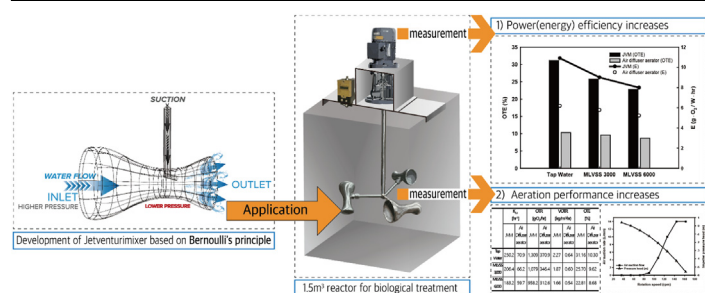


Research article

Application of jetventurimixer for developing low-energy-demand and highly efficient aeration process of wastewater treatment

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GRAPHICAL ABSTRACT



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ABSTRACT

In biological wastewater treatment, the oxygen supply in an aeration tank is the most important factor for removing organic pollutants, but it takes a large amount of electricity to generate the oxygen supply required. The Jetventurimixer (JVM) is a device that applies Bernoulli's principle, and the difference in flow rate pressure through the impeller is generated by the rotational force. Due to this physical mechanism, this device can supply oxygen in the atmosphere to the bioreactor without additional power. In this study, the JVM-based aeration process was developed for more efficient water treatment that demands lower energy. Parameters were measured for validating the efficiency and lower power demands, including the oxygen mass transfer characteristics and power efficiency. The results indicated that all parameters related to the oxygen mass transfer characteristics were advanced in performance by more than 200 % compared to those of the conventional air diffuser. In the case of power efficiency, it was confirmed that performance was 153–176 % higher. Therefore, it was confirmed that the JVM provides high-efficiency and low-energy benefits to the aeration process and, based on these advantages, the developed system seems to require further studies and validation for application to the water treatment system.

1. Introduction

A variety of biological, physical, and chemical technologies have been used for decades for wastewater treatment [1]. Biological treatment technology consists of activated sludge, membrane bioreactor, rotary

bioreactor, aerobic bioreactor, trickling filter, etc. [2]. The activated sludge process is a biological wastewater treatment method capable of removing organic pollutants and is the most widely employed wastewater treatment method today. Within a biological wastewater treatment and recycling system, the process of wastewater aeration is among the

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most important process for removing organic pollutants in wastewater [3]. This is because the supply of dissolved oxygen (DO) is essential to ensure the growth and maintenance of microorganisms necessary to decompose organic matter in wastewater [4]. Low concentrations of DO reduce the efficiency of wastewater treatment due to low growth rates of microorganisms (bacteria). Recently, as low-power, sustainable technology has emerged as an important issue in the field of wastewater treatment, there is a lot of interest in improving the power consumption of the existing water treatment technology that consumes a lot of energy for the aeration tank [5].

The main energy used in wastewater treatment is the electricity consumed to power the machinery [6]. In the biological treatment process, the air diffuser and blower account for more than 50 % of the total plant energy consumption [7]. Because the majority of operating costs is incurred from the aeration process alone, the most effective method for lowering operating costs is to improve the efficiency of the aerator [8, 9, 10]. An increase in the efficiency of the aeration device of the aeration tank is directly related to the saving of treatment plant maintenance costs. In general, in order to apply low-power, sustainable technology of the developed aeration device, the mass transfer coefficient (K_{La}), oxygen transfer rate (OTR), and oxygen transfer efficiency (OTE) are obtained as oxygen mass transfer characteristics, and power efficiency (E), also called standardized aeration efficiency, is obtained to evaluate the efficiency [11]. The oxygen mass transfer characteristics in the aeration tank can be affected by a number of hydrodynamic parameters, including gas flow rate, aeration tank capacity, and bubble size [12]. Currently, to reduce aeration cost and maximize nitrification efficiency, intermittent aeration, use of simulation software, Enhanced Biological Phosphorus Removal (EBPR) method development, modified paddlewheel, and superoxygenation systems are applied and used [13, 14, 15]. Understanding the factors influencing oxygen transport provides useful information about the applicability of the developed technology, energy efficiency, and nitrification process.

