

Energy Efficiency of Full-scale Oxidation Ditch with Dual Dissolved Oxygen Control Technology in Clean Water and Domestic Wastewater

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ABSTRACT

The authors evaluated the energy efficiency of a novel oxidation ditch (OD) system with dual dissolved oxygen (DO) control technology through clean water tests and continuous treatment of domestic wastewater in a full-scale OD. The system maintained a constant DO gradient in the loop channel by independently controlling the aeration intensity and the circulation flow rate. Clean water tests demonstrated that a standard aeration efficiency of 1.4 - 2.1 kgO₂/kWh was obtained in the OD equipped with membrane diffusers, blowers and vertical flow boosters, and these values were relatively higher than the previously reported values. The calculated standard aeration efficiency varied depending on the airflow rate and rotational speed of the flow boosters. Continuous treatment revealed that the power consumption was reduced by 67% when compared with the existing OD system. Reducing endogenous respiration, improving the standard aeration efficiency, and applying dual DO control were estimated to contribute 15%, 28% and 23%, respectively, to the total reduction of power consumption. Overall, this novel OD system showed extraordinary nitrogen removal performance with very low energy consumption.

Keywords: dual dissolved oxygen control, energy efficiency, full-scale experiment, nutrient removal, oxidation ditch

INTRODUCTION

An oxidation ditch (OD) is a typical biological treatment system used in small sewage treatment plants. This system has a high internal circulation rate that results in a unique flow regime in the OD channel. Loop channels of OD are considered to be completely mixed over the hydraulic residence time, but show strong plug flow when observed over one loop (Barnes *et al.*, 1983). Additionally, dissolved oxygen (DO) gradients exist in the loop channels of OD systems, but other components are spatially homogenized. The DO gradient and the long sludge retention time of the reactor enable simultaneous nitrification and denitrification in a single OD. Many researchers have shown that the DO or aeration intensity affects the efficiency of total nitrogen (T-N) removal (Rittmann and Langeland, 1985; Furukawa *et al.*, 1998; Insel *et al.*, 2005). An appropriate DO gradient can provide both aerobic and anoxic zones and enhance the T-N removal efficiency; however, this gradient becomes unstable under fluctuating influent loads (Barnes *et al.*, 1983).

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Received October 23, 2011, Accepted March 22, 2012.

In a simulation, Abusam *et al.* (2002) found that changing the horizontal velocity in the OD channel while applying continuous aeration via surface aerators improved the T-N removal efficiency. However, conventional surface aerators in an actual plant could not control aeration and mixing separately. Roustan *et al.* (1993) operated an OD with intermittent aeration applied by a fine bubble diffuser while maintaining an almost constant horizontal velocity using submerged propellers. They reported the effluent T-N at two plants as 8 mg/L and 14 mg/L. Such intermittent aeration provides relatively good operational strategy, but is not the best solution. This is because the potential high nitrogen removal efficiency of the OD caused by its high internal circulation rate, which can be 50 or 100 times higher than the influent flow rate, could not occur during such operation.

The authors have been developing a novel OD system with dual DO control technology that can maintain a stable aerobic and anoxic zone in an OD channel, regardless of fluctuations in influent load. In this system, airflow rate and internal circulation rates are independently controlled by the dual DO control technology to maintain an appropriate DO gradient (Fujiwara *et al.*, 2005). The authors demonstrated that this novel system had remarkable nitrogen removal performance and the subsequent reduction in nitrate recycling to the anaerobic tank enhanced the biological phosphorus removal (Chen *et al.*, 2010). In addition, mass balance analysis demonstrated that the novel OD system could realize outstanding sewage treatment performance coupled with effective carbon source consumption for aerobic degradation and denitrification (Chen *et al.*, 2012). However, these previous studies were conducted through a bench-scale and/or pilot-scale experiments, and no full-scale studies have been conducted to date.

On the other hand, the wastewater treatment technology that can reduce power consumption is expected owing to the demand for energy savings and reduced carbon dioxide emission.

In this study, the energy efficiency of this novel OD system was discussed along with the results of a full-scale experiment conducted at the second line of the Noichi wastewater treatment plant (WWTP) in Japan. Clean water tests and one year of continuous treatment of domestic sewage were performed using a 1,750 m³ OD tank equipped with vertical flow boosters, membrane diffusers, and blowers to enable dual DO control. The results of process operation in the updated second line were compared with those of the existing first line during the previous year.

