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An In-Situ Experiment on Oxygen Solubility of Micro-Bubble Aeration in A Eutrophic Dam-Reservoir

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ABSTRACT:
In a dam-reservoir with long hydraulic retention time, density field tends to be thermally stratified and the hypolimnion becomes anoxic due to eutrophication. In such anoxic water, nutrients, ionic metals, dissolved organic matters, etc. are significantly released and high amount of hydrogen sulfide and methane are also generated from sediments by biochemical reduction. In order to minimize such environmental hazards, oxygen needs to be artificially supplied into the hypolimnion with some aeration equipments. Micro bubble aeration is one of promising techniques to efficiently feed oxygen to the anoxic water. In this study an in-situ experiment on micro-bubble aeration was carried out in a eutrophic reservoir by using two types of aerator. The experiment was started early summer when the hypolimnion was completely anoxic and the reservoir was thermally stratified with a sharp thermocline. The aeration system was intermittently operated by monitoring dissolved oxygen so that DO concentration was kept in a suitable range of concentration. The aeration was continued until the reservoir being uniformly mixed by fall overturn. A field measurement of temperature, dissolved oxygen and water quality was performed during the experiment. Performance of the two types of aeration systems was examined by evaluating oxygen capacity transfer coefficients.

Keywords: Eutrophication, aeration, micro-bubbles, deoxygenation, purification

1. INTRODUCTION

A dam-reservoir with long hydraulic retention time frequently suffers from eutrophication, which brings various water quality troubles not only in reservoirs but also in river downstream. Algae blooming in photic zone and the resultant production of organic matters are the main causes of oxygen consumption especially in a layer below a thermocline, so-called a “hypolimnion”. Due to capping effects of thermocline, the hypolimnetic water is scarcely exchanged with the aerobic epilimnetic water and kept anoxic during the heating season. In such reductive environment, high concentration of nutrients, ionic metals, dissolved organic matters, etc. are released and high amount of hydrogen sulfide and methane are generated from sediments through biochemical reduction.

Hypolimnetic aeration is one of technical countermeasures against such water quality hazards. Although several aerator models are proposed and equipped in reservoirs so far (for example, Ashley, K. I., 1985, Ashley, K. I. et al., 1987, McQueen, D. J. et al., 1986, Moore, B. C. et al., 1996, and Smith, S. et al., 1975), most of them are to feed coarse air bubbles with diameter greater than several millimeters. Since high solubility of oxygen cannot be expected in these systems, a powerful aerator is required to feed a certain amount of oxygen.

Based on this background, the authors have developed a micro-bubble aerator in order to efficiently feed oxygen into the anoxic hypolimnion with minimum cost. Since the proposed system is able to generate very fine micro-bubbles with diameters ranging around 50-100μm, which provides high oxygen solubility and significant performance of water purification in several reservoirs. In order to furthermore develop higher performance with less power, two types of aerators were devised and an in-situ experiment of aeration was carried out to examine their performance. Behaviours of thermal stratification and water quality were observed by measuring water quality such as temperature, dissolved oxygen, redox potential, electric conductivity, iron, manganese, nitrogen and phosphorus. The anoxic water highly polluted with heavy metals and nutrients was very well purified by the proposed aeration system. In order to compare performance of the two systems, oxygen capacity transfer coefficients were evaluated from the observed data of dissolved oxygen. A strategy for water purification and water quality management is discussed as well.

Figure 1. Mitakara dam reservoir.

2. FIELD SITE

The experiment was performed in Mitakara Reservoir in Hyogo, Japan (Fig. 1). The catchment area is 1.21km^2, the dam is 35.1m high and the total storage capacity is 271,000m^3. The reservoir was used for flood control, irrigation and drinking water supply. Since the exchange rate defined by [annual total discharge]/[total storage capacity] rages between 2-5, the impounded water is thermally stratified with a well defined thermocline during spring to summer and the hypolimnetic water tends to be completely anoxic as shown in Fig. 2. Therefore, nutrients, manganese and iron are released and highly concentrated above the benthic layer.