In this study, we developed a Jetventurimixer (JVM) that increase oxygen delivery and agitation while reducing energy consumption. As a result, the purpose of this study is to apply it to energy saving and biological wastewater treatment processes and to develop sustainable wastewater treatment technology. From the developed aeration system, the oxygen mass transfer characteristics including the power efficiency of the developed JVM and the air diffuser aerator generally used in aerobic tanks were compared and analyzed. Based on the results, we further discussed the findings, related advantages, prospect mechanisms, and limitations posed in this study.

2. Materials and methods

2.1. Reactor

The reactor used in the equipment is the same as the one shown in Figure 1 and is composed of a speed control motor, air pump, air flow meter, impeller, air pump nozzle, dissolved oxygen meter, flowmeter, etc. The measured size of reactor was $1.0 \times 1.0 \times 2.0$ m (Figure 1a). In the experiment, samples were supplied up to 1.5 m, and the effective volume was evaluated based on 1.5 m^3 . Inside the reactor, three venturi type impellers were positioned 1.5 m down. For increased air flow and bubble miniaturization, the diameter of the inflow area was 6 cm, the outflow area was 3.5 cm, and the impeller was angled at 45° (Figure 1b). The dissolved oxygen meter was positioned 1 m from the water surface of the reactor, measuring the dissolved oxygen concentration every 5 s. In all experiments, the JVM motor used 120 W and the air diffuser aerator was 60 W (Hiblow-Hp-60, Korea).

2.2. Measurement of oxygen mass transfer characteristics

To analyze the oxygen mass transfer characteristics in all experiments, DO, pH, and temperature were measured using a YSI meter (YSI-ProQuatro; YSI Incorporated, USA). In this study, the oxygen mass transfer characteristics for evaluating the efficiency of JVM and the air diffuser include K_{La} , OTR, volumetric oxygen transfer rate (VOTR), OTE, and E. Reliable computation has been a subject of extensive research in the past, and research has been conducted primarily with fresh water. Sodium sulfite (Na_2SO_3) and cobalt chloride (CoCl_2) were obtained from Sigma-Aldrich.

K_{La} is an important parameter for the design, operation, scale-up, and optimization of the reactor [16]. To evaluate K_{La} in the presence of Mixed liquor volatile suspended solids (MLVSS) 3000, 6000 mg/L, a comparative experiment with tap water was conducted, and the amount of change in dissolved oxygen with time was measured. In order to drop the DO level of the control experiment (tap water, DO 9.2 mg/L, 20°C) to 0.0, Na_2SO_3 and the catalyst additive CoCl_2 were added; in order to decrease the DO level by 1 mg/L, 7.9 mg/L of sodium sulfate was required, but the actual amount of sodium sulfate added to the water was between 10–20 % higher than the required amount. The catalyst cobalt chloride was added at a concentration of 8 mg/L. Once the DO concentration dropped to 0.0 mg/L, the impeller was used to facilitate airflow into the reactor. Depending on the rpm of the impeller, the DO, pH, and temperature of the water was measured, and afterwards, the oxygen transfer coefficient,

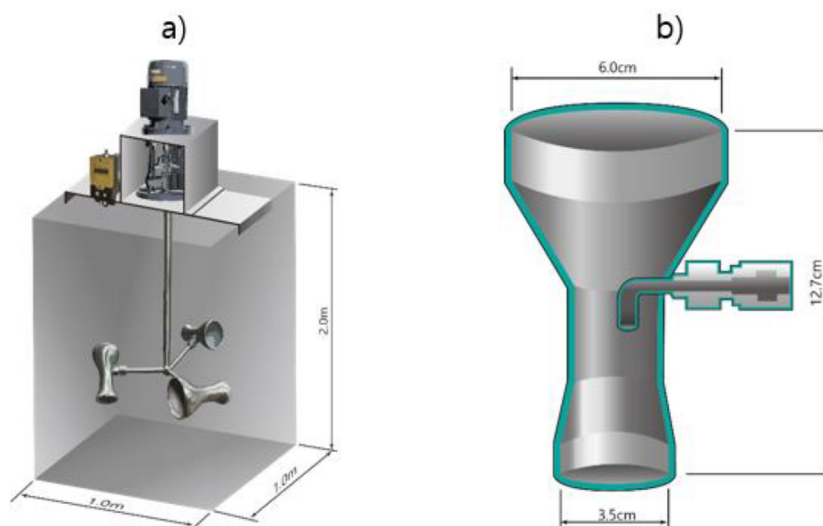


Figure 1. Reactor a) JVM installed inside activated sludge reactor b) venturi type impeller.

