Comprehensive Evaluation of a Sewage Treatment Plant as a Base for Recirculation of Materials and Energy in the Region

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Abstract. Based on the concept that a sewage treatment plant should serve as a base for the circulation of materials and energy in a region, a combined electric power generation system using both digestion gas and sludge incineration for power generation was studied in the use of organics in influent. To function as a base for the circulation of materials, the plant was assumed to employ phosphorus recovery, which was estimated individually for an ash alkali process and a MAP process. Using a model treatment plant with a capacity of 48,000 m^3/day, it was found that introducing high-efficiency solid-liquid separation to recover solid organics proved effective in increasing the electric-power self-supply ratio attained in normal power generation. With digestion gas this ratio was raised from 6.2% to 13.0%, and with combined power generation, the ratio was raised three times higher to 18.6%. Phosphorus recovery was increased by 10% to 30% over the conventional process in an ash alkali process by introducing an AO process using the transfer of phosphorus to sludge as part of the wastewater treatment process. When various measures are evaluated in terms of water eco-efficiency from a viewpoint of environmental performance in the sewage treatment plants, power generation using sludge incineration was 1.96 kg/kWh, compared to the benchmark, which was 1.62 kg/kWh of power generation with digestion gas, and phosphorus recovery was 2.08 kg/kWh. The target for water eco-efficiency may be set to 3 kg/kW/h when various measures are combined.

Keywords: Power self-supply ratio · Phosphorus recovery · Water eco-efficiency

1 Introduction

In Japan, the government issued a new Sewerage Vision in July 2014. It highlights "the use of sewage treatment plants as bases for integration, self-sustainability, and the supply of water, resources, and energy" as a way toward the "Full Development of Sewerage Systems, as a Path for Recycling." Similar activities can be observed elsewhere in the world. China has announced a new concept for sewage treatment plants focusing on energy self-supply and expanding reclaimed water utilization by recovering nutrients and organics in influent. (Chen 2014) Reports have been published in Europe about efforts being made in development methods for recovering organics,

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energy, and nutrients from wastewater (viewed as “used water”) through thickening. (Veratrate et al. 2009) In some cases almost complete energy self-supply has been achieved.

Toward establishing sewage treatment plants as bases for the recirculation of materials and energy in the region, gas power generation using digestion gas, power generation through sludge incineration are being studied as measures to utilize organics in influent.

2 Materials and Methods

Along with a study of water quality and power consumption, a study was conducted of measures adopted to achieve enhanced energy and material recovery. A sewage treatment plant simulator, the Performance Evaluation System (PES), was used to grasp the actions of the sewage treatment plant systems for the model plant shown in Table 1.

Table 1. Conditions at the model plant

Operating condition	Capacity	48,000 m^3/day
	Treatment method	Conventional activated sludge process
	Water temperature	20 °C
	Return sludge ratio	20% constant
	Primary sludge	2% of treated water drawn
	Excess sludge	MLSS drawn at a given rate of 1500 mg/L
Detention time	Primary settling tank	1.5 h
	Reactor	8.0 h
	Secondary settling tank	2.0 h
Influent quality	COD	360 mg/L (soluble: 35%)
	SS	160 mg/L (VSS: 60%)
	T-N	35 mg/L (NH_4-N: 20 mg/L)
	T-P	4.0 mg/L (PO_4-P: 2.0 mg/L)
Sludge treatment	Thickening	Separation thickening (Gravity; GT & centrifugal; CT)
	Digestion	Anaerobic digestion (Gravity thickened sludge only)
	Dehydrator	Centrifugal dewatering equipment
	Incinerator	Fluidized bed incinerator

The energy potential (EP) of the organics in the influent sewage was converted to energy (electric power) based on 3.49 Wh/kg COD (Cornel et al. 2012). Variations in the energy potential and power consumption (negative expressions) in each treatment process are shown in Fig. 1 (Fukushima 2015). Most of the power was consumed in the aeration tank and incinerator where the EP of the organics in the sewage was lost to a