3. AERATION SYSTEM

In order to minimize water quality troubles associated with deoxidation in the hypolimnion, an experiment on hypolimnetic aeration was carried out in 2007 by using a aeration system as shown in Fig. 6. A micro bubble generator, YJ-II (Enviro Vision Co. Ltd.), shown in Fig. 3 was equipped in a hypolimnion below the thermocline, where two-types of aeration system were devised. Micro-bubbles were generated by taking the anoxic water with discharge of Q_L=300 [l/min] by a pump and mixing

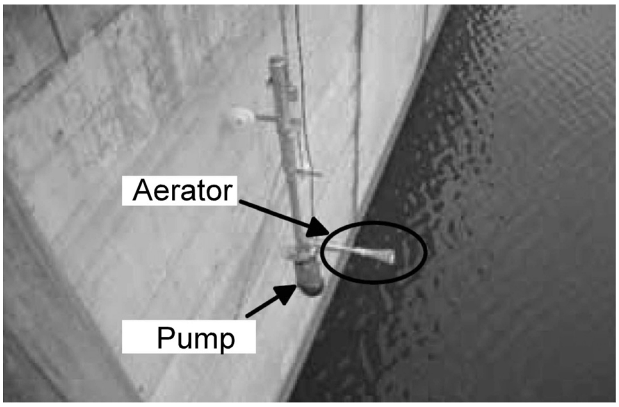


Figure 4. Aeration system (Test I).

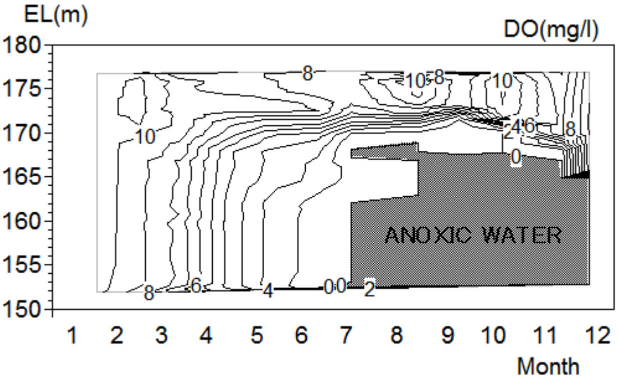


Figure 2. Dissolved oxygen concentration before the aeration (2003).

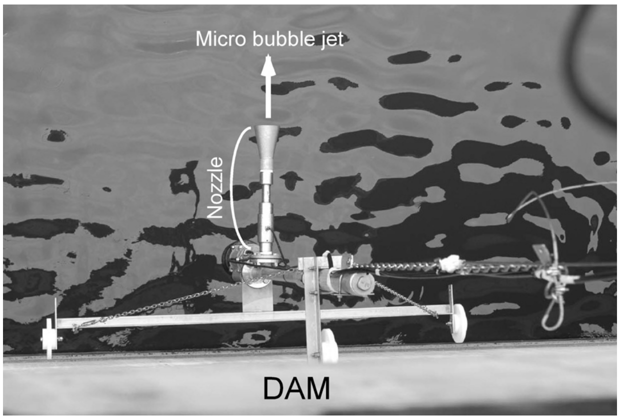


Figure 3. YJ-II micro bubble aerator.

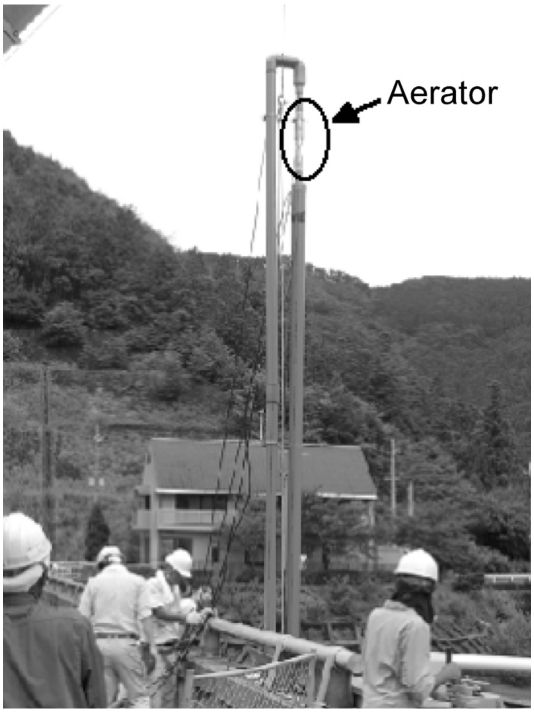
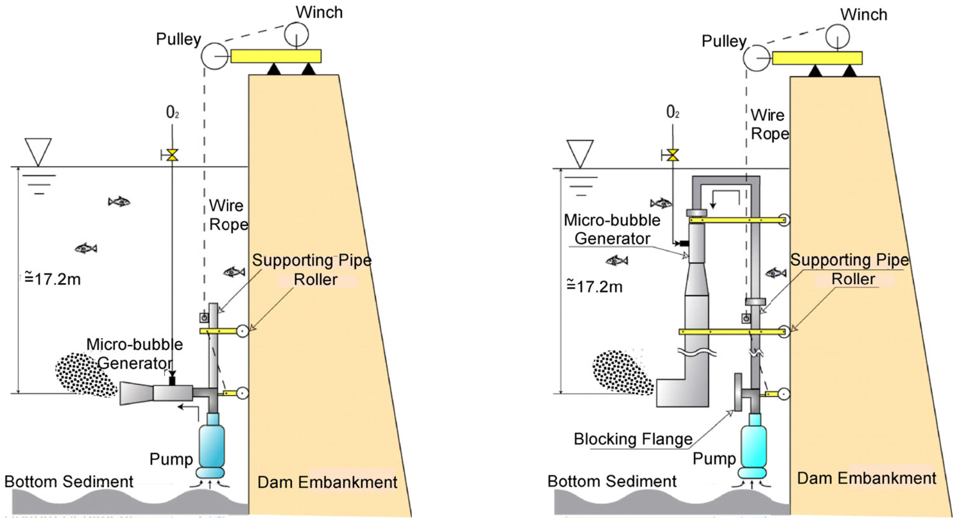