dissolved oxygen amount, oxygen transfer efficiency, etc. were calculated. The amount of sodium sulfite used in the experiment was determined by the following Eq. (1):



As one can see from the equation, one mole of sodium sulfite reacts with 0.5 mol of oxygen, and in order to remove the 9.2 mg/L of DO in the 1.5 m³ space, about 110 g of sodium sulfite was added. Of the water samples with 3000 and 6000 mg/L activation sludge concentrations, after 10 min of rest, the DO level was confirmed to have been aerated to 0.0 mg/L before the experiment began. In order to measure the oxygen transfer efficiency of the JVM, the parameters were set as shown in Table 1.

The experiment was conducted in batches, and the water source used for the samples in the experiment was 1.5 m³ of tap water and wastewater containing activated sludge. The sludge was extracted from water treatment site A in Yongin, Gyeonggi Province, and the research was carried out under three different MLVSS parameters of 0, 3000, and 6000 mg/L. The change in DO levels over time was expressed by multiplying K_{La} and the measured difference in DO levels, as shown in Eq. (2), and the graph was created with the integrated equation as shown in Eq. (3), with the slope of the graph being the mass transfer coefficient.

$$\frac{dc}{dt} = K_{La}(C_s - C) \quad (2)$$

$$-\ln\left(1 - \left(\frac{C}{C_s}\right)\right) = K_{La} \times t \quad (3)$$

Where K_{La} is the mass transfer coefficient (h⁻¹), C_s is the saturated dissolved oxygen concentration at 20 °C (mg/L), and C is the dissolved oxygen concentration over time (mg/L).

OTR refers to the amount of oxygen transferred to the aeration tank volume. In general, it is possible to evaluate the oxygen transfer performance of a system under standardized conditions for transferring oxygen from the gas phase to the liquid phase [17]. The OTR of the JVM and air diffuser aerator is expressed by the following Eq. (4):

$$OTR = K_{La}(20) \times C_s(20) \times V \quad (4)$$

Where OTR is the oxygen transfer rate at 20 °C (O₂-g/hr), $K_{La}(20)$ is the mass transfer coefficient at 20 °C (h⁻¹), $C_s(20)$ is the saturated dissolved oxygen concentration at 20 °C (mg/L), and V is the effective capacity of the reactor (L).

The VOTR was calculated to determine the oxygen transfer efficiency per unit volume, and the following Eq. (5):

$$VOTR = K_{La}(20) \times C_s(20) \times 10^{-3} \quad (5)$$

Where VOTR is the volumetric oxygen transfer rate (kg/m³-hr), $K_{La}(20)$ is the mass transfer coefficient at 20 °C (h⁻¹), and $C_s(20)$ is the saturated dissolved oxygen concentration at 20 °C (mg/L).

Table 1. Oxygen mass transfer characteristics test conditions.

Parameter		Unit	Conditions
Reactor	Total Volume	m ³	2.0
	Effective Volume	m ³	1.5
Sample	pH	-	7.5
	MLVSS	mg/L	0, 3,000, 6,000
	Temperature	°C	20
Motor, Aerator (Impeller)	Power Requirement	W	120, 60
	Installation impeller angle	degree	45
	Impeller rpm	Rpm/min	120

OTE is of paramount importance in the operation of activated sludge wastewater treatment processes [18]. OTE, as assessed for air transfer to sustain microbial respiration, is closely related to overall energy demand and subsequent sustainability of the process [19]. OTE is the percentage of supplied oxygen that actually enters the water [20]. To calculate OTE of the JVM and air diffuser aerator, the following Eq. (6):

$$OTE(\%) = \frac{OTR}{Q_{air}} \times 100 \quad (6)$$

Where OTE is the oxygen transfer efficiency at 20 °C (%), Q_{air} is amount of air supply to the aeration tank (N-m³/hr), and OTR is the oxygen transfer rate at 20 °C (O₂-g/hr).