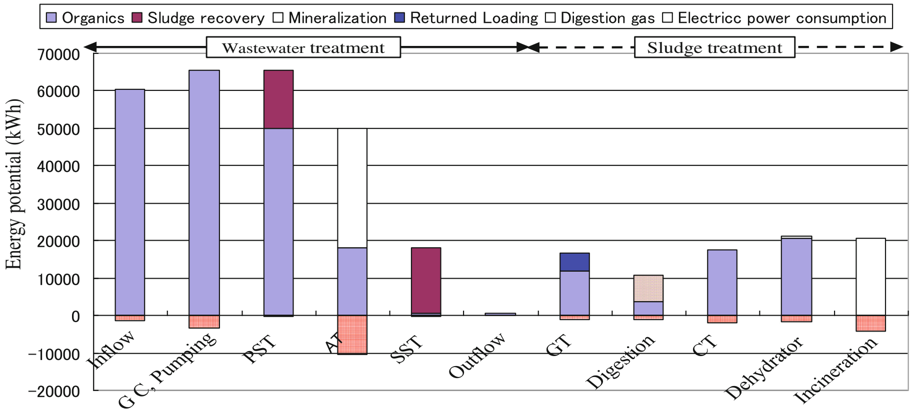

Fig. 1. Energy flows at the model plant

substantial degree. For sewage treatments plant to function as facilities for energy circulation in a watershed, it is essential that electrical energy self-supply be established through maximum utilization of the EP in sewage organics.

3 Results and Discussion

Including the B-DASH project of the Sewerage and Wastewater Management Department of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), many attempts are being made to improve energy saving and energy creation in sewage treatment plants. (B-DASH project HP). This paper deals with digestion gas power generation and power generation with sludge incineration. These systems are increasingly being introduced in sewage treatment plants and their performance is being verified. An evaluation of the energy recovery technology used in these systems in terms of energy self-supply rates will be presented, along with a comparison of the two systems with cases in which intensive solid-liquid separation with improved solid recovery (solid recovery rate raised to 66%) in primary settling is introduced.

The two energy recovery technologies shown below were studied.

(1) Digestion gas power generation (Miyata et al. 2015)
Anaerobic digestion is done only for primary sludge (gravity thickened sludge), with the generated digestion gas used for power generation with a highly efficient fuel cell.
(2) Power generation with sludge incineration (Moriya et al. 2015)
The “high-efficiency waste-heat generation” (with a power generation capacity of 250 kWh/h at 100 t/day) that proved highly effective for dewatered sludge in the 25B-DASH project was selected because it is easy to introduce into existing facilities.

The power self-supply rates attained respectively by power generation with digestion gas, power generation with sludge incineration, and their combination are shown together with the power consumption rates and treated water quality levels in Table 2. The benchmarks, or basic pattern, (for primary settling) are a solid recovery rate of 34%, power generation of 1,580 kWh/day, and a power self-supply rate of 6.2% (with a power consumption rate of 0.53 kWh/m^3). This power consumption rate is the value that is standard in the world (Olsson 2012).

Aggressive recovery of solids, which is the essential point of this study, proved to be highly effective. Introducing high-efficiency solid-liquid separation resulted approximately in a two-fold increase in power generation, which rose to 3,100 kWh/day, and a power self-supply rate of 13.0%. Intensification of the solid recovery function in the primary treatment process as an alternative to primary settling resulted in a decreased amount of air due to the decrease in the organic inflow load into the aeration tank, which led to a decrease in power consumption. (The power consumption rate was 0.50 kWh/m^3).

In cases in which only power generation with sludge incineration was introduced (without anaerobic digestion), power generation was 1,780 kWh/day, which was equivalent to cases in which primary sludge digestion gas generation was introduced. Introducing intensive solid-liquid separation proved not to be effective, with power generation remaining at 1,780 kWh/day.

Combined power generation was greatest, power generation and the self-supply rate increased to 3,170 kWh/day and 12.3%, respectively. The further introduction of high-efficiency solid-liquid separation resulted in power generation and the self-supply rate, to 4,460 kWh/day and 18.6%, respectively.

