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Wave generation in subsurface aeration system: a new approach to enhance mixing in aeration tank in wastewater treatment

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ABSTRACT

Energy crises in the early 1970's created awareness of the cost of wastewater treatment and the energy required for each stage. Aeration process was the focal point of energy saving research, due to its high power consumption, which led to change the use of coarse bubble aeration system to fine bubble aeration. Until now, all commercially existing aeration systems use continuous airflow. Meanwhile, the system investigated in this paper uses pulsation flow to reduce energy consumption in aeration tank by improving oxygen transfer efficiency (OTE). In this study, a new innovative air injection method is proposed to improve OTE in the aeration basin without extra power depletion. The suggested method is simply to inject air alternatingly from two adjacent diffusers into the aeration system. It was found that OTE was improved using this method. This improvement could be attributed to water agitation caused by transient condition operation. Timing the separation between two injections is a very important aspect of the proposed system. The optimum separation time was found by varying the timing between these injections. The highest OTE was obtained at a separation time of 1.5 s and a volumetric flow rate of 42 LPM with a 57.1% enhancement in comparison to the steady state traditional aeration system.

Keywords: Aeration; Wastewater treatment

1. Introduction

Wastewater is defined as any water that is affected by anthropogenic influence. On a daily basis, the industrial facilities byproducts, ground infiltration, stormwater polluted water and municipal discharges are all causes of wastewater generation. Wastewater treatment involves three main stages: primary, secondary and final treatment. Wastewater aeration, the introduction of air to water, then takes place in the secondary stage of the remediation process [1].

Aeration is a substantial process for the wastewater treatment to maintain an aerobic environment for micro-organisms to grow and digest the suspended and dissolved organic matter. It also provides a gentle mixing in the tank keeping the micro-organisms in contact with organic matter, both suspended and dissolved. These two purposes are the critical roles of an aeration process. However, aeration depletes around 50–65% of the total energy consumed in activated sludge redemption process [2].

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Aeration mechanisms are classified into two main categories: diffused aeration (also called subsurface aeration) and mechanical aeration (also called surface aeration) [1]. In the subsurface aeration, air is provided from the bottom of the aeration tank in the shape of air bubbles. Depending on the bubble size, the system may classify into a fine or a coarse bubble diffuser system. Fine pore diffusion is a subsurface form of aeration in which air is introduced in the form of very small bubbles. It was the innovative solution to overcome the energy crises in the 1970's, as converting from coarse bubble to fine bubble increased the system's efficiency up to 50% [3].

In mechanical aeration, the water is agitated on the tank's surface in such a way that water interferes with the atmospheric air [2]. The oxygen mass transfer is achieved by shearing the water into small droplets and expelling it to the atmosphere using brush blades or propellers. Along with the mass transfer from exposing water droplets into the atmospheric air, mechanical aeration encourages the movement of fluid in the aeration tank for better mixing [4]. However, mechanical aeration has a low aeration efficiency (AE) because of the tremendous amount of energy consumed by the electrically driven blades [4]. Another method of aeration that has a similar mass transfer mechanism is the cascade aeration. This type of aeration is naturally happening in streams and waterfalls; where water is released from a height making it split into small droplets. Nowadays, cascade aeration is widely utilized in many wastewater treatment plants, since no power addition is needed.

As energy consumption has become a huge concern for aeration process since the 1970s, one solution to reduce energy demand is to mimic the cascade aeration to avoid any additional energy demand. This study introduces a new system to improve oxygen transfer by similar means. The new system agitates the water inside the aeration tank by injecting air alternatively from adjacent air diffusers. Also, air distribution inside the water is enhanced because the system is always run at a transient condition.

Colombet et al. [5] considered the liquid-side mass transfer coefficient *KLa*, for swarm high-density bubbles for a wide range of gas volume fractions. The study was performed for an air–water system in a square column. Bubble size, shape, and velocity were measured for different gas flow rates with a high-speed camera; the gas volume fraction and bubble velocity were measured using a dual-tip optical probe.

