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Original Paper

Oxygen Transfer Characteristics of an Ejector Aeration System

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Abstract

The objective of this study was to investigate the oxygen transfer characteristics of an ejector aeration system. In order to evaluate the oxygen transfer performance of the ejector aeration system, a comparative experiment was conducted on a conventional blower aeration system. The effect of entrained air flow rate and aerating water temperature on the oxygen transfer efficiency was investigated. The dissolved oxygen concentration increased with increasing entrained air flow rate, but decreased with increasing aerating water temperature for two aeration systems. The volumetric mass transfer coefficient increased with increasing entrained air flow rate and with increasing aerating water temperature for both aeration systems. The average mass transfer coefficient for the ejector aeration system was about 20% and 42% higher than that of the blower aeration system within the experimental range of entrained air flow rates and aerating water temperatures.

Keywords: Ejector aeration system, Dissolved oxygen, Oxygen mass transfer, Aerating water, Entrained air

1. Introduction

Dissolved oxygen (DO) refers to the volume of oxygen that is contained in water, and is a major indicator of water quality. Oxygen is essential for the respiration of almost all life, including most marine and freshwater organisms. The survival of aquatic life depends on a sufficient level of oxygen dissolved in water. Unlike air, which is normally about 21 percent oxygen, water contains only a tiny fraction of dissolved oxygen. The amount of oxygen that can be held by the water depends on the water temperature, atmospheric pressure, and the amount of other substances dissolved in the water. Generally, oxygen is transferred across the air-water interface. Aeration is the process by which air is mixed with or dissolved in water. This process may be accomplished in natural and in artificially constructed water reservoirs. Aeration is a very important factor in many chemical and biological processes. For example, wastewater treatment is one process that requires optimized aeration to sustain the growth of microorganisms responsible for biodegrading organic contaminants [1].

Oxygen is often supplied by means of air or pure oxygen bubbles introduced to the water to create additional air-water interfaces. Oxygen transfer, the process by which oxygen is transferred from the gas phase to the liquid phase, is of primary importance in a number of wastewater treatment processes. Activated sludge process shown in Fig. 1, is a biochemical process for treating wastewater that uses oxygen and microorganisms to biologically oxidize organic pollutants, producing a waste sludge containing the oxidized material. In general, an activated sludge process includes an aeration tank having multiple functions. It provides dissolved oxygen for microorganisms, mixes raw wastewater with the mixed liquor, and provides time for the biology of wastewater treatment to take place. The oxygen supply must be sufficient to maintain a minimum dissolved oxygen concentration in the aeration tank at all times. Because of the low solubility of oxygen and the consequent low rate of oxygen transfer, sufficient oxygen to meet the requirements of the process is not available through a normal surface air-water interface. Supplementary interfaces must be formed to transfer the adequate quantities of oxygen that are needed [2].

Many different types of aeration systems have been employed in the field, depending on specific treatment requirements. A conventional aeration system consists of an air compressor or blower, an air-distributing pipe network at the bottom of the aeration tank and diffusers mounted above the pipes. The diffuser is the most essential element of the aeration system and thus its design, dimensions and membrane pore size define to a great extent the efficiency of the aeration process with respect to dissolved oxygen [3, 4]. A conventional aeration system used in the activated sludge process consumes as much as 60-85% of the total power requirement of a modern wastewater treatment plant. Increased energy costs increase interest in aeration system design, optimization and control. Therefore, research is focused on the design and improvement of aeration systems - searching for new possibilities to provide high efficiency at the lowest possible expense [5, 6].

