

Article

Operational Improvement of Main Pumps for Energy-Saving in Wastewater Treatment Plants

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Abstract: Efforts towards energy independence in wastewater treatment plants (WWTPs) constitute important policy in Japan. Energy-saving strategies consist of operational improvements and the installation of energy-saving devices. The energy consumed by the main pumps is equal to approximately 14% of the energy consumed by WWTPs in average in Japan. The main pumps, which are simple machines, do not have the innovative, energy-saving devices associated with other equipment used in WWTPs; therefore, realizing energy savings through operational improvement is extremely important. In recent years, variable frequency drives (VFDs) have increasingly been used to control the rotation speed of main pumps in order to save energy. However, there are many cases where power consumption increases due to the excessive rotation speed control ignoring pump characteristics. In this study, improvement of the operating method based on the power consumption analysis is examined for A WWTP. Differences in characteristics between water pumps and wastewater pumps are discussed, and simulation results without rotational speed control show a reduction in power consumption of 10%. Daily operational report data of the WWTP are used for the power consumption analysis, and additional data acquisition is not necessary. Thus, the power consumption analysis method used in this study can be easily applied to other WWTPs.

Keywords: wastewater treatment plant; energy-saving; main pump; VFDs; operational improvement

1. Introduction

Wastewater treatment plants (WWTPs) consume a large amount of energy [1]. In Japan, WWTPs accounted for 0.7% (7.2 billion kWh) of the total energy consumption in the 2010 fiscal year [2]. However, part of the energy consumed can be recovered by producing biogas from sewage sludge through an anaerobic digestion process, and great efforts are being made to increase its production [3–6]. Aside from the production of such a renewable energy, WWTPs have challenged the reduction of energy consumption in many ways [1]. Two ways to minimize energy consumption are to install energy-efficient equipment and make operational improvements [1]. Various technologies have been developed to improve energy efficiency in WWTPs [7], among which partial nitrification/anammox is the most innovative [1,8]. Based on these various technologies, new equipment such as membrane-type air diffusers, energy-saving mixers for reactors, and energy-saving sludge thickeners are now available [2]. A survey at A WWTP in Japan demonstrated that these energy-efficient technologies have contributed to an energy reduction of up to 32% [2].

Regarding operational improvements, many researchers have studied the optimization of air flow rate to reactors [9–12]. On average, in Japan, 14% of the energy in WWTPs was consumed by main pumps, while 49% and 28% was consumed for the wastewater treatment process and the sludge treatment process, respectively (formulated from Sewerage Works Statistics in Japan, 2012). Although it is theoretically possible to save energy for pump systems in WWTPs by designing more efficient pumps

or by improving pump performance with effective control strategies [13], few studies on these topics have been reported thus far [13].

Main pumps are often operated with variable speed control to achieve the most energy-efficient flow [1]. During operation, main pump performance is adjusted to meet the process demand [14] using variable frequency drives (VFDs), which offer a rapid return on investment with the payback time ranging from six months to five years [15]. A research study [16] revealed very low energy efficiency in VFDs operated with less than 75% of the full load. This is supported by our study, which showed that the efficiency in VFDs was reduced in the operation with less than 85% of the full load.

As numerous successful applications reported [17], VFDs are also increasingly installed to reduce energy use by the main pumps in WWTPs. In the installation, the performance characteristics of the pump are often ignored due to excessive control of rotational speed, which increases energy consumption. For example, during pump operation, to keep a high level of wastewater in the pump well with the aim of energy conservation by decreasing the actual pump head, the rotational speed is greatly reduced when the inflow is much smaller than average, resulting in low and, eventually, zero energy-efficiency of the operation. About 30% of WWTPs in Japan adopt a water level control of constantly high in the pump well for their pump operational method with the installation of VFDs [18].

This study proposes a strategy for pump operation, focusing on the rotational speed control of main pumps, in order to improve energy efficiency through a case study for power consumption analysis at A WWTP in Japan.

2. Materials and Methods

This study was conducted on A WWTP, which started operation in 1980. A WWTP employed a conventional, activated treatment process with a capacity of 189,040 m³/d. The sludge treatment process consisted of thickening, anaerobic digestion, dewatering, and incineration. The average inflow rate was 127,169 m³/d. The inflow BOD (Biochemical Oxygen Demand) and SS (Suspended Solids) were 240 mg/L and 230 mg/L, and the effluent BOD and SS were 1.5 mg/L and 1.0 mg/L. The collection system was mainly a separate system. The operation method for the main pumps was a constant-water-level, high-control method, which aimed to save pump power by decreasing actual pump head by keeping the water level high (see Figure 1).