METHODS

Experimental facilities and configurations

The layout of the second line of the Noichi WWTP is shown in Fig. 1. Its width is 4.5 m, and the loop length at its center line is 165 m. The equipment specifications of the OD at the Noichi WWTP are shown in Table 1. The first line, whose channel has a shape identical to that of the second line, is equipped with four surface aerators. To update the second line, two vertical flow boosters were installed at the bends in the channel. The vertical flow boosters had sixteen blades that rotated slowly and were suspended by bearing units. These vertical blades extended from the bottom to the surface and generated ideal plug flow. Compressed air from blowers was diffused through

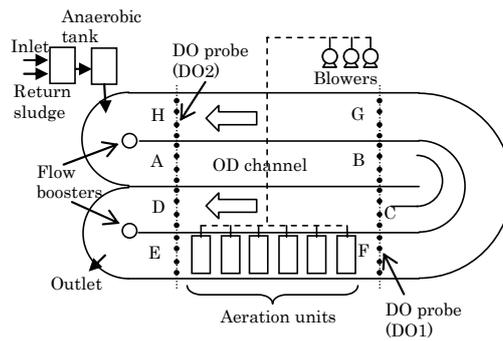


Fig. 1 - Configuration of the second line of the Noichi WWTP.

Table 1 - Equipment specifications of the oxidation ditch.

Line	Name	Type	Specification	Rated power (kW)	Pieces of equipment
1st	Surface aerator	Screw type		9	4
2nd	Flow booster	Vertical	φ1.6 m	4	2
	Blower	Roots	11 m ³ /min, 30 kPa	11	3(1) †
	Aeration unit	Membrane	7 Nm ³ /(h disk)	0	192

†The number of spare machines is indicated in parentheses.

membrane disks that were installed along a straight segment of the OD.

Clean water tests

The impulse responses for dye tracer, velocity distribution, standard oxygen transfer rate (SOTR), and wire power were measured, after which the standard aeration efficiency (SAE) was calculated. The water depth ranged from 1.5 m to 2.5 m, the rotational speed of the flow boosters ranged from 13.2 to 26.3 rpm and the airflow rate was between 0.0 and 20.5 Nm³/min.

The horizontal velocity in the OD channel determines the internal circulation rate and affects the oxygen transfer efficiency (Gillot *et al.*, 2000). In this study, the velocities were measured using a three-dimensional (3-D) electromagnetic current meter (ACM300, Alec Electronics, USA). The 3-D vector data were recorded at 20 points in each of the eight sections of the system (160 points in total). The flow pattern of the OD channel was analyzed using the residence time distribution (RTD). To accomplish this, uranine dye (fluorescein sodium) was injected at the inlet of OD and its impulse responses were measured at section H. The in-situ fluorescence intensities were measured using a handy uranine meter (CHL-5Z, Kasahara Rika Inc., Japan; 460 nm excitation wavelength; 590 nm emission wavelength). The final equilibrium concentration of the dye was 10 µg/L, which was one hundred times greater than the detection limit.

The SOTR was measured in clean water (filtered secondary effluent) based on an unsteady-state method for determining the overall volumetric oxygen transfer

coefficient (K_La) (ASCE, 2007). The time course of DO was recorded within the re-aeration period after deoxygenation using cobalt-catalyzed sodium sulfite. Additionally, two luminescent DO probes (LDO, Hach, USA) were placed as indicated in Fig. 1. The airflow rates were measured by a mass flow meter (454FTB, Oval, JAPAN) and recorded under normal conditions (101.3 kPa, 0°C). The SAE was calculated by dividing the SOTR by the wire power consumption, which was measured separately for aeration and mixing using multi-measuring instruments (ME110-NSR, Mitsubishi, Japan).