2.3. Measurement of power efficiency

The air supply of the JVM and air diffuser aerator generally requires the power consumption of the air diffuser and the rotating motor. In order to estimate the power consumption, the equation as E to find the energy efficiency was used [21]. The power efficiency (E) in the reactor can be expressed according to the following Eq. (7):

$$E = \frac{OTR}{P} \quad (7)$$

Where E is the power efficiency (g-O₂/W-hr), OTR is the oxygen transfer rate at 20 °C (O₂-g/hr), and P is the power of the device (W).

2.4. Computational fluid dynamics (CFD) modelling visualization methods

CFD ANSYS (version 16, Ansys) for CFD modeling and its visualization. For the turbulence model, the realizable k-ε model, a two-equation model using the time-averaged Navier-Stokes equation, and the Reynolds stress model (RSM) with relatively high accuracy were used according to the calculation target and conditions. For rotational flow, LES (Large eddysimulation) technique using the spatially averaged Navier-Stokes equation was applied. Additionally, the multi reference frame (MRF) technique with excellent accuracy was used to simulate the fluid flow generated by the agitator, and the volume of fluid (VOF) was applied among various multiphase analysis techniques to analyze the fluid flow more accurately [22, 23].

3. Results and discussion

3.1. Air suction according to rotation speed and impeller pressure

The amount of air supplied by the JVM impeller changes according to rotation speed. When the rotation is sufficiently fast, the pressure head forms within the air supply pipe installed within the central shaft of the impeller, thereby intaking air from the atmosphere and supplying dissolved oxygen to the reactor. At an impeller rotation speed of 72 rpm, the pressure head of -0.54130 m began to form and air suction began, and at 120 rpm and above, the air suction rate increased to 10 L/min. At 162 rpm, the pressure head reached -5.58406 m, and the air suction rate was measured at 14 L/min. With these findings, it was concluded that the air intake rate could be altered by changing rotation speed (Figure 2).

The oxygen supply of the JVM is supplied by the velocity and pressure change of the fluid passing through the impeller according to Bernoulli's principle. When the fluid flows through the impeller and passes through the thin middle area, the flow rate increases and pressure decreases, thereby allowing air from outside to flow in. Through this principle, the JVM allows both agitation and oxygen to be supplied at the same time (Figure 3).

Surface aeration using kessner brushes or rotor aeration was used in biological treatment until the 1990s, but now, with the development of science and technology, aeration by means of blowers is widely used [24]. There have been studies applying venturi for aeration process and

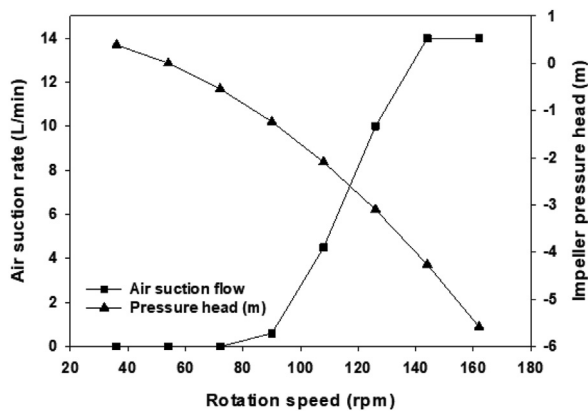


Figure 2. Air suction rate change according to impeller rotation speed and pressure head.

the studies has focused developing devices related to pipe and nozzle to increase aeration efficiency [25]. [26] studied the use of an aerator and venturi tube to increase the aeration efficiency by hydraulic pressure according to pipe diameter and pipe length. To the best of our knowledge, no study has been tried to apply Bernoulli's principle and JVM into aeration process. More importantly, this study additionally quantified the aeration efficiency and power consumption for the first time. The results of this study suggest that JVM provides high aeration and power efficiency to the waste water treatment that proves JVM's potential in the waste water treatment area.

This research means that air can be supplied according to rotational speed and pressure with only JVM, without the need for air supply, which normally uses a lot of power in biological treatment processes.

3.2. Comparison of a JVM-applied system performance with an air diffuser aerator system

The analysis values for K_{La} , OTR, VOTR, and OTE are presented in Table 2. All formulas were compared and evaluated between the JVM and air diffuser aerator, and three cases were analyzed for tap water, MLVSS 3,000, and 6,000 mg/L.