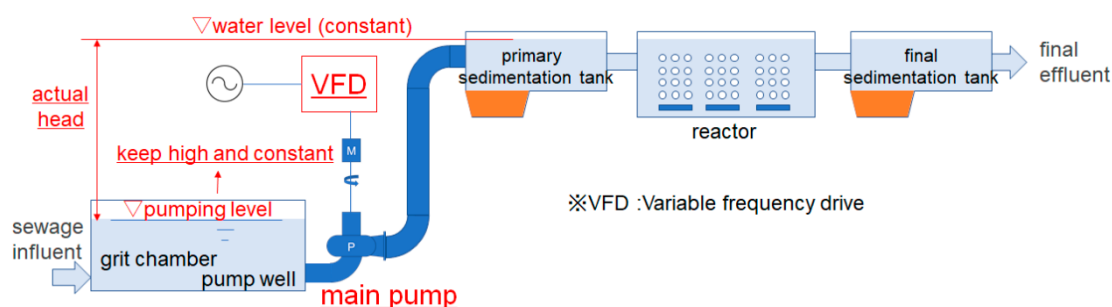


Figure 1. Brief view of main pump and wastewater process.

2.1. Power Consumption Analysis

Power consumption was analyzed using the daily operational data of main pumps in A WWTP. Data (wastewater level in pump well, power consumption, rotational speed, etc.) from the daily operational report for one week were used.

From the data, the operating condition of each pump was analyzed, and the relationship between the wastewater level in the pump well and the power consumption per unit discharge rate was examined. Additionally, we verified that the operation could be performed in the appropriate operational range on the performance curve in the plant test of pumps.

Water level data were collected from the level gauge, which was installed in the pump well. Electric power data were collected from the power gauge, which was installed between the power

switch and the pump motor. The annual operational report of A WWTP showed that daily average inflow was almost constant, and seasonal variation was not observed (see Figure 2). Inflow variation depends on sewerage users, including factories, offices, and business entities' daily activities. As shown in Figure 2, these activities were constant throughout one year. From this observation, one week's data were thought to be enough to analyze the main pump operation.

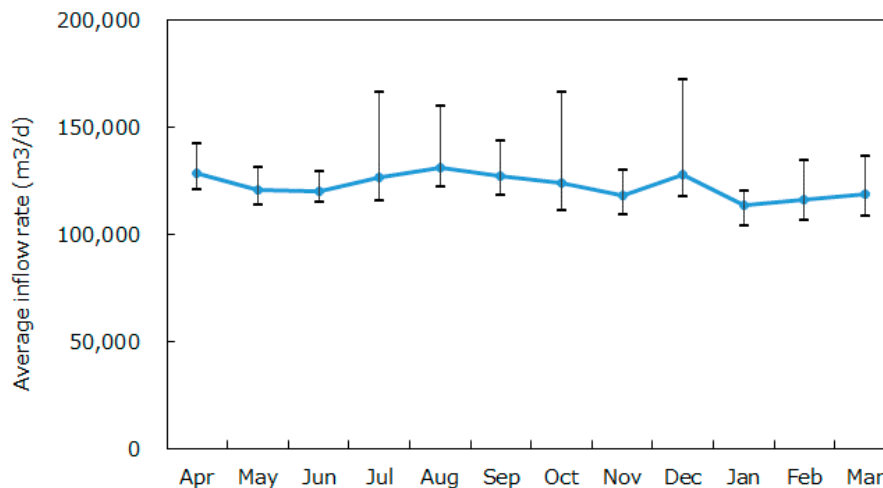


Figure 2. Daily average inflow.

2.2. Improvement of the Operation Method and Benefits

From the results obtained by the power consumption analysis, the energy-reduction effect was estimated when the operational method was improved. The operational method was changed from the high-water level, constant control method to a water level controlled by the set water level. Storage capacity of the inflow pipe to the WWTP and the pump well was fully utilized to simulate pump operation. Rotational speed control was minimized, and the number of pumps in operation was also minimized.

The reduction ratio of power consumption was calculated by simulating an improved operational method. Simulation was conducted as described below.

When the water level in the pump well is h_1 and h_2 at time T_1 and T_2 , respectively, the change value of the water level, Δh , is written as the following formula:

$$h_2 - h_1 = \Delta h = \frac{(Q_{in} - Q_p) \times \Delta T}{S}$$

where

Q_{in} : wastewater inflow rate at each time (m³/min);

$Q_{in} = Q_{inr} - Q_p$;

Q_{inr} : actual wastewater inflow rate (m³/min);

Q_p : pump discharge flow rate (m³/min);

S : sectional; area of grit chamber, pump well, and inlet sewer; and

ΔT : $T_1 - T_2$ (min).