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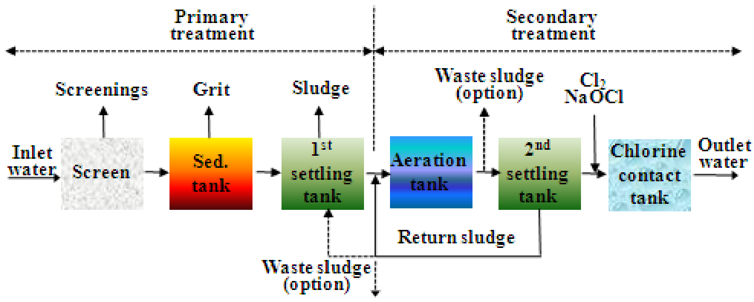

Fig. 1 Schematic chart of an activated sludge process

Ejector type gas-liquid aeration systems that use the kinetic energy of a high-velocity liquid jet to entrain and disperse the gas phase have attracted interest in recent years [7]. Ejectors use pressurized motive fluid to perform various tasks. The motive fluid, known as the primary fluid, is converted to a high-velocity, low-pressure stream by the primary nozzle. This creates a vacuum in a secondary inlet, pulling secondary fluid into combination with the primary flow [8, 9]. Mass transfer and hydrodynamic characteristics of ejectors using air or water as the motive fluid or the entrained fluid have been investigated experimentally and numerically by Balamurugan et al.[10, 11], Kim et al. [12] and Utomo et al. [13]. The effects of different operating conditions such as nozzle velocity, pressure drop, and ejector geometry parameters on the performance of ejectors have been experimentally investigated by several researchers [7, 14-18].

The oxygen transfer rate from air to water depends on factors such as aeration method, power input intensity, mixing intensity, temperature, aeration system geometry, and water conditions. Therefore, the development of new aeration systems for high-efficiency oxygen transfer at low operating costs is a very important issue. Although extensive investigations of oxygen transfer have been made for various aerators, there have not been many studies that compared oxygen transfer efficiency of conventional aeration systems and ejector aeration systems. The objective of this study was to investigate the oxygen transfer characteristics of an ejector aeration system. In order to evaluate the oxygen transfer performance of the ejector aeration system, a comparative experiment was conducted on a conventional blower aeration system. The effect of entrained air flow rate and aerating water temperature on the oxygen transfer rate was investigated.

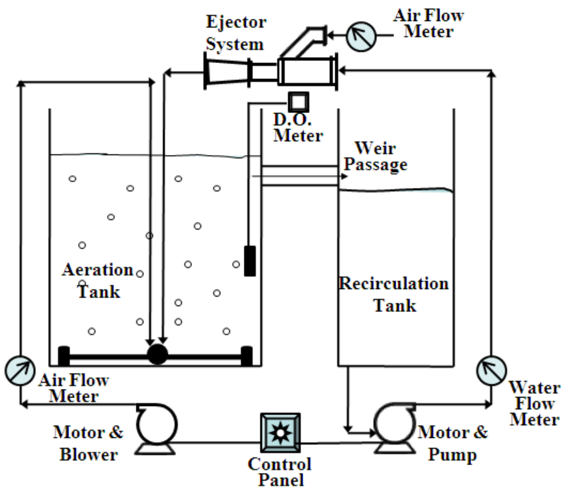

Fig. 2 Schematic diagram of experimental setup

2. Experimental Setup and Method

2.1 Experimental Setup

Experimental investigations were conducted using an apparatus as shown in Fig. 2. It consists of a gas-liquid ejector, an electric motor-pump, a motorized blower, a set of aeration and recirculation tank, a control panel, and other measuring and controlling accessories such as a dissolved oxygen (DO) meter, liquid and gas flow meters, pressure gauges, a thermometer, and control valves. An extended pipe diffuser with holes is installed at the bottom of the aeration tank. All experiments were carried out in a 1.46 m^3 (0.9 m wide × 1.8 m long × 0.9 m height) aeration tank and a 0.73 m^3 (0.9 m wide × 0.9 m long × 0.9 m height) recirculation tank. The water flow meter was used to measure the recirculation water flow rate. An air flow meter was used to measure the entrained air flow rate, Q_a, at the air suction inlet of the ejector, and the air flow rate at the blower outlet was measured by another air flow meter. The air entrainment rates of the ejector were adjusted by varying the recirculation water flow rate. Moreover, air entrainment rates of the blower line were adjusted for comparison with the gas-liquid ejector line. A schematic diagram of the gas-liquid ejector is shown in Fig. 3, and the dimensions of the ejector are given in Table 1. The inlet and outlet diameters of the ejector are 53 mm and 63 mm, the outlet diameter of the ejector nozzle is 16mm, the diameter of the air entrainment inlet is 48.5 mm, and the total length of the ejector is 865 mm.