The evaluation of K_{La} of the JVM was carried out with the rotation speed of 120 rpm, and the measuring of tap water and wastewater with

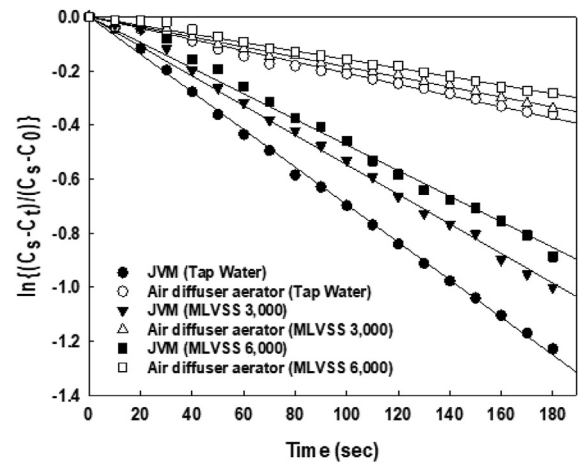


Figure 4. K_{La} measured from the different waste waters treated by the JVM and air diffuser aerator.

MLVSS values of 3,000 and 6,000 mg/L. Also, in order to relatively compare K_{La} with respect to the JVM, a control experiment in which an amount of 10 L/min of external air was supplied through an air diffuser aerator was simultaneously performed. Figure 4 shows the K_{La} of the JVM and the air diffuser aerator. The R^2 for all K_{La} experiments were identical as 0.99. Under the same parameters, K_{La} of the JVM was found to be roughly three times higher than the air diffuser aerator. Another study shows that the highest efficiency in the experiment was achieved when the stirring speed controlled a K_{La} value of 127.2 h^{-1} at 600 rpm [27]. However, high rotational speeds lead to high power consumption, which may not be economical for wastewater treatment applications [28]. Higher K_{La} values than previous studies at 120 rpm may consider application at lower rpm, thereby showing the usefulness of installing a JVM as the aerator of an activated sludge wastewater management system. A lower rpm is directly related to sustainable energy consumption with less electricity consumption.

The oxygen transfer coefficient with the JVM showed a 353 % difference with tap water, 312 % difference with 3,000 mg/L MLVSS wastewater, and a 307 % difference with 6,000 mg/L-1 MLVSS wastewater. One can conclude that the water microorganism concentration and coefficient difference have an inverse relationship. This is due to nitrifying microorganisms in the activated sludge continuously

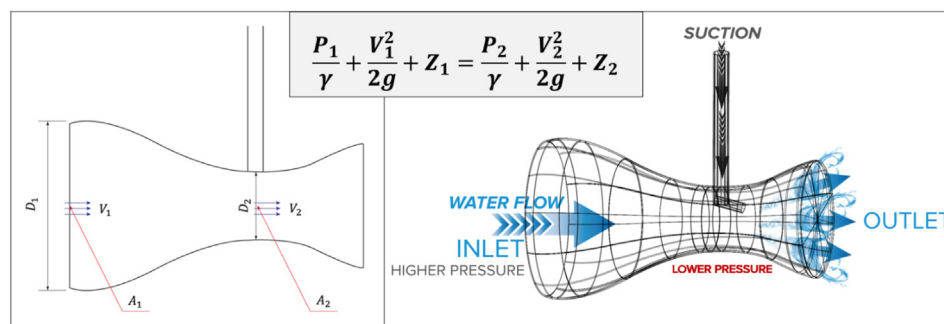


Figure 3. Schematic diagram of Bernoulli's principle and oxygen supply flow applied in this study.

Table 2. K_{La} , OTR, VOTR, and OTE comparison of the JVM and air diffuser aerator according to tap water and MLVSS (3,000 and 6,000 mg/L).

	K_{La} [h^{-1}]		OTR [$g-O_2/hr$]		VOTR [$kg/m^3 \cdot hr$]		OTE [%]	
	JVM	Air diffuser aerator	JVM	Air diffuser aerator	JVM	Air diffuser aerator	JVM	Air diffuser aerator
Tap Water	250.2	70.9	1,308.57	370.92	2.27	0.64	31.16	10.30
MLVSS 3,000	206.4	66.2	1,079.49	346.44	1.87	0.60	25.70	9.62
MLVSS 6,000	183.2	59.7	958.15	312.55	1.66	0.54	22.81	8.68