Q_{in} is the discharged flowrate at constant water level high control (initial value). Q_p is calculated from the pump characteristic at rotational speed and the water level in the pump well. In this case, ΔT was set at 10 min and 500 m of inlet sewer was used for this simulation. The water level (h_2) was repeatedly calculated this way. Water level and rotation speed, which were set for simulation, were set to be able to operate between low-water level (LWL) and high-water level (HWL).

3. Results and Discussion

3.1. Power Consumption Analysis

A power consumption analysis was conducted on the WWTPs that used constant water level high control with the rotation speed control of pumps by VFDs. Table 1 shows the specifications of the main pumps installed in the WWTP. The specifications of all five pumps were the same. However, their performance can change based on the year of installation and whether or not rotation speed control is used.

Table 1. Specification of the pumps.

Machine No.	No.2	No.3	No.4	No.5	No.6
Pump type	Vertical volute type mixed flow pump				
Pump spec.	85 m ³ /min × 13 m				
Motor spec.	260 kW				
Completion year	2006	1990	1988	2006	2014
Rotation speed control method	VFDs	(Fixed)	(Fixed)	VFDs	(Fixed)
Power consumption per unit pumping flowrate (rated)	51 kWh/10 ³ m ³				

3.1.1. Operational Condition of Pumps

Figure 3 shows the distribution of the operation hours of the main pumps per day. Pump No. 2 and pump No. 5, which had VFDs, were mainly operated, while the other pumps were rarely used. When the inflow rate increased due to precipitation on 29 October, pump No. 3 was in operation.

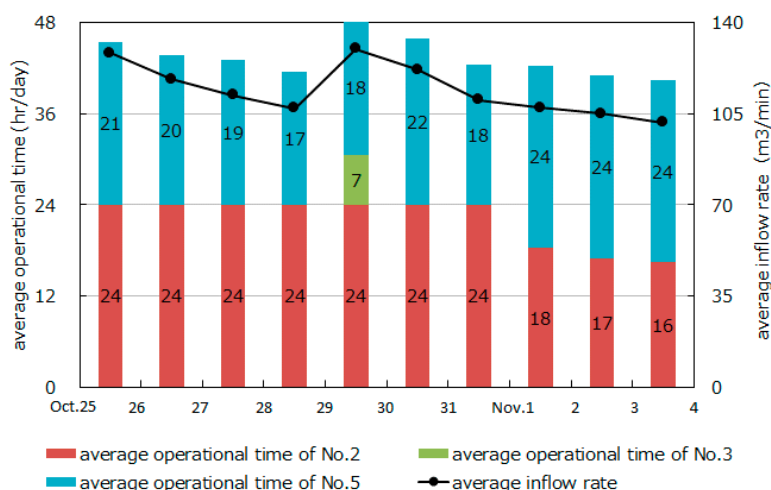


Figure 3. Operational hours of the pumps.

Figure 4 shows the wastewater level in the pump well and the discharge rate of the pumps. The bar graph in Figure 4 shows the pumps in operation. Either pump No. 2 or pump No. 5 was almost continuously in operation, and depending on the inflow rate, both units were in operation. The wastewater level in the pump well was kept constant at around 3.9 m. To keep the wastewater level in the pump well constant, the pumping flowrate fluctuated greatly and frequently by rotation speed control due to the inflow rate fluctuation.

When the water level constantly high operation is applied, the discharge flowrate to the first sedimentation tank varies because the inflow rate varies as shown by ② in Figure 5. After the operational method is improved, fluctuation of the discharge flow rate to the first sedimentation tank

is stabilized; thus, the inflow load is also stabilized. Therefore, effluent quality was not considered in this study. Only the optimization of the pump operational method was focused on in this study.

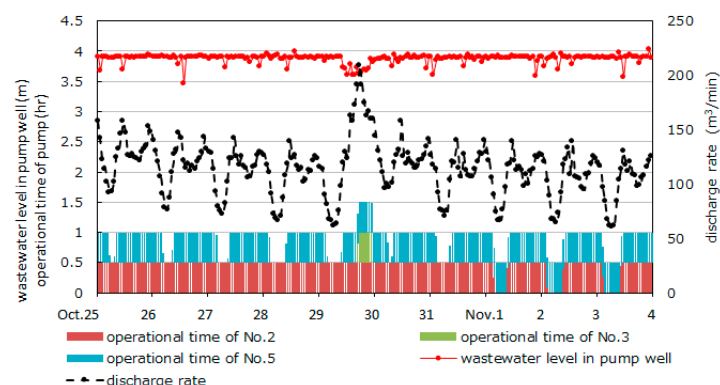


Figure 4. Operational condition of the pumps.