Two processes were employed in trial calculations of phosphorus recovery. Records of the application of these processes were taken into account, and these processes were set as indicated below on the basis of numerical values in the Guidebook on the subject. (Japan MILT 2010)

(1) MAP process: This process was employed for dewatered filtrate, including digested sludge supernatant, with phosphorus recovery efficiency targeted at 85%.
(2) Ash alkaline process: This process was employed for incineration ash, with phosphorus recovery efficiency targeted at 50%.

The results of the calculation of phosphorus recovery are shown in Fig. 2. The amount recovered was high when only sewage sludge was treated and the ash alkali process was applied to the incineration ash. Specifically, the anaerobic-oxic(AO) process that transforms phosphorus positively into sludge (excess sludge) in the water treatment process can lead to recovery of 65 kg of phosphorus, which is equivalent to 30% or more of the phosphorus in influent sewage.

Evidently, sewage treatment plants have a great deal of potential as facilities for circulating materials and energy in a given region. Water eco-efficiency is proposed here as an index for comprehensive evaluation of phosphorus recovery and energy recovery. Water eco-efficiency is determined using the following Eq. (1):

$$\begin{aligned}\text{Water eco} - \text{efficiency (kg/kWh)} = {} & (\text{Water environmental load removed} \\ & + \text{Resources recovered})/\text{Power consumption}\end{aligned} \tag{1}$$

Table 2. Summary of measures used to improve power self-supply rate

Features	Power generation with digestion gas		Power generation with sludge incineration		Power generation with digestion gas & power generation with sludge incineration	
	Primary settling	High-efficiency solid-liquid separation	Primary settling	High-efficiency solid-liquid separation	Primary settling	High-efficiency solid-liquid separation
	Recovery in primary settling: 34%	Recovery ratio improved to 66%	Incineration of dewatered sludge		Sludge from primary settling to be used for digestion gas power generation Dewatered sludge to be incinerated for power generation	
Electric consumption rate	0.53	0.50	0.51	0.47	0.54	0.50
Electric consumption	25390	23910	24510	22670	25680	23980
Power generation (kWh), digestion gas	1580	3100	–	–	1600	3120
Power generation (kWh), sludge incineration	–	–	1780	1780	1570	1340
Total power generation	**1580**	**3100**	**1780**	**1780**	**3170**	**4460**
Power self-supply ratio	6.2%	13.0%	7.3%	7.9%	12.3%	18.6%
MLSS	1490	1510	1490	1510	1490	1510
Treated water quality COD (mg/L)	3.9	3.5	4.0	3.5	4.0	3.5
SS (mg/L)	15.7	15.4	15.7	15.4	15.7	15.4
T-N (mg/L)	22.6	24.7	20.8	21.4	22.5	24.6
T-P (mg/L)	2.2	2.6	1.8	1.9	2.2	2.6
Source	–	23B-DASH	25B-DASH		23 & 25B-DASH	

* Excess sludge withdrawal adjusted so that MLSS becomes 1500 mg/L.

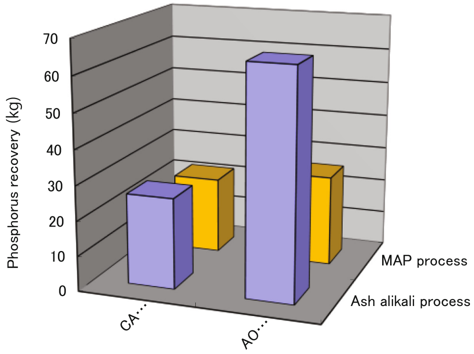

Fig. 2. Phosphorus recovery results

To calculate the water environmental load, T-N and T-P are integrated into COD by using a conversion factor. The conversion factor is: T- N: 19.7; T-P: 142.5. (Ishida et al. 2005)

Figure 3 illustrates the variation in water eco-efficiency in terms of power consumption and water environmental load removed. When compared with the benchmark (x), energy recovery measures (◆) show increased water eco-efficiency and a decrease in power consumption due to power generation. Introducing high-efficiency solid-liquid separation results in increased power generation, and a slight decrease in water environmental load removal due to the influence of the rejected water.