Figure 5. Aeration system (Test II).



(a) Test-I (b) Test-II

Figure 6. Schematic of the experimental aeration systems.

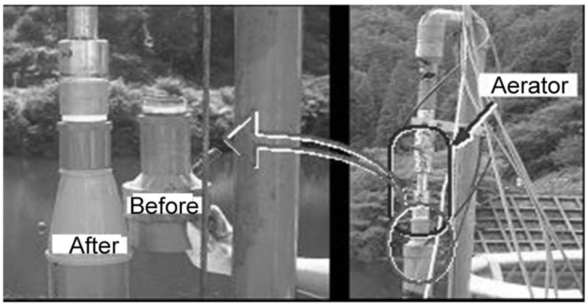


Figure 7. Replacement of rapid pipe contraction to gradual one (Test II).

it with oxygen that was supplied from a compressor. In this manner, liquid-oxygen multi-phase jet is flushed out to the ambient water from the nozzle. The intake and outlet are located 2.3m and 3.0m above the reservoir bed, respectively. Oxygen was used instead of natural air so that higher oxygen solubility could be obtained with less energy.

Test I is to directly discharge the micro-bubble jet to the ambient water. A system's configuration is viewed in Figs. 4 and 5. It has been running during 30th May to 24th July in 2007. Test II is to feed liquid-oxygen mixture that is produced by an aerator inserted in a pipe as shown in Fig. 6(b), which was conducted during 23rd August to 23rd October in 2007. The prototype can be seen in Fig. 5. Since distance between the generator and the nozzle outlet is longer in Test II than in Test I, more oxygen is expected to be dissolved in Test II during running through the confined pipe.

It was found from the authors' preliminary experiment that continuous operation of the present aeration system supplies so much DO that water tends to be oversaturated with DO. Therefore, the system was intermittently operated by monitoring DO concentration in the hypolimnion at 10:00 AM every morning. The aerator was switched on and off so as the DO concentration to be kept within a suitable range between 5~10mg/l both in Tests-I and II. Oxygen discharge was kept 0.6m^3/hr except during Term (3) of 0.4m^3/hr. The aeration was absent and a construction work was carried out for changing the system from Test I to Test II during 24th July and 23rd August. At the beginning of Test I, the bubble's diameter was a little larger than we expected and then the nozzle was exchanged to another model on 5th July in order to decrease bubble size. In Test II, micro-bubble was not well generated at first because the sudden pipe contraction connected to the aerator caused macro-bubbles. It was replaced to a gradual contraction as shown in Fig. 7. After then fine micro-bubbles were well generated.

Table 1. Operation schedule.

TEST	Term	Operation period	Discharge (m^3/hour)	Operated (days)	Absent (days)
TEST-I	(0)	5/30-6/1	0.6	2	12
	(1)	6/13-6/22	0.6	9	14
	(2)*	7/6-7/24	0.6	18	30
TEST-II	(3)	8/24-9/4	0.4	12	14
	(4)**	9/18-10/3	0.6	15	9
	(5)	10/12-10/23	0.6	11	

* Nozzle was exchanged to decrease bubble's diameter on July 5th.
** Pipe contraction was improved to gradual contraction on Sept. 18th.