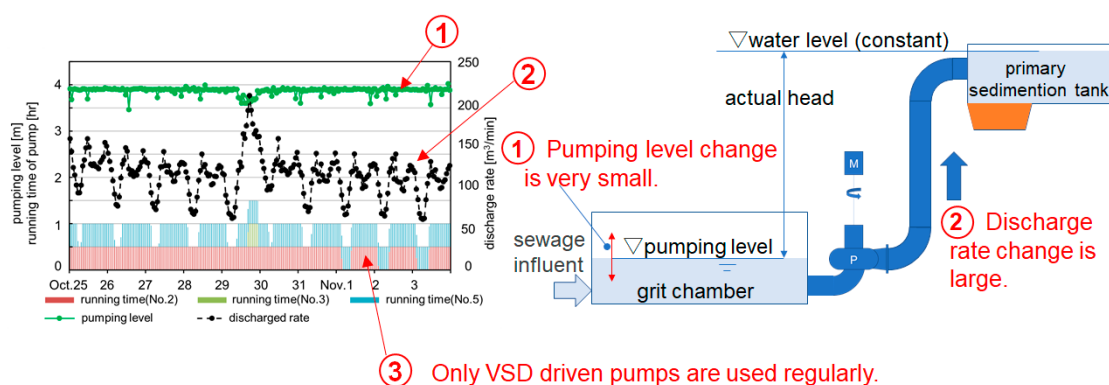


Figure 5. Constant water level high control.

Figure 6 shows the discharge rate and power consumption per unit discharge rate of each pump. The red line in the figure shows the rated discharge rate of the pumps in operation. When the difference between the rated flowrate (red line) and the actual flowrate (height of bar graph) was larger or when the number of operating units was larger, the power consumption per discharge rate tended to increase.

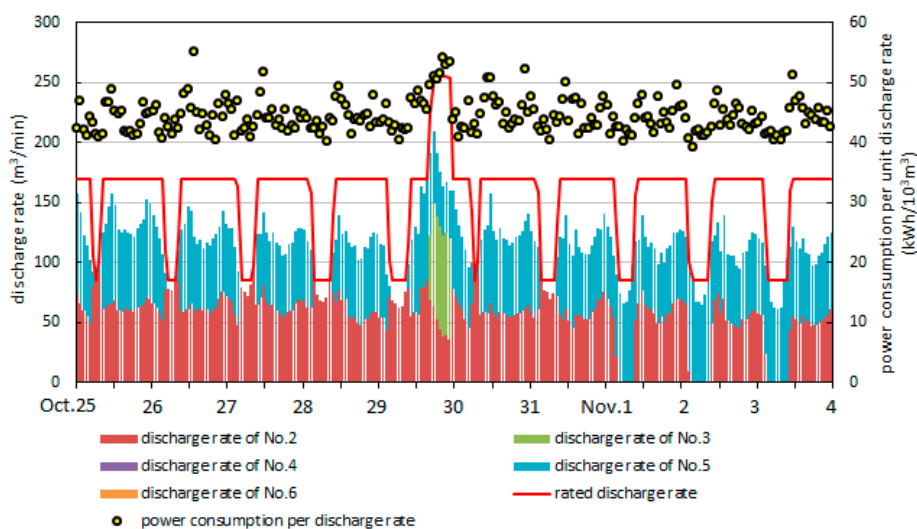


Figure 6. Operational condition of the pumps.

When the difference between the rated flowrate and the actual discharge rate became larger, the rotational speed became slower. Such excessive adjustment of rotational speed reduced the efficiency. Therefore, a rated operation was recommended, and reducing the number of pumps in operation was also recommended for energy saving.

3.1.2. Power Consumption Analysis of Pumps

Figure 7 shows the distribution of power consumption per unit discharge rate of each pump. Data from the No. 3 and No. 6 pumps were also plotted when they were in operation during rainy weather. Pump No. 2 and pump No. 5, which had VFDs, had large fluctuations of power consumption per unit discharge rate. On the other hand, the power consumption per unit discharge rate was stable for pump No. 3 and pump No. 6, which were fixed-speed pumps. The power consumption per unit discharge rate on pump No. 2 and pump No. 5 increased as the discharge rate decreased. To reduce energy consumption, these pumps should operate near the rated discharge rate.

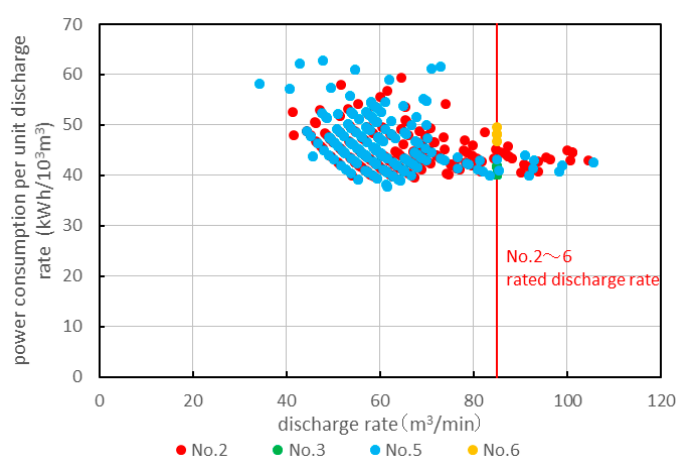


Figure 7. Distribution of power consumption per unit discharge rate.