Process operation

The influent wastewater of the WWTP was passed through a bar screen with a 5 mm mesh, then mixed with water that was returned from the sludge treatment process and pumped into the distribution tank, after which it flowed into the OD tanks. There were two water treatment process lines. On 6 April 2010, the second line used for the novel system was activated in place of the first line. Continuous treatment started on 25 May 2010. The total influent of wastewater was treated in the second line, and the results were compared with those obtained after treatment in the first line during the previous year. The second line was operated with a water depth of 1.5 meters, which was one meter shallower than in the first line. In addition, the second line was operated at a higher volumetric loading rate than the first line. The minimum hydraulic retention time (HRT) during dry weather was 12.3 hours. The operational conditions of the experiments are shown in Table 2, but some information from the first line is unknown.

In the first line, four aerators operated intermittently for a total of 16 hours per day using a preset timer. However, the second line used a programmable logic controller to control the function of the blowers and the flow boosters to maintain a constant DO at two points. One DO probe (DO1) was set immediately downstream of the aeration units and another (DO2) was set at the end of the aerobic zone. Twice a week, composite

Table 2 - Operational conditions of the oxidation ditch.

Line		1st Line	2nd Line
Term	Units	From April 1, 2009 to March 31, 2010	From May 25, 2010 to March 31, 2011
Influent flow rate	m ³ /d	1539	1719
Water depth	m	2.5	1.5
HRT of OD	h	27	16.5
Circulation time of OD	min	Unknown	15.9
Return sludge ratio	%	131	114
DO1/DO2	mg/L	Unknown	2.35/0.23
Aerobic zone/anoxic zone ratio	–	Unknown	0.38/0.54
Temperature of OD	°C	21.4	20.7
MLSS concentration	mg/L	3350	3260
BOD volumetric loading	kg/(m ³ d)	0.09	0.19
Sludge Retention Time (SRT)	d	64	30

samples of the influent and effluent and grab samples of the OD, anaerobic tanks and return sludge were analyzed. Four times a year, 24-hour tests with two-hour intervals were conducted. An effluent T-N concentration of 1.3 ± 0.5 mg/L was achieved and the average T-N removal efficiency was 94% (Fujiwara *et al.*, 2011).

RESULTS AND DISCUSSION

Clean water tests

Modelling of flow characteristics: The normalized impulse response of the dye tracer is plotted in Fig. 2. Strong plug flow without shortcuts was observed owing to the vertically uniform shape of the flow boosters. The number of tanks (N) was analyzed using a closed loop continuous-stirred tank reactor model. The closed loop indicates that there was no influent or effluent; therefore, the amount of dye was conserved in the OD. The RTDs of the N tanks were convoluted from the 1st lap to the kth lap as shown in Equation (1) assuming that neither peak was overlapped because of strong plug flow,

$$E(\theta)_N = \sum_{i=1}^k \frac{N(N\theta)^{iN-1}}{(iN-1)!} e^{-N\theta} \quad (1)$$

where, $E(\theta)$ is the normalized residence time distribution function at the Nth tank, N is the number of tanks, i is the circulation lap number, k is the convoluted number, θ is the normalized time (t/t_{ave}) and t_{ave} (h) is the circulation time of an OD loop.

Without aeration, an N value of 100 was observed. However, this value decreased to approximately 65 with aeration because of back mixing induced by aeration. Although the flow characteristics of each aerated and non-aerated zone differed, equal volumes were assumed in this study for simplicity. Nonetheless, the curves calculated from Equation (1) and the RTD plots agreed well (Fig. 2).

As shown in Fig. 3, the authors selected an N value of 55 to model the flow characteristics of the OD loop channel. This value, which was slightly lower than the observed values, was selected to provide a safety margin for design purposes. This value was also selected because the six aeration units were arranged with 3 m pitch spacing; therefore, 55 provided a number equal to the 165 m loop length divided by 3 m. The

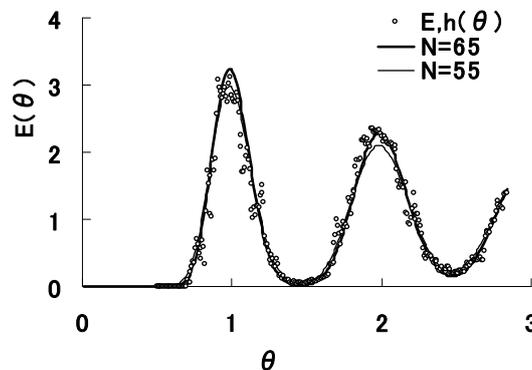


Fig. 2 - Normalized impulse response curve of dye tracer (H = 2.5 m, air flow rate = 22.0Nm³/min).