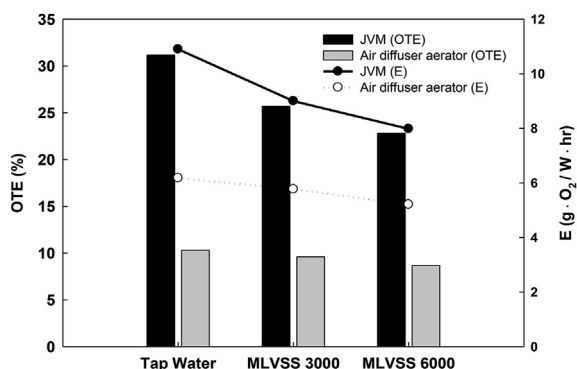


Figure 5. Changes in OTE and E of the JVM and air diffuser aerator according to tap water and MLVSS (3,000 and 6,000 mg/L).

consuming oxygen. The nitrification process is described by the following reaction equation: $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$; for 1 g of ammoniacal nitrogen that is reduced in the nitrification process, 4.57 g of oxygen and 7.14 g of alkalinity are consumed [29].

The changes in E and OTE for the JVM and air diffuser aerator are shown in Figure 5. In the case of power efficiency in the reactor to which the JVM is applied, it was confirmed that the efficiency was 176 %, 156 %, and 153 % higher compared to the air supply in tap water, MLVSS 3,000, and MLVSS 6,000 mg/L, respectively. In a study of the power

efficiency of a total of five aeration devices (venturi jet, scorpion jet, wavesurge, modified paddlewheel, commonly used paddle wheel), the modified paddlewheel showed the highest efficiency at 2.038 kg·O₂/Kw·hr [30]. In OTR, VOTR, and OTE, the JVM was evaluated to have about 200 % better oxygen mass transfer characteristics than the air diffuser aerator. In particular, JVM was 31.16, 25.70, and 22.81% in tap water, MLVSS 3000, and MLSS 6000 mg/L, respectively, and the highest is reported from activated sludge process water [31]. According to European Standard (UNE EN 12255-15, 2003), standard oxygen transfer efficiency (SOTE) is generally around 10 %. As the concentration of microorganisms increased, the oxygen transfer efficiency gap between the JVM and the air diffuser aerator gradually decreased. OTE and E had a positive correlation with each other ($R^2 = 0.9999$) [32]. have already shown a negative correlation between OTE and MLVSS concentrations, which is consistent with our results.

In conclusion, it was confirmed that the value of oxygen mass transfer characterization of the developed JVM was much better than that of the generally used air diffuser aerator. This means that in biological treatment processes that require sufficient dissolved oxygen concentration for nitrification, it can be highly effective with less power efficiency than conventional methods, indicating that it can be applied to biological treatment processes. Since the study was conducted in a single reaction tank (aeration tank) with an effective area of 1.5m³, further validation seems required to validate the performance of the developed aeration process in bigger scales. Further researches also need to determine

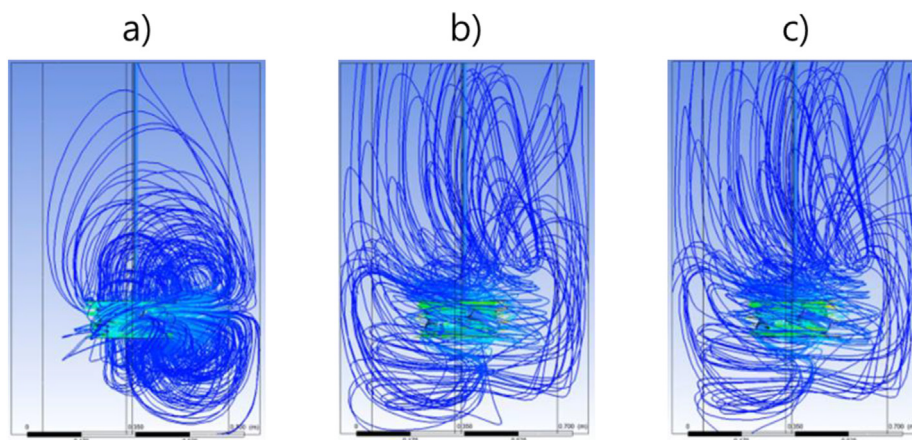


Figure 6. Agitation and fluid flow CFD modeling. (Blue line indicates agitation, fluid flow; Green line indicates impeller turning radius) a) Tap water b) MLVSS 3,000 c) MLVSS 6,000.