Figure 8 shows the relationship between the wastewater level in the pump well and the power consumption per unit discharge rate. Pump No. 2 and pump No. 5 had VFDs, whereas, pump No. 3 and pump No. 6 did not have VFDs. As the inflow rate varied on an hourly basis, the wastewater level in the pump well was always kept constant, at around 3.9 m, by using the VFDs of pump No. 2 and pump No. 5, as shown in Figure 4. At a wastewater level of 3.9 m, the power consumption per unit discharge rate showed a large variation from 20 kWh/1000 m³ to 105 kWh/1000 m³. On the other hand, the power consumption per unit discharge rate of pump No. 3 and pump No. 6, which did not have VFDs, was almost constant despite the wastewater level in the pump well, and was smaller than that of pump No. 2 and pump No. 5. These results showed that keeping the wastewater level in the pump well high and keeping the pump head low did not always contribute to efficient power consumption. The reason was that the pump efficiency was deteriorated by the excessive rotational speed adjustment by the VFDs.

A pump's characteristic curve and operational point explain the results shown in Figure 9. The operational point is the intersection of the total head curve and the pipe resistance curve. When the actual head changes, the slope of pipe resistance does not change, and the value of total head changes when the discharge rate is zero. The operational range of the pump is the intersection of the total head curve pipe resistance at maximum actual head and minimum actual head (see Figure 9).

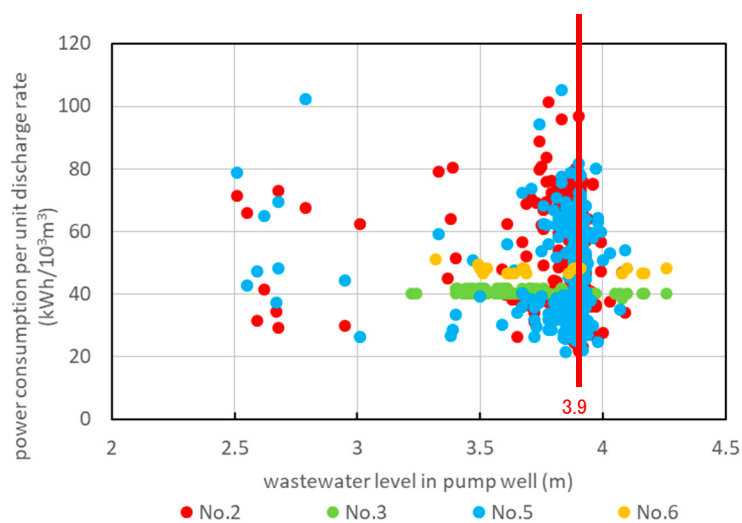


Figure 8. Wastewater level in the pump well and the power consumption per unit discharge rate.

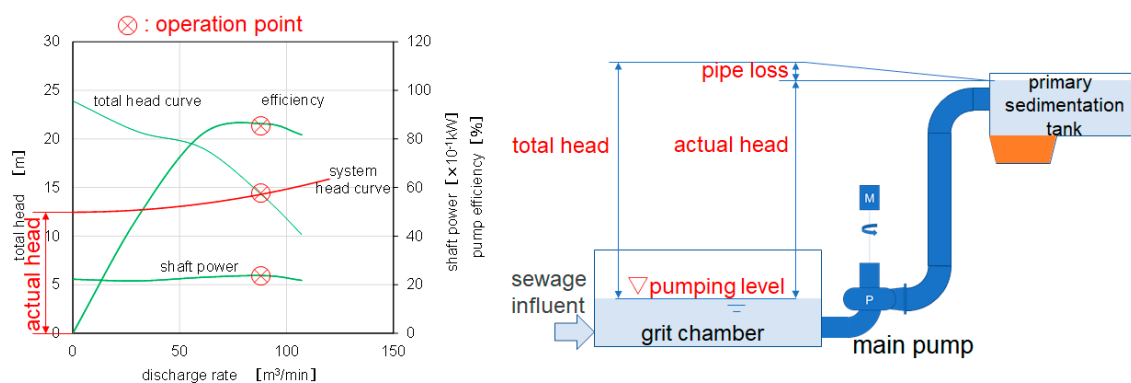


Figure 9. Characteristic curve and operational point.

At the same actual head, the operational point changed when the rotational speed control was conducted (see Figure 10). This figure shows the performance curve when the rotation speed of the pump is changed.

