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The Basic Study on the Energy Potential Flow Analysis of a Sewage Treatment Plant

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Abstract: To improve the independent generation of electric power by utilizing the organics in sewage influent an analysis was made of the behavior of organics within the plant, together with electric power consumption, in the form of energy flow. The energy potential was calculated from COD, and the behavior in each process was studied. About 10% of the energy potential could be recovered (4% in the form of electric power) through power generation with digestion gas, but most of the energy potential was lost in mineralization in the aeration tank and incinerator. Methods that could be used to raise electric power independence were evaluated in terms of "COD concentration necessary for independence." Estimated values compared to 5800 mg/L in the case of a normal primary settling tank were as follows: 2800 mg/L (51% down) when the high-efficiency solids-liquid separation was introduced; 1800 mg/l (69% down) when activated carbon from sludge was charged. It may be concluded that electric power independence is difficult to achieve with any single method, but it might be achieved when these methods are combined.

Key words: energy independence, energy potential, organic matter, sewage treatment plant

1. Introduction

In Japan, since the Great East Japan Earthquake, concern about possible insufficient supplies of electric power has led to studies on the feasibility of energy recovery and the promotion of further power saving in sewage treatment plants. The "B-DASH Project (Breakthrough by Dynamic Approach in Sewage High Technology Project) to establish sewage treatment plants capable of supplying their own power through the recovery of energy and resources by utilizing the characteristics of sewage)" started by MLIT in 2011 is now in the verification stage [1] (see Fig. 1).

A March, 2013 report produced by the Water Environment Management Study Group (Japanese MLIT) analyses present conditions and issues related to the water environment. The report stated that "Conventional sewerage service has lacked due attention to reducing energy consumption and thermal discharge in certain respects by giving top priority to conserving the quality of the water used by the public and to sludge treatment. In many cases, sewerage services managed by local authorities accounted for a high percentage of greenhouse gas emissions. The water, biomass, gathered by sewerage facilities in cities can be converted to resources and energy." Sewage treatment plants can also be expected to function as resources and energy supply bases in a watershed.

The energy content of municipal wastewater is two to four times greater than the energy required to treat it [2]. However current technologies and practices do not utilize this potential enough. As a result, the energy demand for sewage treatment remains significant all over the world. But recently some studies for innovative technologies in achieving energy neutral are accomplished by the anaerobic fluidized membrane bioreactor (AFMBR) [3] and energy optimization opportunities combinations [4].

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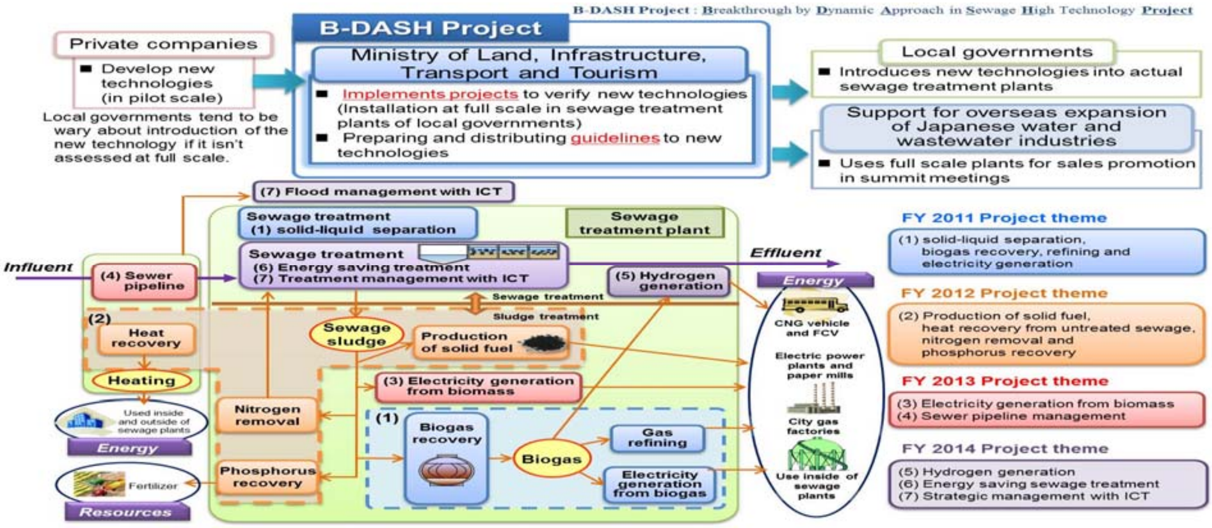

