy saving and energy production can be realized at the same time.

Lastly, we would like to express our deepest gratitude to Kobe City Public Construction Project Bureau for allowing us to use the demonstration facility to perform an advanced technical development and for your overall cooperation and kind advice.

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