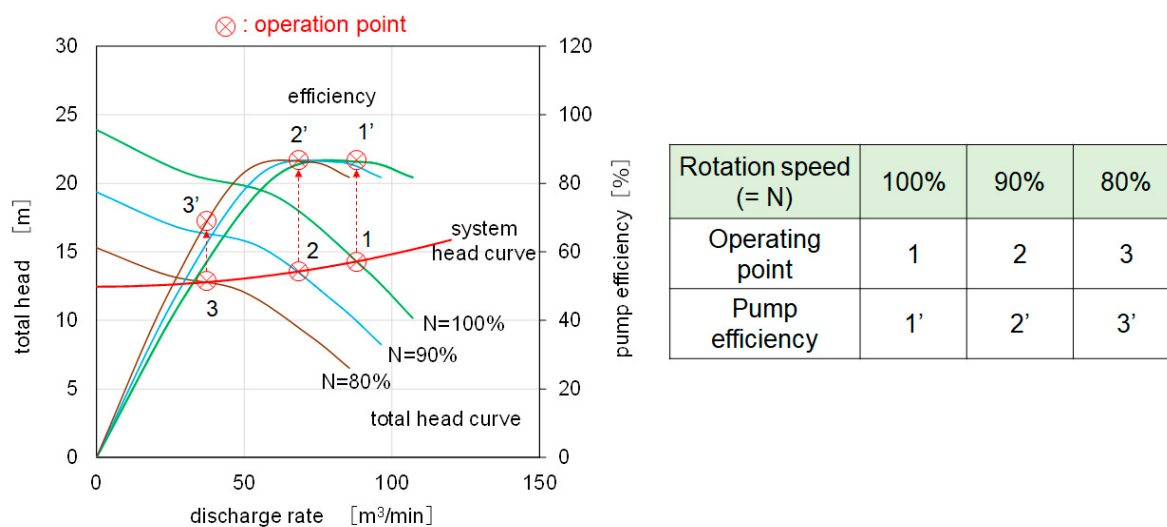


Figure 10. Change of pump efficiency when rotational speed control was performed.

If the rotational speed is reduced from 100% to 80%, the operation point changes from 1 to 3, and the pump efficiency changes from 1 ft to 3 ft. In such a case, if the rotational speed decreases, the efficiency may be drastically lowered. Based on this information, pump performance in A WWTP was studied.

Figure 11 shows the relationship between the rotational speed and pump efficiency of pump No. 2 and pump No. 5. The curve was drawn based on the pump performance curve. Pump efficiency was high between 85% and 100% of pump rotational speed, whereas pump efficiency decreased below 85% of rotational speed. A lower limit of pump rotational speed with high pump efficiency varies by pump specifications, pump head, and pipe layout. It is important to confirm the operational range with high pump efficiency when the VFDs operation is carried out to reduce power consumption. To reduce the power consumption of the main pumps in this WWTP, it was effective to keep the rotational speed higher than 85%.

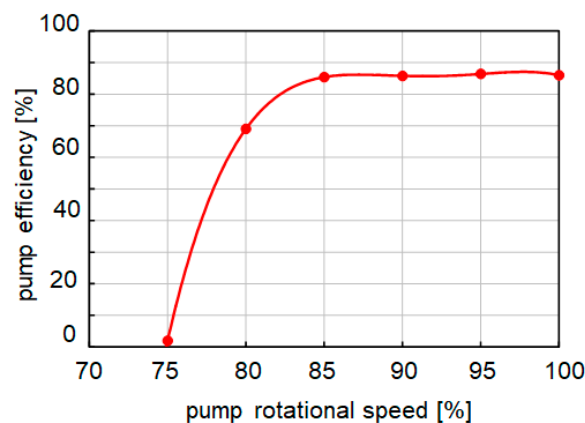


Figure 11. Rotational speed and pump efficiency.

A research study [16] revealed very low energy efficiency in VFDs operated with less than 75% of the full load. In this study, operational efficiency became very low when the rotational speed was less than 85% of the full load. Rotational efficiency becomes very low at less than some percentage of the full load, because the actual head occupies the total head, which consists of actual head and pipe resistance (see Figure 12). When the rotational speed decreases, the power consumption and discharge rate also decrease. Wastewater continuously flows into WWTPs. When the discharge rate was excessively decreased, the operational duration became longer and, as a result, the power consumption per unit of wastewater became greater. This finding was supported by the result that occurred when the water level was kept at 3.9 m, during which power consumption per unit of wastewater largely varied, as shown in Figure 8.