Sussman [6] introduced a method for computing growth and collapse of vapor bubbles using a coupled level set/volume-of-fluid method for computing growth and collapse of vapor bubbles. The liquid in this model was assumed incompressible and the vapor was assumed to have constant pressure in space. Second-order algorithms were used for finding "mass conserving" extension velocities, for discretizing the local interfacial curvature, and also for the discretization of the cell-centered projection step.

Several authors investigated mixing and flow pattern in aeration tanks. Levitsky et al. [7] studied the water oxygenation in an experimental aerator with different air/water interaction patterns. Authors have experimentally investigated a device for water saturation by gas using enhanced air–water. The process improved water oxygenation and reduced aeration expenses as compared with existing aerators this device was organized in a way to provide efficient gas dispersion into fine bubbles at relatively low gas and liquid supply pressures.

Chudoba [8] experimentally investigated the effect of mixing and hydraulic regimes on aeration tanks. Four different activated sludge systems, operating at the same detention period of 8 h and approximately at the same sludge loadings, were investigated with different flow patterns. These results agree with what Eckenfelder [9] found in industrial wastewater treatment. Eckenfelder found that oxygen transfer in wastewater treatment was usually accomplished by diffusion from air bubbles discharged from submerged orifices. In cases where high transfer rates are required, a turbine was employed to increase the turbulent mixing and the mass transfer rate. The rate of oxygen transfer is dependent on the nature of the diffusion device, the submergence depth, and the gas flow rate. Also, the chemical nature of the waste mixture affected the rate of oxygen diffusion.

Dani et al. [10] investigated methods to measure oxygen concentration in the liquid phase by developing a non-intrusive experimental technique. The chosen technique relies on digital image of water field that had a laser sheet and fluorescent dye to form a planar laser-induced fluorescence (PLIF) system. The principle of the oxygen concentration measurement rested on the fact that the oxygen molecules inhibit this fluorescence in proportion to their concentration. After calibration, analysis of the gray levels produced an image of the 2D field of oxygen concentration.

Alkhalidi and Amano [11] reviewed air bubble creation and the factors that affect it in a wastewater treatment system using both computational fluid dynamic and experimental techniques. Based on the results of this work, it was revealed that the bubble size depended on several factors such as flow rate, inlet pressure, and contact angle for the rubber membrane. Among these factors, it was observed that the flow rate had the largest effect on the bubble size followed by the membrane material contact angle. The punch size has a moderate effect on the bubble size, while the punch length and punch direction have a slight impact on the bubble size. Fine bubbles are desired to provide larger surface area and longer residence time that will improve the standard oxygen transfer.

Based on the literature review, authors have found that aeration process efficiency depends on several factors such as the air mass flow rate, depth of diffuser submergence, mixing the aeration tank, and the nature of the contents in the wastewater [9]. Dani et al. [10] found that air bubbles leave a trail of the oxygenated path behind it while it is traveling toward the top surface of the water. Because the air diffusers are commonly installed at the bottom of the aeration tank in a fixed location, all bubbles travel on the same path forming what was called in literature bubble column. Furthermore, Fick's law states that concentration difference is the driving force for mass transfer. These two facts led authors to conclude, that oxygen mass transfer from a bubble that travels on an oxygenated path by the bubble released before it will be less than the mass transfer from a similar bubble that travels on a new path that no bubble has traveled on it before.

In this work, the authors propose a solution to the low concentration difference problem by using pulsating airflow instead of continuous flow used in wastewater treatment industries. Furthermore, the proposed system will help agitate the water, which is expected to improve the efficiency with no additional power consumption for a turbine as Eckenfelder [9] suggested. Experimental setup used to examine the proposed system is described in the next section.