Fig. 1 List of B-DASH Project Technologies

Japan is reported to achieve the electric power energy self-supply ratio of around 50% but cases of exceeding 100% are reported in the world [5]. They point to the need for increased energy generation by raising organics recovery rates as well as the need to promote energy saving through control of the aeration ratio and efficient treatment of NH_4-N.

For the purpose of improving power self-supply ratio through utilization of organics in sewage influent in Japan, power consumption and the behavior of organics in treatment plants (recovery, mineralization) was analysed as energy flows. This was done to identify issues related to organics consumption and measures for improvement of the self-supply ratio.

2. Materials and Methods

To better understand the behavior of organics in Sewage treatment plants, the Performance Evaluation System (PES) was applied for a model plant as shown in Table 1, and an energy flow analysis was conducted on the basis of changes in water quality and electric power consumption in each process. PES is a system utilizing data on water flow and quality for an overall determination of the quality of treated water and power consumption in coordination with sewage and sludge treatment for an entire plant, including common facilities, water treatment facilities, sludge treatment facilities and sludge incineration facilities. PES handles COD, SS, T-N, and T-P as water quality. The system can be used to display the results individually in a flow chart [6-8]. The target was a medium-sized plant with a capacity of 48,000 m^3/day, which was operated on the basis of conventional active sludge process for water treatment. 2% of treated water of primary sludge was withdrawn while excess sludge was withdrawn in such a manner as to keep MLSS constant at 1500 mg/L (The return sludge ratio was fixed at 20%).

Table 1 Model Plant Specifications

Operation Condition	Capacity	48000 m^3/day
	Method	Conventional activated sludge process
	Water temperature	20 degree Celsius
	Return Sldge Rate	20% constant
	Raw Sludge	2% of inflow sew age quantity
	Excess Sludge	Pull it up to assume MLSS with 1500 mg/L
Retention time	Primary settling tank	1.5 hours
	Reaction tank	8.0 hours
	Secondary settling tank	3.0 hours
Water quality in inflow	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	Separated thickening (gravity & centrifugal)
	Digestion	Anaerobic digestion with middle temperature
	Dehydrator	Centrifugal dehydrator
	Incinerator	Fluidized incinerator

Sludge was treated through the steps of separated thickening, anaerobic digestion, dehydrator, and incineration. For each of these steps, the widely-employed processes in Japan of centrifugal thickening, mesophilic digestion, centrifugal dehydrator, and fluidized bed incineration were applied. For the quality of influent, the medians of nationwide distribution, “COD at 360 mg/L, SS at 160 mg/L,T-N at 35 mg/L, and T-P at 4.0 mg/L” were chosen from the Sewerage Statistical Data of 2006, and the breakdown used for internal calculation of PES (the ratios of soluble COD and VSS) employed conventional values. Note that the COD value was converted from the BOD value.

The energy potential of organics in sewage influent was evaluated while referring to the data gathered by the Water Environment Management Study Group. With a view toward introducing digestion gas power generation assumed, the thermal energy of methane (CH_4) was converted to energy (electric power) on the basis of the methane amount per 1 g of COD, and 3.49 kWh/kg COD [9] was used for calculation. For the sake of simplification, the same conversion coefficient was used for all, though the total amount of organics in the sewage influent was not always gasified and the decomposed gas was not limited to CH_4.