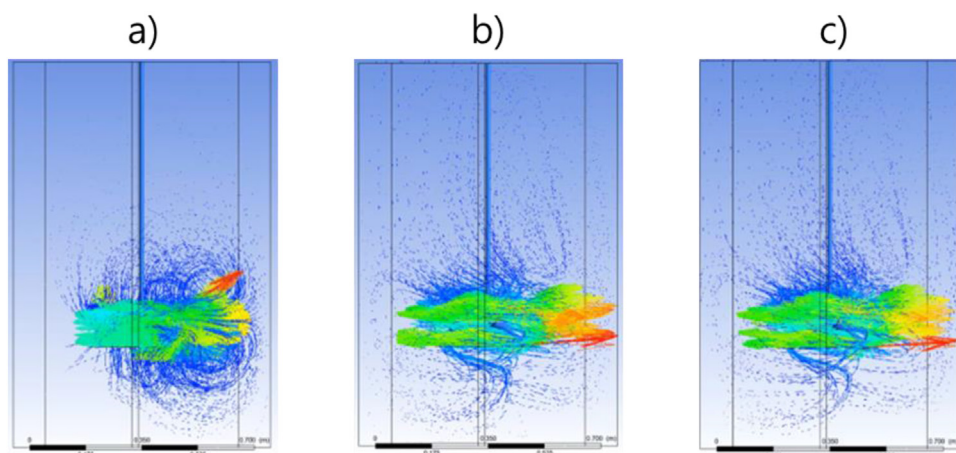


Figure 7. Oxygen distribution CFD Modelling a) Tap water b) MLVSS 3,000 c) MLVSS 6,000.

whether the newly developed aeration system can be applied to denser activated sludge concentrations higher than MLVSS 6000 mg/L.

3.3. Visualization of aeration performance to conditions of water using CFD modeling

CFD has been used as an advanced design and visualization tool in the development of new aeration devices [33]. Agitation and fluid flow CFD modeling results for tap water and MLVSS concentrations are shown in Figures 6a-6c. As a result of CFD modeling for tap water, smooth fluid flow and stirring ability were confirmed in the reactor to which the JVM was applied. Even when the MLVSS concentration was 3,000 and 6,000 mg/L, the fluid flow due to good stirring efficiency was confirmed. The density of activated sludge is at least five times higher than that of water, so the higher MLVSS can be attributed to the higher turbulent viscosity ratio [34].

The oxygen concentration distribution according to tap water and MLVSS concentration is shown in Figures 7a-7c. It was confirmed that a lot of oxygen was distributed near the impeller in the reactor in which fresh water and MLVSS (3,000 and 6,000 mg/L) were present. It can be seen that oxygen is supplied according to the fluid flow. This is considered to be because oxygen in the atmosphere flows into the central part of the impeller due to the flow velocity and pressure difference according to Bernoulli's principle. Even when the MLVSS concentration was 3,000 and 6,000 mg/L, it was confirmed that oxygen introduced near the impeller started with a high concentration and that oxygen could be distributed more widely in the reactor according to the flow of the fluid.

4. Conclusions

The oxygen mass transfer characteristics were studied for a JVM that can simultaneously supply and stir oxygen without injecting external air by applying Bernoulli's principle. The investigation was conducted focusing on K_{La} , OTR, VOTR, OTE, and E analysis, which are oxygen mass transfer characteristics, by comparing the developed JVM with air supply. It showed that the efficiency was more than three times superior in all items except power efficiency, and power efficiency was also excellent economically by showing that it was 153–176 % more efficient than the air diffuser aerator. It was confirmed that the JVM is a device that can increase the agitation and oxygen delivery power in the bioreactor where active microorganisms are present. As a result of checking the agitation, fluid flow, and oxygen distribution conditions in the reactor by applying CFD modeling, it was confirmed that not only fresh water but also agitation was better as the MLVSS increased. It was confirmed that oxygen introduced due to the pressure difference was also widely distributed throughout the reactor. Therefore, the oxygen mass transfer characteristics of K_{La} , OTR, VOTR, OTE, and E were evaluated higher than the air supply and previous studies, confirming the applicability of the wastewater biological treatment system.

Declarations

Author contribution statement

Byeongwook Choi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Tae-Yong Jeong; Sungjong Lee: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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