The operation schedule is listed in Table 1. Twenty one times of water quality measurement was carried out during 16th May through 30th November. Vertical profiles of temperature, dissolved oxygen, electric conductivity, COD, etc., was measured at the deepest point about 15m distance from the aeration point.

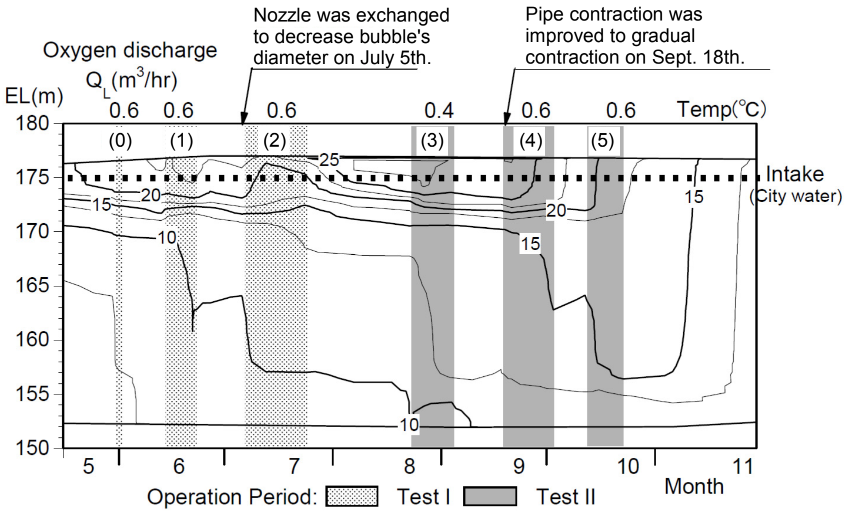


Figure 8. Seasonal variation of temperature profile.

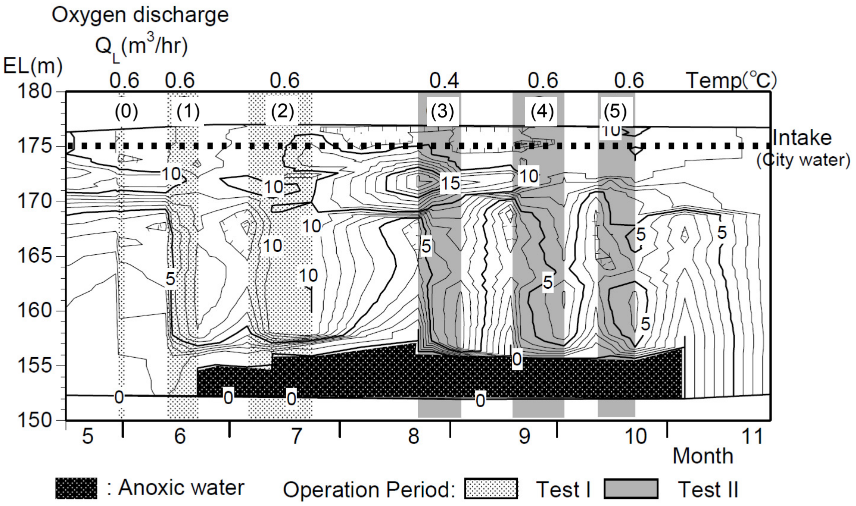


Figure 9. Seasonal variation of dissolved oxygen concentration.

4. TIME-DEPENDENCY OF WATER QUALITY

Temperature isopleths observed during the aeration is shown in Fig. 8. A sharp thermocline has already developed at El.172m on 16th May 2007 and a stable thermal stratification was kept until the fall overturning in late November. Shaded stripes with numbers correspond to periods during the system being operated and the rest of period is the duration of no aeration. Since the micro-bubble plume generates a weak turbulence, the epilimnetic water was entrained into the hypolimnion and temperature of the hypolimnetic water slightly increases during the system being operated. Despite the turbulence, full-depth scale vertical mixing has never occurred and the epilimnetic and hypolimnetic waters were well separated.