2. Experimental setup

The experimental setup consists of a 750-L tank equipped with three dissolved oxygen (DO) probes fixed on its top, mid, and bottom. These probes measure the DO concentration at aforementioned three levels with a frequency of 1 Hz (see Fig. 1). Additionally, the DO probes are capable of self-calibrating relying on the atmospheric pressure and the water temperature obtained by integrated sensors. Depending on the temperature and the pressure, the probes can determine the oxygen saturation concentration and then calculate the saturation percentage. A data acquisition device obtains the measurements from the DO probes to represent and save the data on a computer. To achieve an oscillating flow, two fine pores commercially used diffusers are fixed at the bottom of the tank to inject air alternatively from them. In other words, one of them is on, while the other is off.

Control system, shown in Fig. 2, was designed to control the flow for each diffuser in the aeration tank. The pulsation flow was achieved using two on/off solenoids allowing the generation of the on/off pattern described earlier. The two automated valves are controlled by digital signals from a microcontroller chip. The time between these signals is uploaded to the microcontroller to fully control the airflow pattern into the tank.

The data obtained from the three DO probes are analyzed to find the oxygen transfer efficiency (OTE), which is the main parameter of interest in this research. The investigation was done based on clean water oxygen transfer test. Clean water tests are based on removing the DO from water by adding sodium sulfite to clean water. The sodium sulfite amount was calculated based on the amount of DO in the water. The reaction for removing oxygen is:

$$2\mathrm{Na_2SO_3(aq)} + \mathrm{O_2(aq)} \xrightarrow{\text{cobalt}} 2\mathrm{Na_2SO_4(aq)} \tag{1}$$

The OTE shows the effectiveness of an aeration system in transferring oxygen to water. It is defined as the ratio of the oxygen transfer rate (OTR) to the mass flow rate of oxygen supplied to the system:

$$\mathrm{SOTE} = \frac{\mathrm{SOTR}}{\dot{W}_{\mathrm{O_2}}} \times 100\% \tag{2}$$

where OTR can be calculated using the two-film theory as follows:

$$\mathrm{SOTR} = KLa_{20}(C_\infty - C_0)V_\mathrm{w} \tag{3}$$

The oxygen-dissolved concentration (in mg/l) is monitored during the aeration process by DO probes at three different places: top, middle, and bottom, as previously shown. The obtained data were analyzed to find the volumetric mass transfer coefficient KLa, according to the following equation:

$$KLa = \ln\left(\frac{C_\infty - C}{C_\infty - C_0}\right)/t \tag{4}$$

The corrected KLa_{20} for a temperature of 20˚C is given by [12]:

$$KLa_{20} = KLa\theta^{(20-T)} \tag{5}$$

where θ is a constant equal to 1.024.

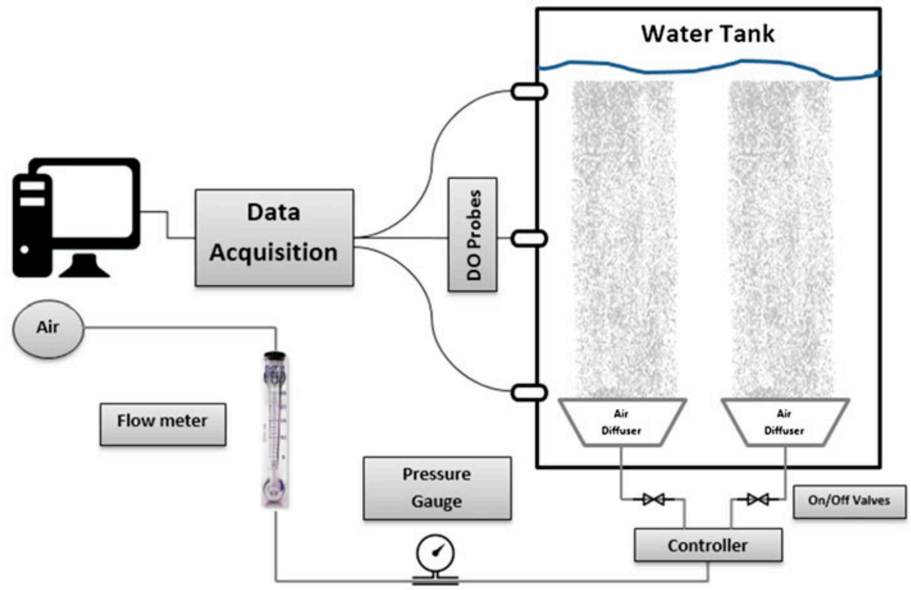


Fig. 1. DO measurement setup for real size aeration membranes.