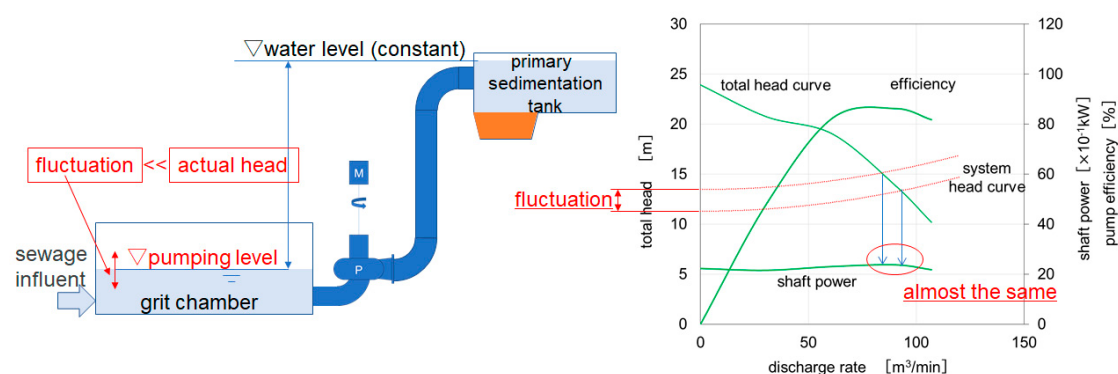


Figure 12. Relationship between actual head and shaft power.

Since the pumps in A WWTP had relatively flat shaft power curves, the power consumption per wastewater unit did not show significant change, as shown in Figure 12. Thus, an on/off control based on the fixed rotational speed and water level instead of on VFD control was recommended to reduce power consumption.

Pumps for water supply and for the desalination plant have large pipe resistance compared to the actual head. Since the slope of the pipe resistance curve is steeper than that of the total head curve on such pumps, pumps are operated efficiently when the rotational speed is reduced (see Figure 13). A study stated that VFDs may not be effective when a large static head must be overcome or when the flowrates are approximately constant [16]. From these considerations, a range of rotational speed control for main pumps in WWTPs was decided by the characteristics of the pumps and the conditions of the facilities.

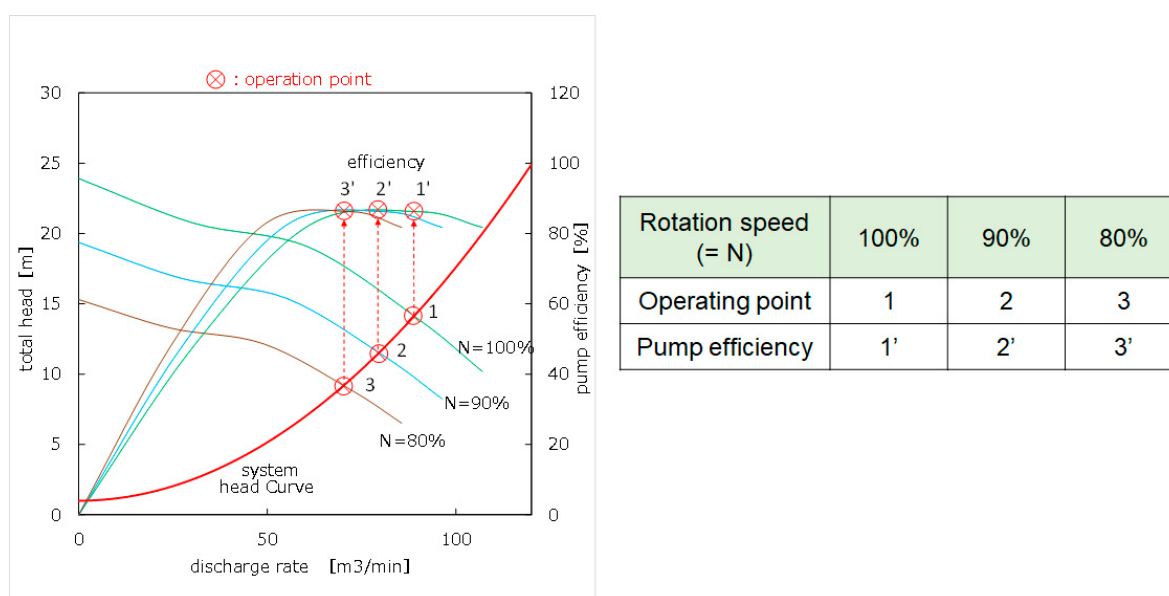


Figure 13. Change of operational points on pumps for water supply.

3.2. Improvement of the Operation Method and Benefits

Based on the results of the power consumption analysis, an operational simulation was performed to improve the operational method in the condition described below.

Case 1: Pump No. 3 and pump No. 6 were operated with an on/off control, which is described in Figure 14. Pump No. 3 was mainly operated, and pump No. 6 was additionally operated when pump No. 3's capacity was not high enough.