RTD curve was less sensitive when a high N value was used. However, the curves of N = 55 and N = 65 were almost identical (Fig. 2).

Measurements of SOTR: Figure 4 shows the time course of the DO ascent during the unsteady-state K_La measurement. Stepwise DO ascent was observed because the aeration equipment was installed in a segment of the loop channel. This phenomenon was also reported by Boyle *et al.* (1989) and the German Association for Water, Wastewater and Waste (DWA) (2007). The measured average DO was not representative of the entire reactor owing to its lack of spatial uniformity; therefore, the estimated SOTR deviated from the actual value. The ASCE standard recommends that multiple DO probes be used to attenuate this disturbance. Although this is a good solution when the flow characteristics of the reactor are unclear, the stepwise DO ascent could not be simulated using this method. Therefore, the authors chose to use the N tanks model shown in Fig. 3 to calculate the SOTR.

The mass balance equation of the DO at each segment is given by Equation (2). The upper portion is for aerated segments and the lower is for mixing segments,

$$\frac{dC_i}{dt} = \frac{C_{i-1} - C_i}{t_i} + K_L a (C_{\infty}^* - C_i) \quad (i = 1 \sim 6)$$

$$\frac{dC_i}{dt} = \frac{C_{i-1} - C_i}{t_i} \quad (i = 7 \sim 55) \quad C_o = C_{55} \quad (2)$$

where, C_i is the DO (mg/L) at the i^{th} tank; C_{∞}^* is the saturated DO value (mg/L); K_La is the overall volumetric oxygen transfer coefficient (1/h); and t_i is the circulation time (h) of the i^{th} tank (t_{ave}/N).

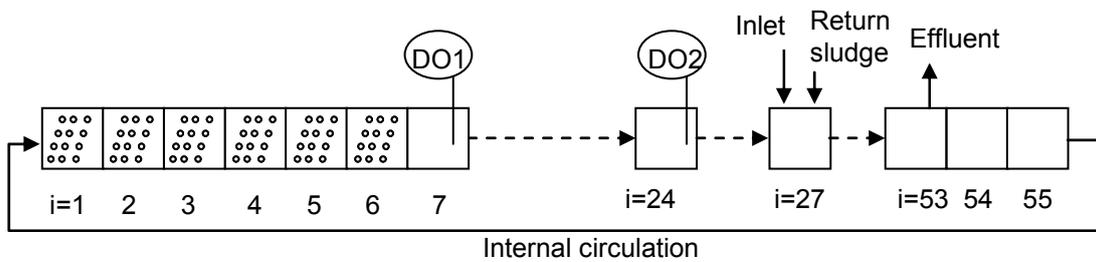


Fig. 3 - Modelled configuration of flow characteristics in the OD loop channel.

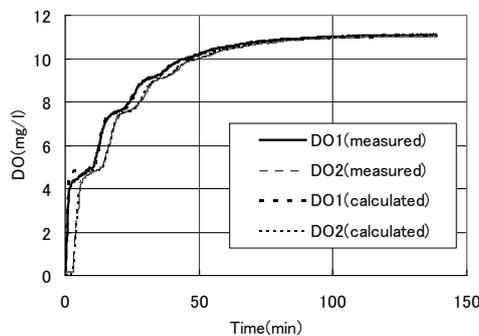


Fig. 4 - Time course of DO ascent (water depth = 2.5 m, air flow rate = 20.5 Nm³/min, 26.3 rpm).