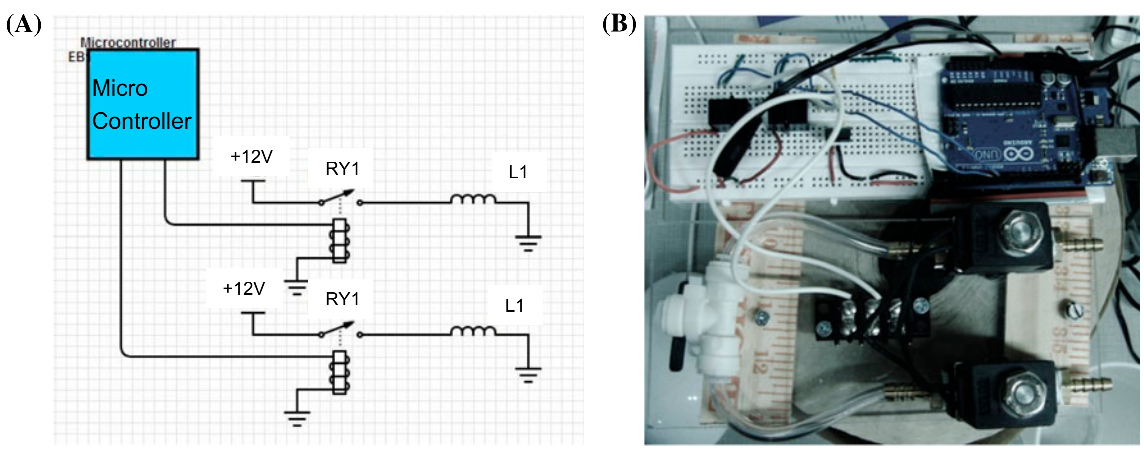


Fig. 2. (A) Circuit schematic diagram and (B) flow control circuit design layout.

The most important factor affecting the pulsating system is the timing between each air pulse. The system was tested under five different pulsating timings: 0.5, 1.0, 1.5, 2.0, and 2.5 s. The purpose was to identify the best separation time between the two successive pulses that results in the highest efficiency possible. The non-steady state aeration method is utilized to conduct the aeration testing in this study, as described in [11]. A total of 24 experiments were carried out to test the flow range of 14–56 LPM with a 14-LPM step at each separation timing and then compared to the steady state airflow condition. Reproducibility checks were done on three different days; results showed high reproducibility of SOTE in those experiments with average deviation around 4%.

3. Results and discussion

Results are presented in Fig. 3, Tables 1 and 2 show the improvement in SOTE caused by pulsation flow system.

The results tabulated in Table 2 show that the 1.5-s pulsating time at a flow rate of 42 (LPM) has the best improvement with an efficiency enhancement of up to 57.1% in comparison to the traditional system. The rest of pulsating time and flow rate showed