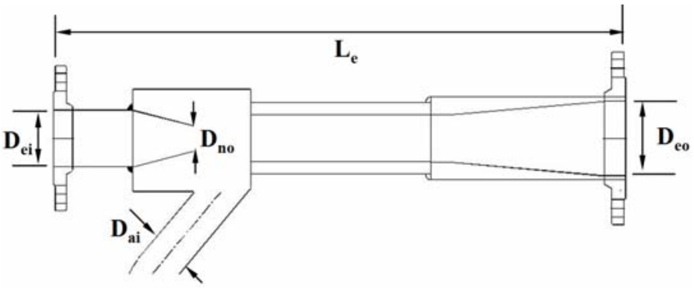

Fig. 3 Schematic diagram of gas-liquid ejector

Table 1 Dimensions of the ejector

Parameter	D_{ei}	D_{no}	D_{ai}	D_{eo}	L_e
Values[mm]	53	16	48.5	63	865

2.2 Experimental Method

There are many different methods for experimental determination of oxygen mass transfer coefficients. The clean water unsteady-state method, the ASCE standard method, is selected in this study. This method uses an unsteady-state re-aeration technique and is presently the most broadly accepted test procedure. The rate of oxygen mass transfer, i.e. from the gas (air bubbles) to the liquid phase (water) by an aeration system can be expressed as follows [2, 5, 19]:

$$\frac{dC_t}{dt} = K_L a \cdot (C_{st} - C_t) \quad (1)$$

where C_t is the dissolved oxygen concentration at time t, C_{st} is the saturated dissolved oxygen concentration, and $K_L a$ is the volumetric mass transfer coefficient for oxygen. Equation (1) can be readily integrated to yield the expression for C_t as a function of time. A nonlinear regression analysis is recommended by ASCE to fit eq. (2) to the experimental data using $K_L a$, C_{st} and C_0 as three adjustable parameters.

$$\ln \frac{C_{st} - C_t}{C_{st} - C_0} = -K_L a \cdot t \quad (2)$$

where C_0 is the initial dissolved oxygen concentration at time $t = 0$.

The experiment was initiated by removing the oxygen from a known volume of clean water by addition of sodium sulphite (Na_2SO_3) with a cobalt chloride ($CoCl_2$) catalyst. Afterwards the increase of oxygen level was recorded and the volumetric mass transfer coefficient could be determined. The total amount of sodium sulphite required for each test run was calculated based on the theoretical demand for sodium sulphite using eq. (3).

$$O_2 + 2Na_2SO_3 \rightarrow 2Na_2SO_4 \quad (3)$$

In this study, a continuous circulating aeration system was used to investigate oxygen transfer characteristics. The experimental parameters are given in Table 2. The Reynolds number and the temperature of the aerating water were varied from 5.71×10^3 to 1.034×10^4 and from 13 ℃ to 23.5 ℃. The dissolved oxygen concentration (C_t) was measured at 10-second time intervals for 6~8minutes with a DO meter (YSI model 5B). Table 3 shows the saturated dissolved oxygen concentrations with the temperature of pure water at standard atmospheric conditions [5].