3. Results and Discussion

The treated water quality, the result of calculations with PES, is shown together with removal rate in Table 2. Power consumption is shown for each unit of equipment in Fig. 2. Since the conventional activated sludge process was employed, the treated water quality indicated a satisfactory removal efficiency of 90% or more for organics (COD and SS), but it proved to be unsatisfactory for T-N and T-P removal efficiency at 50% or less. However the water temperature was set at 20°C, allowing the nitrification reaction to proceed to reach a state of nearly complete nitrification. Most of the nitrogen in treated water was converted to NO_3-N.

Table 2 The Calculation Results of Water Quality

	Influent	Effluent	Removal rate
COD (mg/L)	360	3.9	98.9%
SS (mg/L)	160	15.7	90.2%
T-N (mg/L)	35	22.6	35.4%
T-P (mg/L)	4	2.2	45.0%

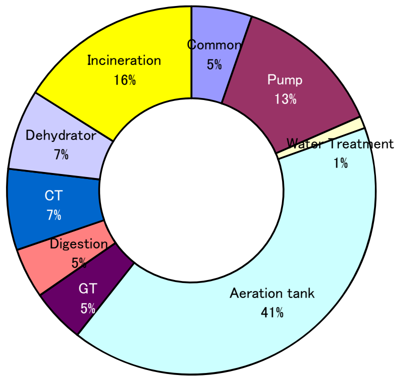

Fig. 2 The Breakdown of Electricity Consumption

Power consumption was 23,590 kWh/day (at a rate of 0.53 kWh/m^3) for the entire plant, which was approximately with the general report. Power consumption in the aeration tank (including the blower equipment) was the highest at 10,440 kWh/day (42%) (of which 10,010 kWh/day was for the blower equipment), accounting for about one half of the total, followed by the incinerator at 4,080 kWh/day (16%) and by the pump equipment at 3,330 kWh/day (13%). These three accounted for 70% or more of power consumption of the entire plant.

3.1 COD Flow Analysis

Changes in the COD load (t/day) were summarized for each treatment process, as shown in Fig. 3, to understand the behavior of the organics within the treatment plant. (The numerical value of COD in the flow chart represents the load at the process exit.)

The 17.3 t of organics flowing into the plant increased to 18.8 t, in the grit chamber, under a return water load from the sludge treatment system. In the wastewater treatment process, 4.5 t (about 30%) of the organics were removed (recovered) through withdrawal in the course of primary settlement tank (PST), while 14.3 t joined together with 2.2 t of return

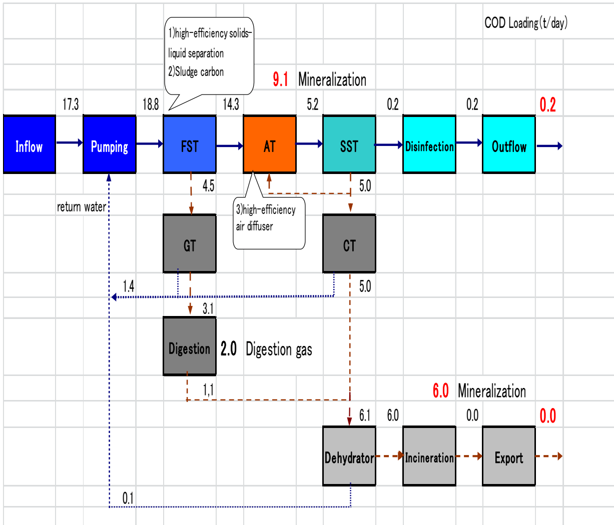

Fig. 3 The COD Flow

sludge and flowed into the aeration tank. (The COD of the activated sludge itself was not included.) In the aeration tank, which is the core of the biological treatment function of the conventional activated sludge process, most of the soluble organics were decomposed by aerobic microorganisms. Solid organics, which are slow to decompose, were partially decomposed. As a total, 9.1 t of organics were mineralized. (Although some of these organics can be utilized for denitrification of NO_3-N in the return sludge that is not taken into account this time.) During the secondary settlement tank, satisfactory solids were removed by liquid separation, and only 0.2 t was allowed to overflow to be disinfected and discharged. After settlement it became return sludge, and the residual 5.0 t was withdrawn as excess sludge.