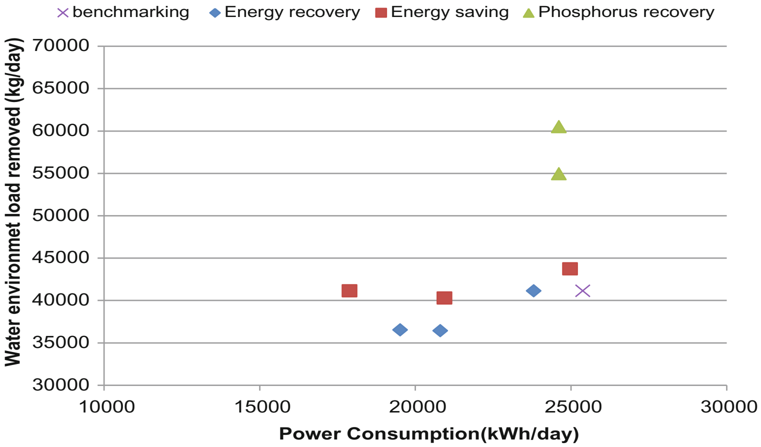

Fig. 3. Power consumption and water environmental load removed

Although power consumption did not change with the phosphorus recovery measure (▲), water eco-efficiency improved due to an increase in the water environmental load removed in line with the phosphorus recovery.

Also energy saving measures decrease power consumption, leading to increased water eco-efficiency. Therefore, the three measures (■) that facilitate introduction were examined. They are (1) pseudo recycled nitrification/denitrification pattern, (2) nitrification suppression operation, and (3) non-aeration recirculation sewage treatment with highly effective energy conservation.

When the reactor is operated in the pseudo recycled nitrification/denitrification pattern by partially reducing aeration (1/4) of its front half, organics in the influent are used partially as a carbon source for denitrification of NO_3-N in the return sludge. This in turn enables energy saving while leading to improved treated water quality. With the power consumption decreasing to 24,970 kWh and the water environmental load removal increasing to 43,728 kg, the water eco-efficiency was 1.75 kg/kWh. The process employed this time was the conventional one with complete nitrification. This meant its operation, while suppressing nitrification, could reduce aeration for nitrification. Power consumption could be reduced to 20,940 kWh, and water eco-efficiency was 1.92 kg/kWh. In addition, the non-aeration recirculation sewage treatment process, which is currently being demonstrated in the 26B-DASH project, is expected to achieve a 70% reduction of power consumption in the sewage treatment process, 23 with water eco-efficiency estimated to be at 2.30 kg/kWh.

It should be noted that the anaerobic-anoxic-oxic process (A2O process), which is one of the advanced treatment processes, can achieve a substantial removal of water environmental load by removing nitrogen and phosphorus while offering high environmental performance, with an eco-efficiency rate of 2.70 kg/kWh.

In all cases, the challenge is to develop technology that will enable reaching a water eco-efficiency rate of about 3 kg/kWh for sewage treatment plants. Demonstrations of combinations are also considered necessary.

4 Conclusions

(1) The power self-supply rate approximately doubled to 13.0% when high-efficiency solid-liquid separation was introduced into a digestion gas electric power generation system used. With the addition of power generation from sludge incineration, the power self-supply rate approximately tripled to 18.6% when combined power generation expected to generate 4,460 kWh/day was adopted.

(2) When the material and energy recovery functions were evaluated using a "water eco-efficiency index". It increased to 1.75 kg/kWh when digestion-gas electric power generation incorporating high-efficiency solid-liquid separation was implemented. The phosphorus recovery process achieved higher water eco-efficiency than the energy recovery process.

(3) The eco-efficiency of functions was estimated for the water, material and energy circulation base through the combination of technologies. Remaining challenges include technology development aiming at an eco-efficiency rate of about 3 kg/kWh for sewage treatment plants. Demonstrations of combinations are also considered necessary.

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