Table 2 Experimental parameters

Parameter	Re	T_w[℃]	T_a[℃]	$V_w[m^3]$
Values	5,710~10,340	13~23.5	26.5	1.701

Table 3 Saturated dissolved oxygen concentrations

T_w[℃]	13.0	16.5	20.0	23.5
C_{st}[mg/L]	10.53	9.76	9.08	8.48

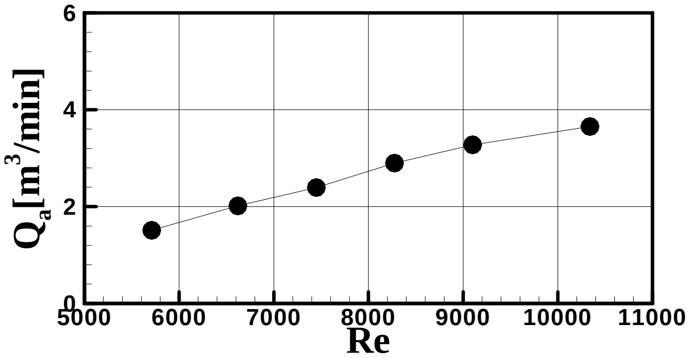

Fig. 4 Variation of entrained air flow rate with Reynolds number of the circulating water

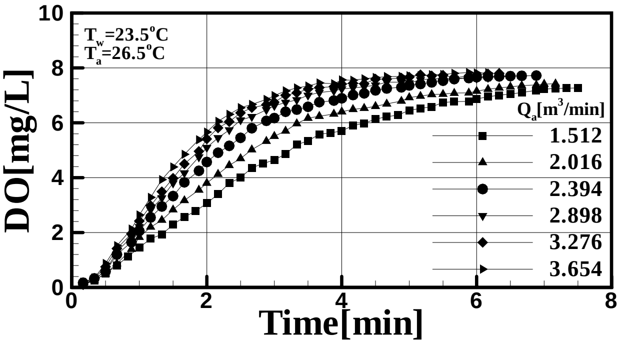

Fig. 5 DO at different entrained air flow rates for the ejector aeration system

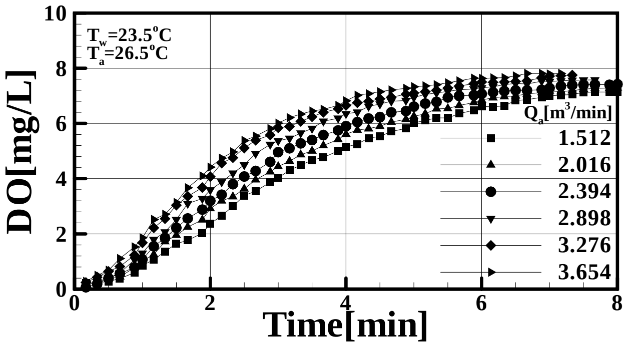

Fig. 6 DO at different entrained air flow rates for the blower aeration system

3. Results and Discussion

The experimental parameters of this study were entrained air flow rate and aerating water temperature. Figure 4 shows that the volume flow rate of the entrained air, Q_a, is increased by increasing the Reynolds number of the circulating water or the circulating water flow rate. This may be ascribed to the increased vacuum pressure in the suction chamber near the ejector nozzle outlet, as shown in Fig. 3. The range of the entrained air volume flow rate was 1.512～3.654 m^3/min.

Dissolved oxygen concentrations at six different entrained air flow rates but constant entrained air and aerating water temperature with re-aeration time are given in Figs. 5 and 6 for the ejector and blower aeration systems. The entrained air and aerating water temperatures were 23.5 ℃ and 26.5 ℃. As shown in Figs. 5 and 6, dissolved oxygen concentrations increased with re-aeration time and entrained air flow rate, and it took approximately 6~7 and 7~8 minutes re-aeration time to achieve saturation (or steady-state) for oxygen concentration. The increase of dissolved oxygen concentration with re-aeration time may be attributed to the longer persistence time of air bubbles in the aerating water. An increase in dissolved oxygen concentration with increasing entrained air flow rate may be ascribed to the increase of interfacial area between air bubbles and the aerating water. At the conditions of 1.512 and 3.654 m^3/min entrained air flow rates in the ejector aeration system, the dissolved oxygen concentrations were increased to 7.2 and 7.8 mg/L for about 7 and 6 minutes of re-aeration time, respectively. At the same conditions in the blower system, the steady-state values were 7.15 and 7.8 mg/L for about 8 and 7 minutes of re-aeration time, respectively. Therefore, on the average, the dissolved oxygen concentration increased by about 1.06 mg/L per minute in the ejector aeration system, whereas the corresponding value was about 1.02 mg/L per minute in the blower system. At the conditions of 1.512 and 3.654 m^3/min of entrained air flow rates, the average dissolved oxygen concentrations were 4.25 mg/L and 5.87 mg/L for 6 minutes of re-aeration time in the ejector aeration system, whereas the average values were 4.15 mg/L and 5.54 mg/L for 7 minutes of re-aeration time in the blower aeration system. Therefore, as the entrained air flow rate increased by about 147%, the dissolved oxygen concentrations increased only by about 38% and 33% in the ejector and blower aeration systems, respectively. This result may be due to the low solubility of oxygen in water and the slow speed of oxygen transfer compared to the entrained air flow rate.