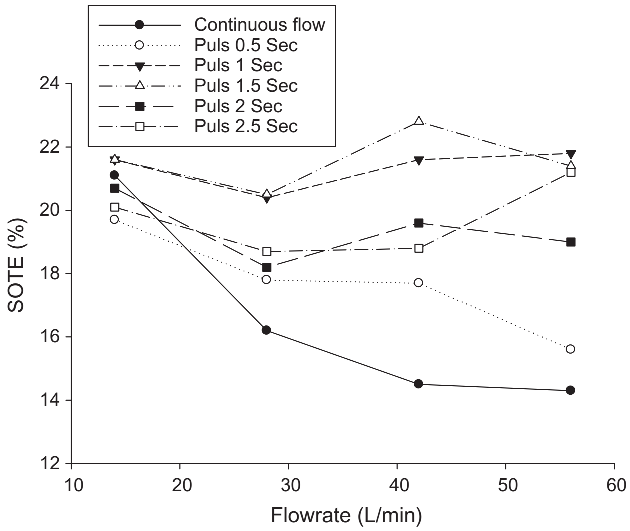


Fig. 3. Summarizes the averaged SOTE for the tested five timings.

improvement in most cases except the case of 14 LPM. The increase in SOTE for the 14 LPM case could be attributed to the fact that SOTE is highest at a very low flow rate. Improvement in SOTE by alternating air sequence imposes better distribution of air inside the water due to transient condition operation. Transient condition operation increases mixing inside the water tank, hence according to Eckenfelder [9], it is expected to increase the OTE. It must be noted that this increase did not require any additional devices such as turbines or mixers, so no additional power consumption. Fig. 4 shows the pulsating and the steady state bubble distribution inside the tank.

Through capturing the flow pattern using a high-speed camera, a wider bubble dispersion can be seen when using the proposed pulsating system, as more clearly depicted in Fig. 5, if compared to air bubbles dispersion in the steady state condition. This could be attributed to the fact that once the diffuser has started the bubble has to shove through almost stagnant water on the diffuser. Wider dispersion gives the bubble more resident time inside water that leads to a higher mass transfer.

Flow pattern inside the tank could be considered as another factor in improving SOTE. Chudoba [8] investigation showed that flow pattern has a strong effect on OTE. The developed flow pattern inside the aeration tank due to the pulsating system was investigated using Particle Image Velocimetry (PIV) to shed light on the factors that led to improvement in SOTE inside the tank.

Fig. 6 shows water velocity vectors in the pulsating flow system. It is worth mentioning that the high-velocity vectors had been filtered from this image to show the lateral movements in water aeration tank. The formed bubble column forces the water column on top of the other diffuser to shift away from the diffuser and a new low oxygenated water column forms on the top of the diffuser. This action will force the bubble to travel on a new low oxygenated path, which reduces the effect of bubbles traveling on the same oxygenated path by the bubble traveling before it. Recalling findings [10] of bubble traveling upward

Table 1
SOTE summary

Flow rate LPM	Regular OTE (%)	500 ms OTE (%)	1,000 ms OTE (%)	1,500 ms OTE (%)	2,000 ms OTE (%)	2,500 ms OTE (%)
14	21.1	19.7	21.6	21.6	20.7	20.1
28	16.2	17.8	20.4	20.5	18.2	18.7
42	14.5	17.7	21.6	22.8	19.6	18.8
56	14.3	15.6	21.8	21.4	19.0	21.2

Table 2
SOTE improvements percentage

Flow rate LPM	500 ms (%)	1,000 ms (%)	1,500 ms (%)	2,000 ms (%)	2,500 ms (%)
14	–	2.5	2.7	–	–
28	9.6	26.0	26.7	12.2	15.4
42	22.0	49.2	57.1	34.9	29.3
56	9.8	53.0	50.0	33.1	48.9