In the sludge treatment process, 3.1 t of primary settled sludge that had been charged into the gravity thickening tank was then charged into the anaerobic digester as thickened sludge. However, because of a low solids recovery rate (70%), 1.4 t equivalent to 30% of it became a return load to wastewater treatment. The anaerobic digester enabled recovery of 2.0 t of the organics (approximately 10% of the inflow organics) as digestion gas through methane fermentation. The remaining 1.1 t was mixed with 5.0 t of centrifugally thickened sludge and dewatered. (The digestion supernatant was returned from the dewatering machine. The organic load did not increase much, but 10% of nitrogen and 20% of phosphorus relative to the inflow load became the return load.) 6.0 t of dewatered cake was charged into the incinerator and mineralized fully through incineration.

Of 17.3 t of COD in sewage influent, 9.1 t (53%) and 6.0 t (35%) were mineralized in the aeration tank and in the incinerator for consumption, respectively, as shown in Fig. 4. 2.0 t of COD was recovered as digestion gas.

3.2 Energy Flow Analysis

Changes in the energy potential in each treatment process are presented, together with the electric power consumption (shown as negative values), in Fig. 5 (Left: wastewater treatment, Right: sludge treatment).

The energy potential of the organics in the sewage influent was reduced by about 30% due to primary sludge withdrawal (recovery) and by 50% through mineralization in the aeration tank. Except for a small portion discharged as effluent, the remaining potential was mostly reduced by withdrawal of excess sludge at the final sedimentation tank. In the gravity thickening tank, about 30% of the potential became the return

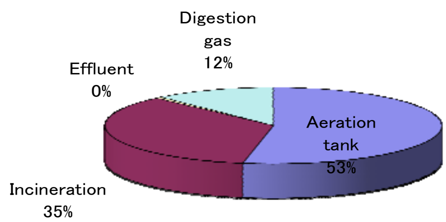

Fig. 4 The Breakdown of COD Consumption

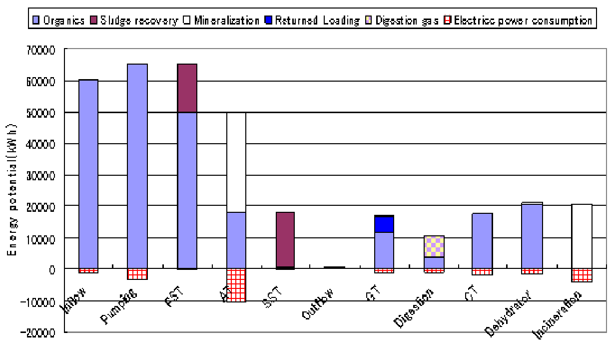

Fig. 5 Change in Sewage Treatment Plant Energy

load because of a low recovery ratio, while, in the digestion tank, 60% (about 10% of the potential of the sewage influent) was recovered in the form of digestion gas. Digested sludge was mixed with centrifugally thickened sludge and dewatered for final mineralization in the incinerator (about 35% of the energy potential in the sewage influent). The total electric power consumption of the sewage treatment plant is about 25,000 kWh/day (consumption rate: 0.53 kWh/m^3), and 90% of the energy potential (60,000 kWh/day) of organics in the sewage influent, other than the 10% recovered in the form of digestion gas, is lost. It was, therefore, estimated that energy equivalent to about 40% of the consumption came from the additional energy applied. In addition, a considerable amount of energy potential was consumed in the aeration tank and incinerator where the organics were heavily mineralized (wasted).