Figures 7 and 8 show the percentage dissolved oxygen concentrations at the same conditions as Figs. 5 and 6. The percentage dissolved oxygen concentrations were calculated as the measured dissolved oxygen concentrations shown in Figs. 5 and 6 divided by the saturated dissolved oxygen concentration (C_{st}), 8.48 mg/L, as given in Table 3. Dissolved oxygen concentrations were measured at 10 second time intervals while the data used in Figs. 7 and 8 were selected at 30 second time intervals from Figs. 5 and 6. At all entrained air flow rate conditions, the maximum percentage dissolved oxygen concentrations were ranged from 85.6% to 92.2% and from 84.3% to 92% for 6~7 and 7~8 minute re-aeration times for the ejector and blower aeration systems, respectively. Therefore, at these experimental conditions, the blower aeration system needed about 1 minute more re-aeration time to reach steady-state dissolved oxygen concentration. This result may be attributed to longer persistence of air bubbles due to the reduced buoyancy force resulting from their smaller size, and the increased contact area between the smaller air bubbles and the aerating water in the ejector aeration system. Air that is entrained into water from the suction inlet of the ejector is forced downstream in the form of small air bubbles. The dissolution of oxygen into water is usually greater in systems with smaller air bubbles than in systems with larger air bubbles. This is because smaller air bubbles present a greater surface area to the aerating water than larger air bubbles. The persistence time of entrained air bubbles in the aerating water is an important parameter since it not only directly affects the gas phase residence time, but also is related to oxygen transfer efficiency.

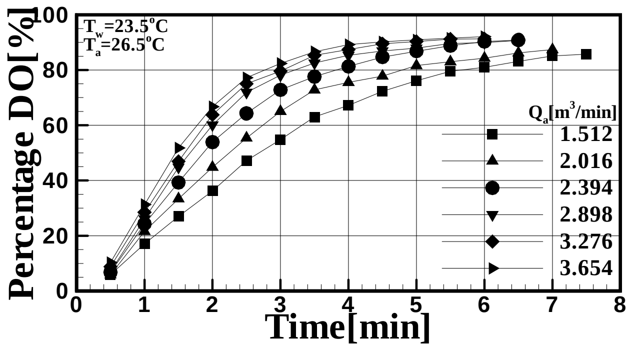

Fig. 7 Percentage DO at different entrained air flow rates for the ejector aeration system

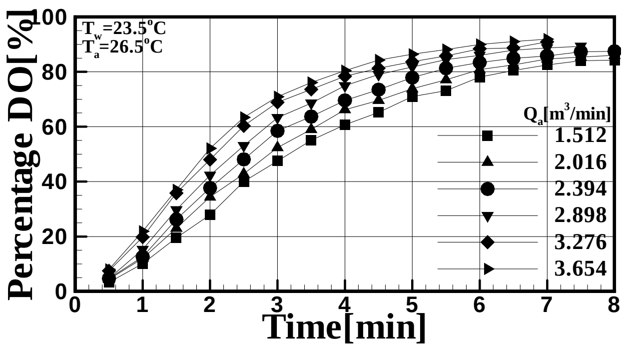

Fig. 8 Percentage DO at different entrained air flow rates for the blower aeration system