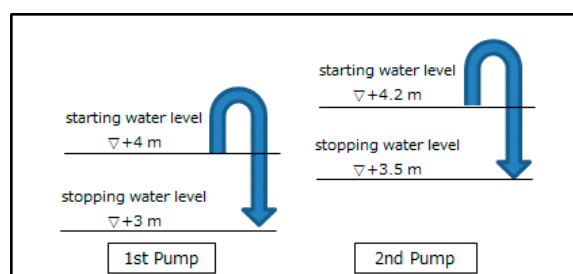


Figure 14. Water level setting.

Case 2: Pump No. 2 and pump No. 3 were operated. Pump No. 3 was mainly operated with on/off control. Pump No. 2 was additionally operated in a previously-allocated time zone with 85% of full load.

Case 3: Pump No. 2 and pump No. 5 were operated. Pump No. 2 was mainly operated with 85% of full load. Pump No. 5 was additionally operated with 85% of full load when pump No. 2's capacity was not high enough.

Case 4: Pump No. 2 and pump No. 5 were operated. Pump No. 2 was mainly operated with 90% of full load. Pump No. 5 was additionally operated with 90% of full load when pump No. 2's capacity was not high enough.

In each case, the total operational hours of the pumps and the power consumption were calculated. Results are shown in Table 2. In Case 1, Case 2, and Case 3, the operational hours of the pumps were reduced. In all cases, power consumption was reduced. As shown in Table 2, Case 1 was the most effective operational method, showing about a 10% reduction in power consumption.

Table 2. Calculation results through simulation.

CASE		Total Operation Hours of 2-Units		Power Consumption	
		hrs./Day	Reduction Rate	kWh/Day	Reduction Rate
Before		36.5	—	6200	—
After	①	26.3	27.9%	5597	9.7%
	②	28.6	21.6%	6192	0.1%
	③	36.7	−0.5%	5867	5.4%
	④	32.2	11.8%	6112	1.4%

The simulation results, the reduction rate on total operation hours, and the power consumption, are shown in Table 2. The total pump operation hours were reduced by 28%, and power consumption was reduced by 10%.

3.3. Discussion

A systematic approach to saving energy on main pumps during operation in WWTPs has not been tried until now. As shown in Figure 6, a power consumption analysis can be performed by using the operational hours of pumps, the discharge rate, and the power consumption per unit discharge rate. Figures 7 and 8 showed that excessive rotational speed adjustment by VFDs deteriorated pump efficiency. Figures 9 and 10 showed changes in pump efficiency, when rotational speed control was performed, using characteristic curve and operational points. Additionally, Figure 13 showed a change of operational points on pumps for water supply, to clarify the difference between operational points of wastewater pumps and those of water supply pumps. Based on the power consumption analysis, an energy-efficient operational method can be proposed through operational simulation, as shown in Figure 14 (the results were shown in Table 2). To achieve the best result, we set four possible cases; however, obtaining a better result than Case 1 may be possible. The case-setting method needs to be improved.

Since main pumps using rotational control by VFDs are said to be used in 70% of the WWTPs in Japan, the energy-saving method in this study is expected to contribute to widely reducing energy consumption in WWTPs.

Energy-saving equipment, such as energy-saving blowers, energy-saving diffusers, energy-saving sludge thickeners, and energy-saving sludge dewatering machines, has been developed and recently applied to WWTPs. Additionally, an automated aeration process saves considerable amounts of energy [1]. Automated aeration processes such as the ammonia-based aeration control (ABAC) system, ammonia versus nitrate (AVN) control, and the bioprocess intelligent optimization system (BIOS) have been developed [1]. The energy-saving methods for main pumps in WWTPs reported in this study are applicable, in addition to the other energy-saving technologies mentioned above.

4. Conclusions

In this study, a power consumption analysis was performed and the operational simulation results from four cases were reported. Through this process, the energy-efficient operational method was found to reduce power consumption by 10%. Of the four cases reported, the best result was selected; however, a better case than the four cases presented may exist. Consequently, more cases should be examined to achieve an optimum condition. In the future, using artificial intelligence (AI) may be effective for producing optimum conditions.

Through this study, the following items were confirmed:

- (1) Excessive rotational speed control increased the power consumption per unit discharge rate;
- (2) The power consumption analysis and operational improvement based on the daily report data was effective;
- (3) Since the changing patterns of the operational points were different from the pumps for water supply, VFDs were not effective for pumps in WWTPs;
- (4) Pump operation to keep wastewater level constantly high in the pump well was not effective for saving energy.

Since 70% of WWTPs in Japan adopt main pumps with VFDs and 30% of WWTPs adopt high water level constant control in the pump well as their pump operational methods [18], the results of this research will contribute to reducing power consumption in many WWTPs.

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