A time history of dissolved oxygen concentration is shown in Fig. 9. While hypolimnion was completely anoxic before starting the aeration, DO was tremendously recovered by the micro-bubble aeration. However, a little amount of bottom layer below El.156m was still kept anoxic, since only the water around EL.156m was withdrawn by the pump and the bottom layer lying below there was left without being entrained. The figure well documents that DO concentration increased during aeration especially in the layer between EL.156m~EL.169m, while it rapidly decreased when the aeration system was stopped. Most of DO consuming materials is organic matters, ammonia, ionic metals and other reductive components. It was confirmed that high amount of manganese was also removed as well due to oxidation, which is an advantage for water works.

In order to estimate how much DO was spent in hypolimnion, temporal change of DO concentration, $d[\mathrm{DO}]/dt$, during periods without aeration was computed from data provided by Fig. 9. Vertical profiles of $d[\mathrm{DO}]/dt$ in each duration are plotted in Fig. 10. When DO is produced, $d[\mathrm{DO}]/dt$ takes a positive value and vice versa. The data points are classified into three categories as shown in the figure. Group (A)

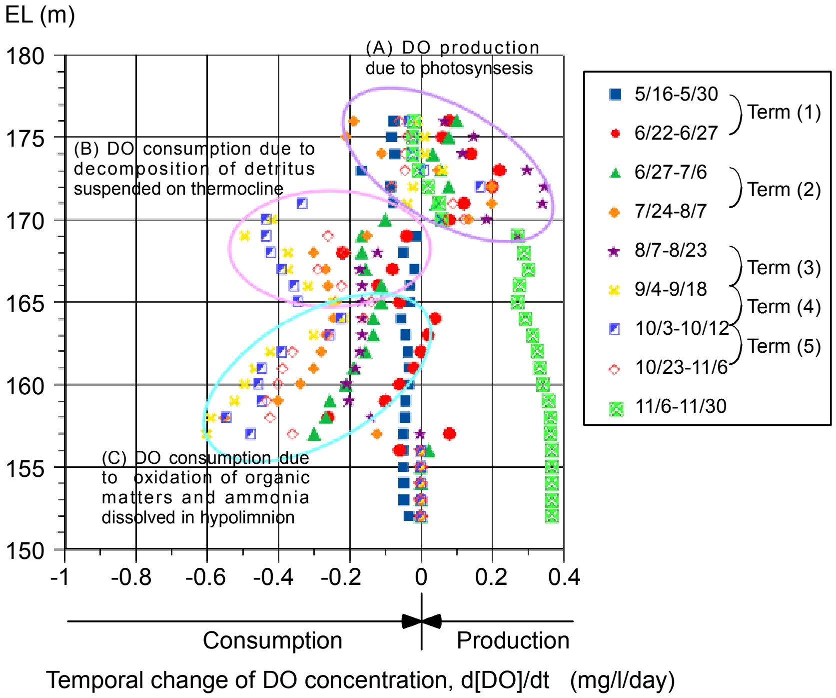


Figure 10. Increasing rate of DO concentration *d*[DO]/*dt* in mg/l/day.

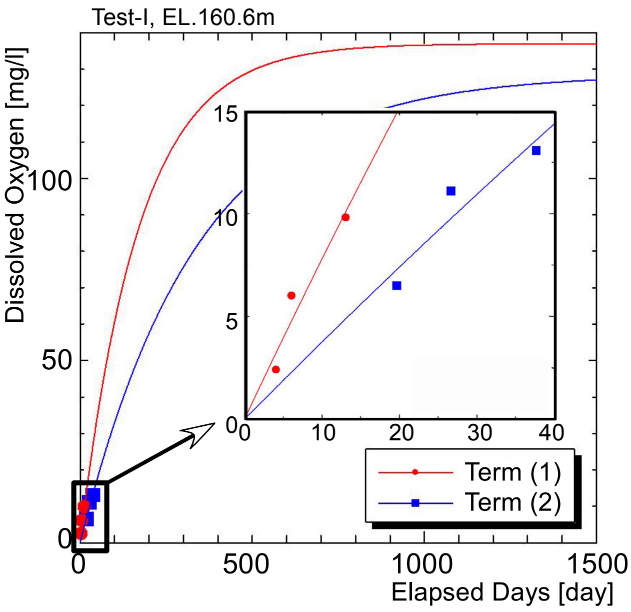


Figure 11. Plotting of dissolved oxygen concentration as a function of elapsed time compared with Eq. 2 for Test I.