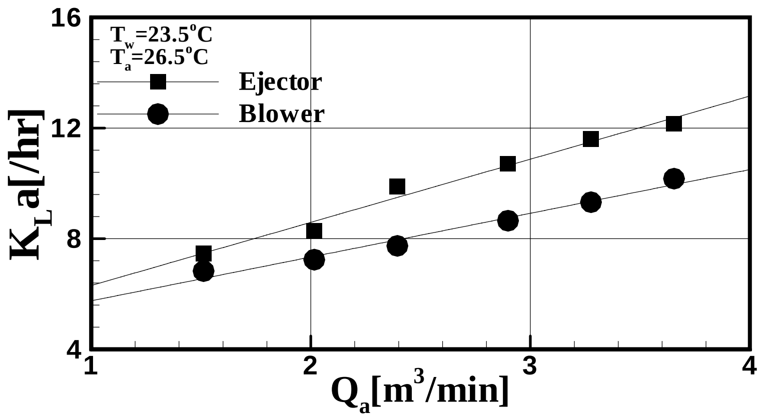

Fig. 9 Comparison of the oxygen transfer coefficients with entrained air flow rates

Figure 9 presents the calculated volumetric mass transfer coefficient derived from the experimental data of dissolved oxygen concentrations from Figs. 5 and 6. The oxygen volumetric mass transfer coefficients were calculated by eq. (2). The volumetric mass transfer coefficients increased with increasing entrained air flow rate. The result may be ascribed to the increase of contact between air bubbles and aerating water per re-aeration time. Under operating conditions of entrained air flow rate for the ejector aeration system, the minimum and maximum values were 7.46 hr^{-1} and 12.16 hr^{-1}. In contrast, the values were 6.84 hr^{-1} and 10.17 hr^{-1} for the blower aeration system. Comparing these data, it can be seen that the average mass transfer coefficient of the ejector aeration system was about 20 % higher than that of the blower aeration system.

Figures 10 and 11 show the dissolved oxygen concentrations at four different aerating water temperatures but constant entrained air flow rate and temperature with re-aeration time for the ejector and blower aeration systems. The entrained air flow rate and temperature were 2.394 m^3/min and 26.5℃, respectively. Dissolved oxygen concentrations decreased with increasing aerating water temperature for two aeration systems. This result is attributed to the larger removal rate of oxygen compared to the soluble rate of oxygen that results from the change of molecular structure and active motion of electrons in water molecules at higher water temperatures. It can be seen in Fig. 10 that at 13 ℃ and 23.5 ℃ in the ejector aeration system, the steady-state dissolved oxygen concentrations were 9.3 mg/L and 7.7 mg/L. In contrast, at the same conditions in the blower system, the steady-state values were 8.6 mg/L and 7.4 mg/L. Dissolved oxygen concentrations in the ejector and blower aeration systems decreased by about 0.15 mg/L and 0.12 mg/L per degree of increase in aerating water temperature, respectively. The results are lower than the decreasing rate of about 0.2mg/L per degree of increase in temperature at standard atmospheric conditions for pure water. The aerating water temperature is important because it not only determines the maximum oxygen solubility of the aerating water, but also directly influences the rate of oxygen transfer within the aerating water. Aerating water temperature is also a crucial factor in the metabolic rate of organisms, which affects nitrification, photosynthesis, and respiration. The metabolic rate increases with increasing aerating water temperature [20].