The DO value of the tank number ‘i’ at time t was calculated step by step with a one second interval from the given initial values of $C_{i,t=0}$. The parameters C_{∞}^* , $K_L a$ and t_{ave} were estimated using the non-linear least squares method. The average ratio of the estimated t_{ave} to the measured value was 0.95 (n = 9). The curves calculated from equation (2) are also illustrated in Figure 4 and agree well with the measured data. The DO profile was well simulated mathematically by solving the spatial and temporal DO distribution. The SOTR was calculated by Equation (3) (ASCE, 2007).

$$SOTR(kgO_2 / h) = K_L a_{20} \times C_{\infty 20}^* \times V \times 10^{-3} \quad (3)$$

where, *SOTR* is the standard oxygen transfer rate (20°C, 101.3kPa, DO = 0mg/L); $K_L a_{20}$ is the overall volumetric oxygen transfer coefficient (1/h) at 20°C, $K_L a = K_L a_{20} 1.024^{T-20}$; *T* is the temperature (°C); $C_{\infty 20}^*$ is the saturated dissolved oxygen (mg/L) under standard conditions (20°C); and *V* is the tank volume (m³).

Figure 5 shows the combined effects of airflow rate and rotational speed in rpm of the flow boosters on the SOTR. Positive effects were observed when the rotational speed of the flow boosters increased. This phenomenon has also been reported by Gillot *et al.* (2000). In addition, the SOTR was proportional to the aeration depth, which is the length from the diffuser surface to the water surface (data not shown). Based on this information, the SOTR can be determined using the operational parameters.

Calculation of SAE: Calculation of SAE was made by Equation (4). The power consumption characteristics of the flow boosters were obtained from the experiments, while those of the blowers were procured from the manufacturer. By using the above factors, the authors could estimate the SOTR and power consumption of the operational parameters. In this study, the wire power rather than the shaft power was used for calculation. The wire power includes all efficiencies of the motor, reducer and frequency converter. Equation (4) is expressed as:

$$SAE(kgO_2 / kWh) = \frac{SOTR}{P} \quad (4)$$

where, *SAE* is the standard aeration efficiency (20°C, 101.3 kPa, DO = 0 mg/L) and *P* (kWh) is the wire power (kW), which is equal to the power for aeration plus the power for mixing.

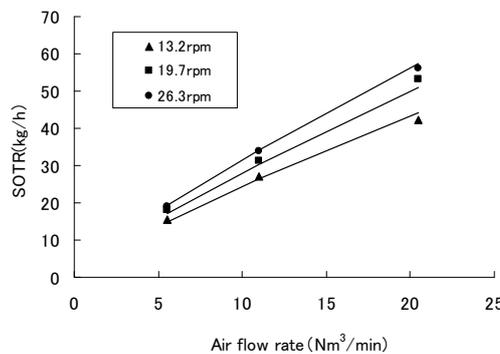


Fig. 5 - Effects of air flow rate and rotational speed of flow boosters on the SOTR.

Figure 6 shows the contour plot of SAE calculated at depths of 1.5 m (left) and 2.5 m (right) based on the rotational speed of flow boosters versus the airflow rate. As shown in the figure, the SAE at 2.5 m ranged between 1.4 and 2.1 kgO₂/kWh, and it was greater than that at 1.5 m. The one hour average data, which showed the rotational speed and air flow rate in the process operation, was also plotted. The contour lines of the SAE in Fig. 6 ranged from 1.1 to 1.6 kgO₂/kWh, but the process was operated at an area of more than 1.5 kgO₂/kWh.

Comparison with existing lines and literature: The SAE values of the first line and the second line are plotted against the water depth in Fig. 7. The reported SAE (Mueller *et al.*, 2002) obtained with various types of aerators are also plotted in the same figure. The second line had higher values than the previously reported values, despite the lower aeration depth. These findings indicated that the new aeration system installed on the second line had the potential to save 26 - 51% of the energy required for operation of the first line.