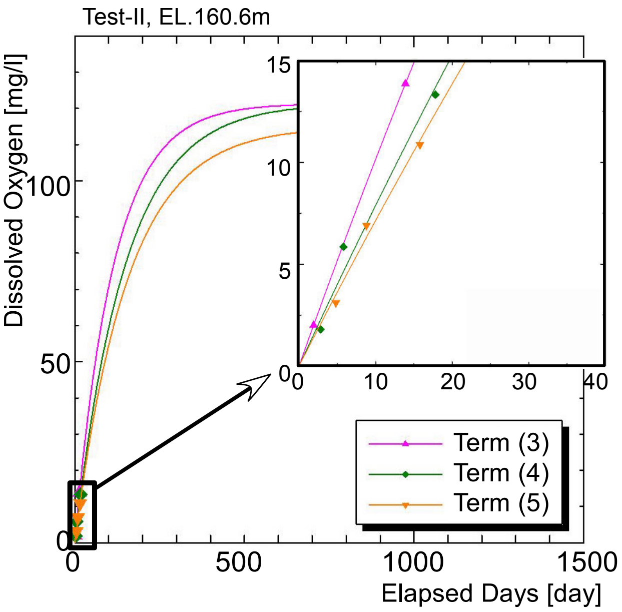


Figure 12. Plotting of dissolved oxygen concentration as a function of elapsed time compared with Eq.(2) for Test II.

corresponds to DO production due to algae photosynthesis in photic zone occurring above the thermocline. On the other hand, there is no DO source in the aphotic zone or in hypolimnion, where DO was always consumed. The data points plotted there consist of two groups, (B) and (C). The group (B) corresponds to DO consumption due to decomposition of detritus that is floated and highly concentrated on the thermocline. In the group (C), *d*[DO]/*dt* monotonically increases with depth. This suggests that DO is consumed by oxidation of reductive components such as metal ions, ammonia, dissolved organic matters, etc., which have a tendency to be more concentrated in deeper layer.

5. AERATION PERFORMANCE

DO solubility or aeration performance can be evaluated from the observed DO concentration. An increasing rate of DO is described by the following equation.

$$\frac{d[\mathrm{DO}]}{dt} = k_{\mathrm{L}a}\left([\mathrm{DO}^*] - [\mathrm{DO}]\right) \qquad (1)$$

where [DO] is DO concentration in mg/l, [DO*] is a saturation concentration for a given water temperature, k_{La} is an oxygen transfer capacity coefficient in sec^{-1} and t is time in second.

Integrating Eq. 1 with an initial condition that [DO]=0.0mg/l at $t=t_0$, a solution for time-dependency of DO concentration is obtained as follows.

$$[\mathrm{DO}] = [\mathrm{DO}^*]\left(1 - \exp\{-k_{\mathrm{L}a} \cdot (t - t_0)\}\right) \tag{2}$$

k_{La} is evaluated from the best fitting of observed time dependency of DO concentration to Eq. 2. In this manner, k_{La} is indentified in respect to each aeration duration for Tests I and II, respectively.

The elevation of monitoring DO concentration is EL.160.6m that is the middle layer of hypolimnion. The observed increasing behaviours of DO concentration during the Tests I and II are respectively compared with the solution in Fig. 11 and 12, respectively. It is recognized from the figures that DO measurements well agree with Eq. 2. As a result, k_{La} is identified as listed in Table 1, which shows that Test II gives higher oxygen transfer rate than Test I.

6. CONCLUDING REMARKS

In this study oxygen micro-bubble aeration was carried out in order to operate a high-performance aeration system with minimum energy. In the in-situ experiment in a dam-reservoir, two types of aerators were tested. Test I is to directly inject micro-bubbles to the hypolimnetic water and Test II is to feed the liquid-oxygen mixture that is produced by an aerator equipped in the pipe. Through measurements of thermal stratification and water quality, it was confirmed that the anoxic water polluted with heavy metals and nutrients was very well purified by the proposed aeration system. In order to compare performance of the two systems, oxygen capacity transfer coefficients were evaluated from the time-dependent DO concentration. Test II shows a better performance of oxygen transfer than Test I. It is expected that the present aeration system would be a powerful engineering tool as a countermeasure against water quality troubles.

Table 2. Oxygen transfer capacity coefficient $k_{\mathrm{L}a}$ at hydraulic pressure.

Q_{L}=300 [l/min]	Test I		Test II		
Period	(1)	(2)	(3)	(4)	(5)
Oxygen discharge Q_{G} [l/min]	10.0	10.0	6.7	10.0	10.0
$k_{\mathrm{L}}a \times 10^{-3}[\mathrm{sec}^{-1}]$	5.85	2.96	8.79	6.71	6.41

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