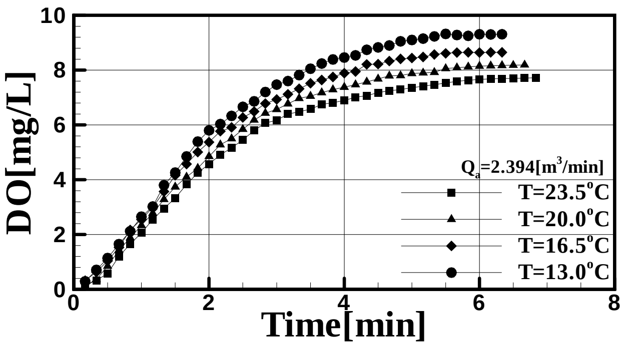

Fig. 10 DO at four aerating water temperatures for the ejector aeration system

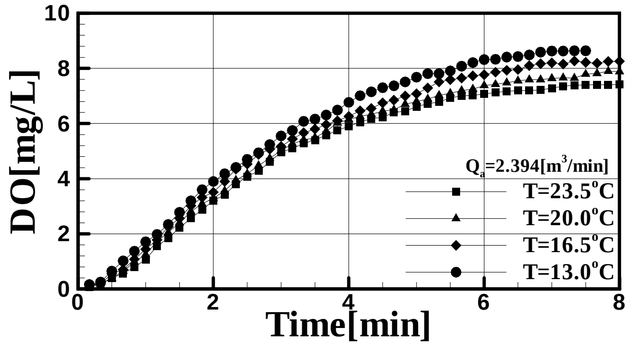

Fig. 11 DO at four aerating water temperatures for the blower aeration system

Figures 12 and 13 show the percentage dissolved oxygen concentrations at the same conditions as Figs. 10 and 11. These percentage dissolved oxygen concentrations were calculated as the measured dissolved oxygen concentrations shown in Figures 10 and 11 divided by the saturated dissolved oxygen concentrations, 10.53~8.48 mg/L, as given in Table 3. For all aerating water temperatures, maximum percentages of dissolved oxygen concentrations ranged from 88.4% to 90.3% and from 82.0% to 87.5% for 6~7 and 7~8 minutes of re-aeration times in the ejector and blower aeration system, respectively. At standard atmospheric conditions for pure water as given in Table 3, the oxygen saturation concentration decrease about 20% as temperature increases from 13.5 ℃ to 23.5 ℃, whereas in this study, the steady-state oxygen concentration decreased about 17% and 14% at the same temperature range in the ejector and blower aeration system. An increasing temperature results in lower oxygen solubility due to the smaller driving force ($C_{st} - C_t$) and the decrease of persistence time of entrained air bubbles resulting from the increased buoyancy force. However, the diffusion rate of oxygen increases with increasing aerating water temperature, while the aerating water viscosity and surface tension decrease [21-23]. In general, these effects result in an increased oxygen mass transfer rate that might offset the lower oxygen solubility as shown in Figs. 12 and 13.

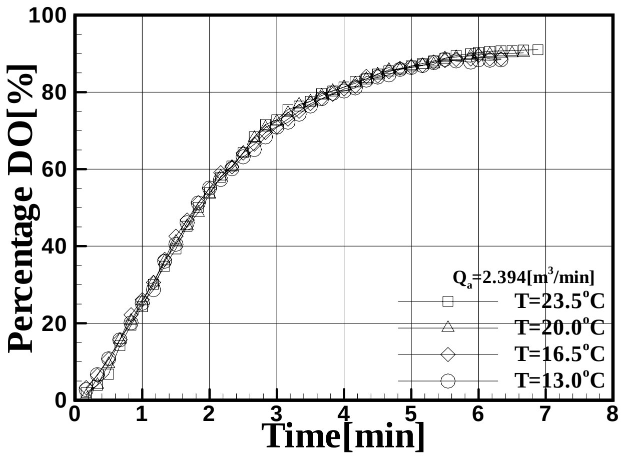

Fig. 12 Percentage DO at four aerating water temperatures for the ejector aeration system