Even when the generating efficiency (40%) is considered, effective utilization of the total amount of energy potential in sewage influent should make it possible for the plant to achieve electric-power independence. Nevertheless, the self-supply ratio remains at about 4%.

3.3 Improvement of Self-Supply Ratio in Electric Power

If a sewage treatment plant is to become an energy cycle base in a watershed, a focus should be such approaches as (1) utilization of wastewater heat, (2) utilization of organics in wastewater, and (3) micro hydropower generation. Considering the possibility of future instability in electric power supplies, sewage treatment plants should strive for electric power independence by fully exploiting power generation using organics in wastewater.

Energy potential changes in each process, which are essential for energy creation with increased power generation inside the plant, were considered to be due to increases in organics recovery during primary settlement and decreased decomposition of aerobic organics in the aeration tank (decreased decomposition through pre-recovery, decomposition of organics not requiring oxygen such as the carbon source for denitrification). Shifting priorities is necessary, from wastewater treatment to recovery of organics. For the sludge treatment process, increase in the solids recovery rate in the gravity thickening tank, charging excess sludge into the anaerobic digester, and power generation through sludge incineration can be considered, and thorough energy saving must be promoted in line with energy creation.

In the discussion we examined enabling simultaneous energy creation and energy saving while checking for any adverse effects on the treated water quality and for additional effects on other processes.

In this report, the improved electric-power self-supply ratio enabled by a decrease of the consumption rate due to an increase in the organics recovery rate and by promoting energy saving was calculated as "COD concentration necessary (required COD) for independence."

$$\text{Required COD (mg/L)} = \text{Consumption rate}/3.49 \times \text{electric power recovery ratio} \qquad (1)$$

Note that the electric power recovery ratio was calculated from the COD recovery ratio, gasification ratio, methane ratio, and generating efficiency.

The result is shown in Fig. 6. With a normal power consumption rate of 0.5 kWh/m^3, 1500 mg/L of COD will be required even at 100% recovery of solids, which means that the possibility of energy independence is very low. However, 800 mg/L of COD is calculated if the power consumption rate could be reduced by 50% to 0.25 kWh/m^3 by promoting energy conservation. This indicates an increased possibility of energy independence.

Three methods described below were studied as specific measures for improving electric power independence (Primary SS recovery rate: 34%, power consumption rate: 0.53 kWh/m^3, required COD: 5800 mg/L).

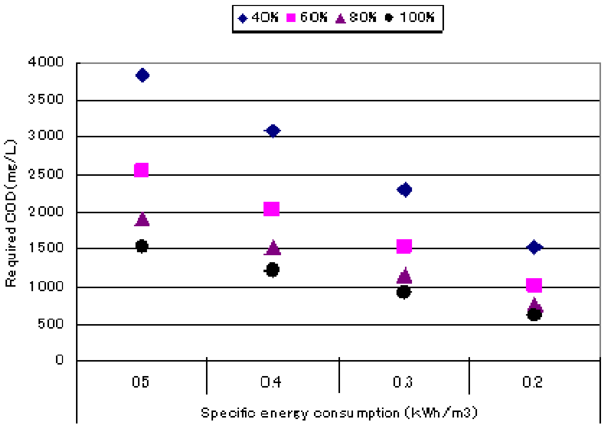

Fig. 6 Required COD for Independence with SS Recovery Ratio

(1) Introduction of high-efficiency solids-liquid separation: SS recovery rate increased to 66%.

(2) Sludge carbon charging to the primary settling tank: The SS recovery rate rose to 85%, and soluble organics became partially recoverable.

(3) Introduction of high-efficiency air diffuser: Diffusing efficiency doubled.