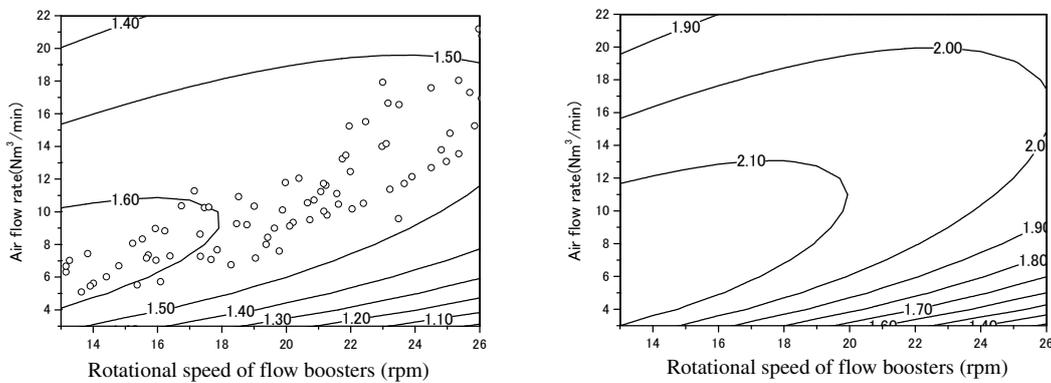


Fig. 6 - Contour plot of SAE based on operational parameters.
(water depth = 1.5 m (left), 2.5 m (right), SAE units are kgO₂/kWh)

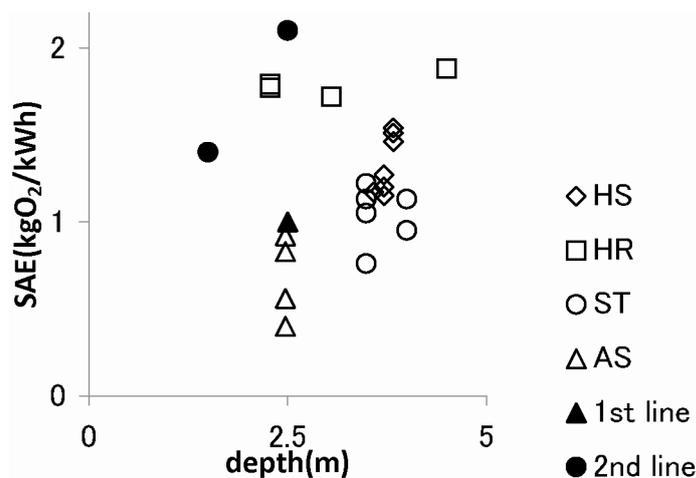


Fig. 7 - Comparison of SAE values for the first line, second line and those reported by Mueller *et al.* (2002).

*1 HS: high speed surface, HR: horizontal rotor, ST: submerged sparged turbine.

*2 These data were calculated by wire power.

Process operation

Effluent water quality: During continuous treatment of domestic sewage, the influent loading was maintained at approximately twice that of the existing OD system at Noichi WWTP during the previous year. The water temperature shifted between 15°C during winter and 28°C during summer. Successful maintenance of the aerobic/anoxic zone despite the large fluctuations in influent loading resulted in good effluent quality. An effluent T-N concentration of 1.3 ± 0.5 mg/L was achieved and the average T-N removal efficiency was 94% (Fujiwara *et al.*, 2011).

Power consumption during process operation: Figure 8 shows the chemical oxygen demand (COD) volumetric load and the power required for aeration and mixing with respect to time for 29 June 2010. The COD volumetric load was calculated by Equation (5),

$$COD \text{ volumetric load} \{gCOD / (m^3 h)\} = Q_{inf} \times COD_{inf} / V \tag{5}$$

where, Q_{inf} is the influent flow rate (m^3/h) of OD (one hour average measured by an ultrasonic flow meter), COD_{inf} is the influent COD concentration (g/m^3) (interpolated value for every 2 h of analysis) and V is the volume (m^3) of OD.

There were two peaks of influent COD load in the morning and evening. The power consumption for both aeration and mixing was well controlled to compensate for this fluctuation in influent load.

The area between the real time course of power consumption and the virtual horizontal line at 11.2 kWh, which was the maximum power consumption for aeration at 8 : 00, is shaded with oblique lines as seen in Fig. 8. The shaded area in Fig. 8 indicates the reduced power consumption for aeration due to the use of the dual DO control. This reduction in power consumption, including mixing power, was 40% when compared to the virtual case of constant aeration at maximum power shown in Figure 8.