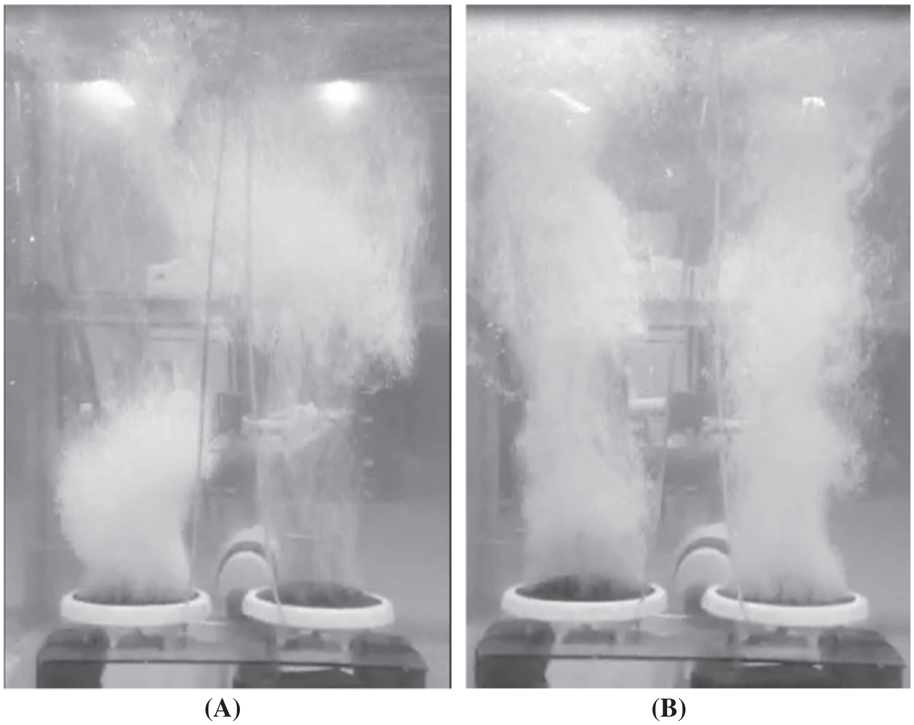


Fig. 4. Comparison between (A) pulsating flow and (B) steady state flow.

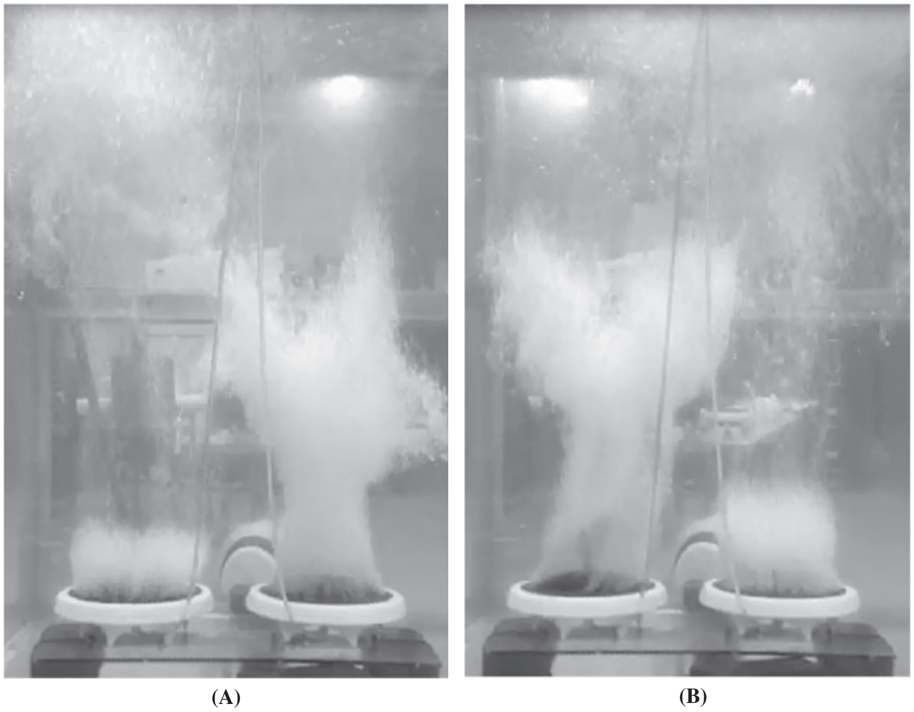
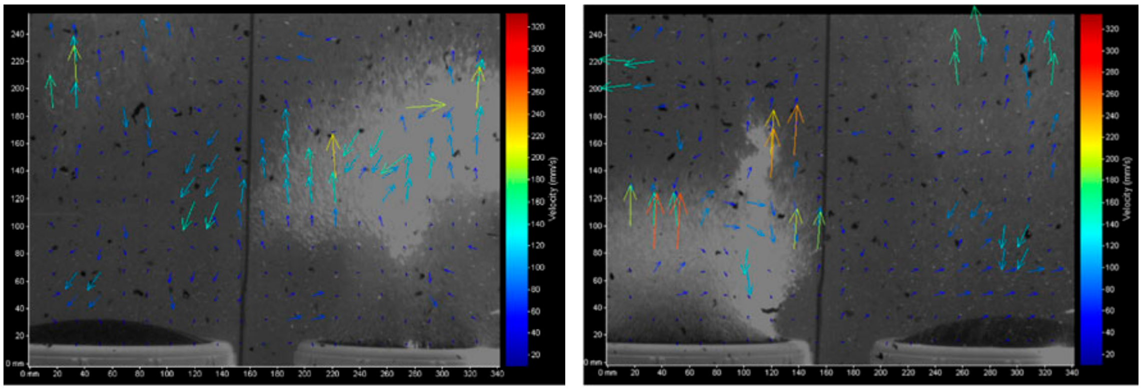