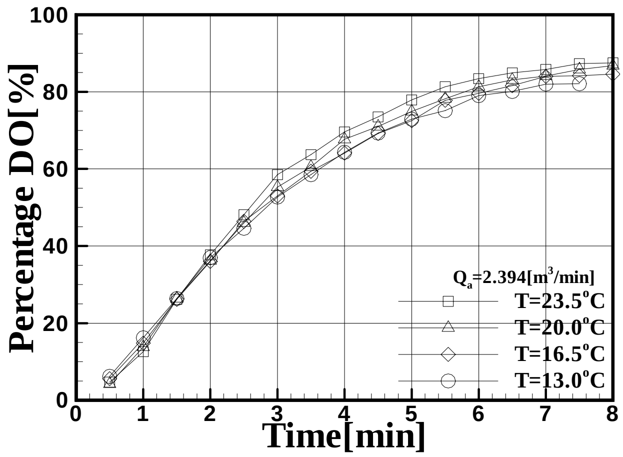

Fig. 13 Percentage DO at four aerating water temperatures for the blower aeration system

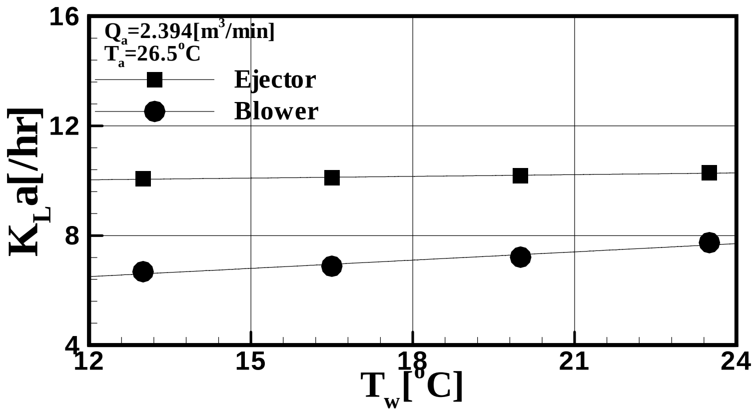

Fig. 14 Comparison of the oxygen transfer coefficients with aerating water temperatures

Figure 14 shows the calculated volumetric mass transfer coefficient derived from the experimental data of dissolved oxygen concentrations from Figs. 10 and 11. While the solubility of oxygen is inversely related to aerating water temperature, the volumetric mass transfer coefficients increased with increasing aerating water temperature. As is demonstrated in Figs. 12 and 13, the increased temperature leads to a higher diffusion rate and lower viscosity of the aerating water. This results in higher volumetric mass transfer coefficients, K_La, thus having a positive effect on oxygen transfer rates. Under operating conditions of aerating water temperature, the average mass transfer coefficient of the ejector aeration system is about 42% higher than that of the blower aeration system. However, from Fig. 14 it can be seen that the volumetric mass transfer coefficients remained nearly constant over the specified temperature range for the ejector aeration system and showed a slight increase for the blower aeration system. Therefore, it can be concluded that oxygen transfer rate is only slightly affected by aerating water temperature [22, 24].

4. Conclusion

Dissolved oxygen concentration and oxygen transfer performance of continuous circulating ejector and blower aeration systems were investigated at varying entrained air flow rates and aerating water temperatures. Dissolved oxygen concentrations increased with increasing entrained air flow rate, but decreased with increasing aerating water temperature for two aeration systems. The volumetric mass transfer coefficient increased with increasing entrained air flow rate and aerating water temperature for both systems. The average mass transfer coefficient for the ejector aeration system was about 20% and 42% higher than that of the blower aeration system within the experimental range of entrained air flow rates and aerating water temperatures. It can be concluded that oxygen transfer performance of the ejector aeration system is superior to that of the conventional blower aeration system.

Acknowledgments

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Nomenclature

C_0	Dissolved oxygen concentration at time zero [mg/L]	Q	Entrained air flow rate [m^3/min]
C_{st}	Saturated dissolved oxygen concentration [mg/L]	Re	Reynolds number
C_t	Dissolved oxygen concentration at time t [mg/L]	T	Temperature [℃]
D	Diameter [mm]	t	Time [min]
DO	Dissolved oxygen	V	Volume [m^3]
K_La	Volumetric mass transfer coefficient		

Subscripts	
a	Entrained air
w	Aeration water

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