When high-efficiency solids-liquid separation was introduced, the aeration ratio decreased due to pre-recovery of organics, with the electric power consumption rate decreasing to 0.50 kWh/m^3. Along with an increase in power generation due to a higher SS recovery ratio, the required COD decreased to 2800 mg/L (51% down). Soluble organics decreased due to pre-recovery in the case when the method of introducing charging sludge carbon was used, and the electric power consumption rate decreased to 0.47 kWh/m^3. The required COD decreased further to 1800 mg/L (69% down). On the other hand, the introduction of a high-efficiency air diffuser, one of the measures used to reduce power consumption, reduced the electric power consumption rate by 20% or more to 0.42 kWh/m^3, but the SS recovery ratio remained the same, which meant that the required COD remained at 4700 mg/L (20% down).

We have discussed the substantial effects realized from positive efforts to recover organics, and how the COD decrease needed was 50% or more along with sludge carbon in high-efficiency solids-liquid separation to achieve independence. In both methods, strengthening organics recovery functions in pre-treatment was an alternative to primary settlement. The organics inflow load into the aeration tank decreased, which caused a decrease in the amount of air and power consumption. (Excess sludge withdrawal also decreased, along with a decrease in sludge treatment power consumption, which was done to maintain MLSS at 1500 mg/L.) Note that the return load of nitrogen and phosphorus increased by 20 to 40% along with an increase in sludge introduced into the anaerobic digester. The fact that this caused a deterioration of the treated water quality must be taken into account when the advanced treatment process is employed. This paper deals with the conventional process, which does not take into account the treated water quality in terms of nitrogen and phosphorus. The high-efficiency air diffuser discussed here as an energy-saving approach could achieve about 15% energy saving. It is considered to be an effective approach at present when the supply of electric power is not stable. In particular, this approach proves effective because the advanced treatment process intended to remove nitrogen tends to suffer from an increase in the volume of air if the current nitrification-denitrification method is employed.

Although it can be seen that it is difficult to achieve electric power independence by simply using one of the three methods described above, it is thought that further study is needed of measures to improve the power self-supply ratio through combinations of the technologies and accumulation of energy saving achievements.

The required COD relative to the SS recovery ratio (for example, the solid recovery ratio during primary settlement tank) and the power consumption ratio are shown in Fig. 6. The required COD was 2000 mg/L or more at around 40%, which is close to the recovery rate in normal primary settling. This is an indication of little possibility of independence. This decreased to nearly 1000 mg/L when the recovery rate exceeded 60%, as in high-efficiency solids-liquid separation or sludge carbon, which is considered to indicate a greater possibility of electric power independence. Note here that a cumulative energy-saving effect is needed because the power consumption rate must also drop to around 0.2 kWh/m^3.

4. Conclusions

Using the performance evaluation system (PES) of sewage treatment plant for overall evaluation of the effluent quality and energy consumption we examined the behavior in the sewage treatment plant by energy flow analysis from a quality effluent and use electric power with organic energy potential in influent for model treatment plant. Furthermore, I examined some electric power independence improvement measures with an index of the COD concentration necessary (required COD) for independence. The result is summarized below:

(1) Approximately 10% of the energy potential of organics in sewage influent could be recovered through power generation with digestion gas (4% as electric power). Most of the potential was lost due to mineralization in the aeration tank and incinerator.

(2) It was calculated that, because of the loss of 90% of the energy potential of 60,000 kWh/day of organics in sewage influent, 25,000 kWh/day of energy, equivalent to 40%, was additionally applied.

(3) Electric power independence is difficult to achieve at the normal power consumption ratio, but the possibility of doing so can be expected to rise through positive recovery of organics and promotion of energy saving.

(4) The study of specific measures showed that COD required for electric power independence could be expected to be as follows: 2800 mg/L (51% down) when high-efficiency solids-liquid separation is utilized; 1800 mg/L (69% down) for charging of sludge carbon; and 4700 mg/L (20% down) for the use of a high-efficiency air diffuser.

Development of methods of recovering organics in sewage influent is under way [10]. In the future, detailed studies are essential for the development of applications in actual treatment. This includes studies of energy conversion factors.

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