Fig. 5. On and off flow patterns (A) the right diffuser is on and the left is off, and (B) the left diffuser is on and the right is off.



(A) (B)

Fig. 6. Velocity vectors for pulsation flow system (A) the right diffuser is on and the left is off, and (B) the left diffuser is on and the right is off.

Table 3
Uncertainty in SOTE

Flow rate (LPM)	14	28	42	56
Uncertainty	0.047679	0.069057	0.079699	0.08333

leaves a high oxygenated path behind it and the fact that each bubble travels on the same path as the bubble ahead of it. The authors have found that changing the water column on top of the diffuser with a new low oxygenated column forces the bubble to travel on low oxygenated path. The new column increases the oxygen concentration difference between inside the bubble and outside. Based on literature review, concentration difference is considered as the driving force of mass transfer, so increasing the driving force will improve the mass transfer and therefore, SOTE. Uncertainty analysis had been done and the results are tabulated in Table 3.

4. Conclusion

The authors have proposed a new air injection approach called a pulsating system. This system operated by pumping air to two different air diffusers alternatively, i.e. one diffuser works, while the other stops for a particular time. It was observed that this system was able to achieve improvement in OTE up to 57% at a flow rate of 42 LPM and a separation time of 1.5 s.

The increase in oxygen transfer could be attributed to two factors. First, the proposed system agitates the water without adding any external power. This agitation improves the OTE. Second, it helps the air bubble travel through a low oxygenated path that increases the oxygen concentration difference between inside and outside the air bubble. The increase in oxygen concentration difference drives more oxygen to transfer from the air bubble to the water.

Nomenclature

AE	—	aeration efficiency
aq	—	aqueous
C	—	dissolved oxygen concentration at a certain time (mg/L)
C_A	—	species molar concentration (kmol/m^3)
C_0	—	dissolved oxygen concentration at time zero (mg/L)
C_∞	—	dissolved oxygen concentration at saturation (mg/L)
D_{AB}	—	binary diffusion coefficient (m^2/s)
DO	—	dissolved oxygen
KLa	—	volumetric mass transfer (h^{-1})
KLa_{20}	—	volumetric mass transfer (h^{-1}) at 20°C
LPM	—	liter per minute
N''_A		species molar flux (kmol/s m^2)
OTE	—	oxygen transfer efficiency (%)
PLIF	—	planar laser-induced fluorescence
SOTE	—	standard oxygen transfer efficiency (%)
SOTR	—	standard oxygen transfer rate (Kg/h)
t	—	time (s)
V_w	—	water volume (ml)
$\dot{W}_{O_2}$	—	oxygen mass transfer rate (KgO$_2$/s)

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