Figure 9 shows the relationship between influent flow rate and unit power consumption. The unit power consumption, which is the power consumption divided by treated volume of wastewater, decreased when the influent flow rate was large. The power

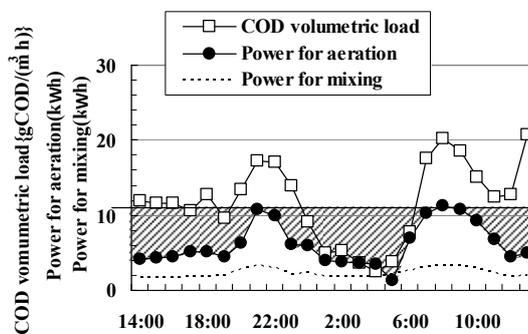


Fig. 8 - Influent load and power for aeration on 29 June 2010.

consumption of the second line was one third that of the first line. During the year, 166,000 kWh of power was saved by this novel system. Table 3 shows the annual average operational conditions of the second line and the SAE calculated using the results of the clean water tests.

The breakdown of this energy saving was roughly estimated. Figure 10 shows the specific energy consumption, which is the ratio to the unit energy consumption of the first line. An approximately 15% reduction in oxygen demand was determined based on the calculation of the reduction of endogenous respiration as a result of the relatively high load operation. The contributions from the improvement of SAE and the dual DO control were estimated to be 28% and 23%, respectively. Overall, the specific energy consumption of the second line was 34%, which agreed with the results presented in Fig. 9.

Table 3 - Annual average operational conditions of the second line.

	Air flow rate	Rotational speed of flow booster	Water depth	Estimated SAE
Units	Nm ³ /min	Rpm	m	kgO ₂ /kWh
	10.5	21.6	1.56	1.56

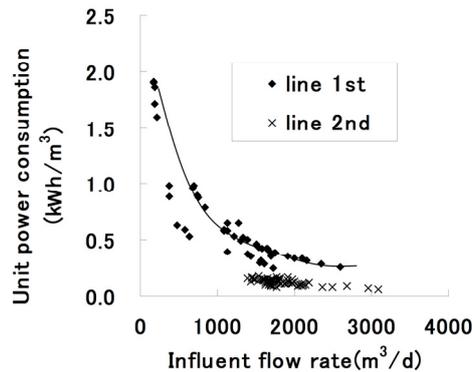


Fig. 9 - Comparison of unit power consumption between the first line and the second line.

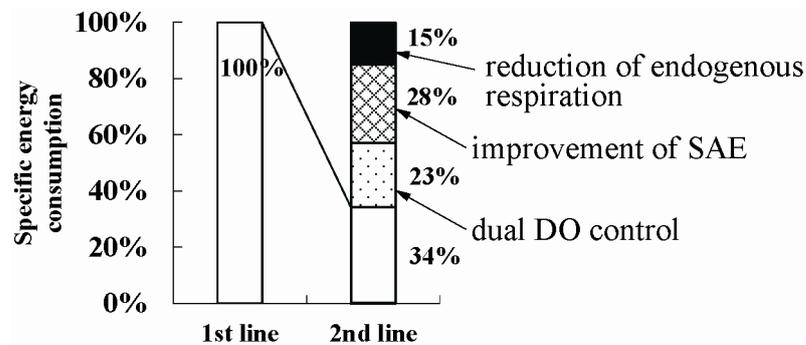


Fig. 10 - Energy saving analysis.

CONCLUSIONS

The energy efficiency of a full-scale OD with dual DO control technology was evaluated through clean water tests and process operation. Clean water tests demonstrated that an SAE of 1.4 - 2.1 kgO₂/kWh, which was higher than that of previously reported values, was obtained for the full-scale OD equipped with vertical flow boosters, membrane diffusers and blowers. The calculated SAE varied with the flow velocity and the aeration flow rate, and the proper range of the operational conditions was determined using a contour map. During process operation, two thirds of the power consumption (166,000 kWh per year) was saved when compared with the existing OD system. This power savings occurred simultaneously with an extraordinary T-N removal efficiency of 94%. The results presented here demonstrate that this novel OD system can enable extraordinary nitrogen removal performance with very low energy consumption.

Acknowledgments: This study was a part of the joint research program of the Japan Sewage Works Agency (JSWA) entitled, “*Development of energy saving process of wastewater treatment - development of an efficient high-rate oxidation ditch using dual DO control technology.*” The study was conducted in cooperation with Kochi Prefecture and the City of Konan. A part of the study was financially supported by “The Kochi University President's Discretionary Grant”. We especially appreciate the support provided by Mr. K. Tanaka, Mr. N. T. Phong and Mr. T. Tsumuraya.

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