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Optimizing oxygen dissolution in water with microbubble flow

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ABSTRACT

Sustaining a specific level of oxygen in water is critical for aquatic organisms. Many factors can affect the dissolution process of oxygen and ultimately its required concentration. The influence of temperature, flow rate, pH, and turbidity on the oxygen gas content and its mass transfer coefficient through water in a micro-bubble column has been investigated. The tested temperatures were 7, 13, 16, 25, and 30 ± 1 °C, the flow rates of oxygen gas were 0.5, 1, and 1.5 L min⁻¹, the pH values were 4, 7, and 10, and turbidity of 0.2, 35, 65, and 95 NTU. Compressed air was bubbled into the distilled water column via a ceramic diffuser (Point Four microbubble diffuser) with the most frequent bubble size of 300-400 µm. The oxygen concentration was monitored online every 1 minute via an oxygen meter. The results demonstrate that the oxygen content increases with time at each temperature and its saturated concentration oscillates around 7 minutes of the oxygenation process. The greatest O₂ concentrations in pure water (0.2 NTU) measured at flow rate of 0.5 L min⁻¹ and pH 7 were 16.5, 15, 14.5, 12, and 11 ppm as corresponded with the particular related temperatures. Increasing the flow rate to 1 and 1.5 L min⁻¹ at constant temperature of 16 °C enhanced earlier saturation to only 4 min and increased the mass transfer coefficient ($K_{1,a}$) to 2.3 and $2.7 \times 10^{-2} s^{-1}$ respectively, comparing with 1.23×10^{-2} s⁻¹ at 0.5 L min⁻¹. However, the oxygen concentration at equilibrium was not considerably changed. The data of turbidity effect showed decreasing of dissolved oxygen and the $K_{1,2}$ by less than 10% after increasing turbidity to 95 NTU. Without generating micro-bubbles, the oxygen content of the pure water (0.2 NTU) was around 6 ppm and the K_{1a} of about 0.94 × 10⁻² s⁻¹ at 16 °C, pH 7, flow of 0.5 L min⁻¹, and turbidity 0.2 NTU, indicating the effectiveness of the micro-bubble flow scenario.

Keywords: microbubbles, bubble flow, oxygen dissolution, aerobic environment, oxygen transfer.

INTRODUCTION

With the absence of oxygen, water becomes invalid for the life of organisms. Waste disposal in water resources can affect oxygen degradation due to the interaction of microbes with wastes, consuming oxygen (Zhang et al., 2021). For the life of organisms, the concentration of the dissolved oxygen in water should not be less than 4 ppm (Patel and Vashi, 2015). Numerous treatment scenarios have been considered to improve water quality and control these global environmental issues. Several water treatment efforts substantially use air, oxygen, and ozone with the aid of the bubbly flow technique in its micro-bubble mode (Ryu et al., 2012; Sadatomi et al., 2012). In addition to the water treatment, the micro-bubbles approach has been efficiently employed in medical

therapeutic purposes such as genetic carriers and organ scanning. The selection of a particular gas mainly relies on the targeted application and the properties of the specific gas. For their antibacterial functions, micro-bubbles have been utilized in aerobic and/or anaerobic settings (Himuro et al., 2009). Aerobic environments require oxygen, while anaerobic ones do not (Michioku et al., 2006). Aerobic settings have distinct benefits over the anaerobic treatment due to their better nutrient removal efficacy (facilitating direct discharge into surface waters or disinfection) and not producing carbon dioxide, hydrogen sulfide, and methane (Himuro et al., 2009).

Due to their mass transfer functions, the bubbly flow has been industrially employed in environmental applications such as water treatment (Durán et al., 2016; Garcia-Ochoa and Gomez, 2009). Minimizing the diameters of bubbles allows a high ratio of surface area per unit volume, which enlarges the required interfacial area for mass transfer (Agarwal et al., 2011; Parmar and Majumder, 2013; Takahashi, 2005; Xiong et al., 2021). The generating of small bubbles (microbubbles) commonly occurs by mixers where the gaseous phase is introduced to a rotating flow and breaks into tiny bubbles (Kawahara et al., 2009; Li and Tsuge, 2006). Micro-bubbles of more than 100 microns (µm) are characterized for fluid physics phenomena (Xiong et al., 2021), which are commonly investigated to improve floatation techniques (Calgaroto et al., 2014, 2015; Etchepare et al., 2017; Rodrigues and Rubio, 2007; Rubio et al., 2002). However, their aeration properties have been studied only with narrow limitations (Liu et al., 2018; Muroyama et al., 2013; Terasaka et al., 2011). The majority of studies on the mass transfer coefficient of aerating streams with the aid of micro-bubble flow have been performed theoretically (Brenner, 1963; Figueroa-Espinoza and Legendre, 2010; Takemura and Yabe, 1998).

The last few years, coinciding with ecological concerns, have seen remarkable progress in studying the mass transfer coefficient of aerating gases (air, oxygen, and ozone) enhanced by the micro-bubble technique through dissolving these gases in water. The effect of different factors on the mass transfer coefficient of the dissolved gases including pH values of water and the flow rate of gas (Ratnawati et al., 2018), contaminants (Abadie et al., 2022), and salinity (Xu, 2022) were explored for different types of water. At a constant temperature of 28 ± 1 °C, the gas flow rate and pH of water affected the ozone concentration, and the highest value of the mass transfer coefficient $(K_{I_{2}})$ of 2.1 × 10–2 s⁻¹ was obtained at pH=4 and a gas flow rate of 4 L min⁻¹ (Ratnawati et al., 2018). Also, contaminating water with alcohol (Pentanol, C5H12O) reduced coalescence, which increased the specific interfacial area and ultimately decreased the mass transfer coefficient (Abadie et al., 2022). In the case of water-containing bacteria, the high salinity results in a low content of bacteria which is reflected as high dissolved oxygen in water. In the current work, the effect of pH, gas flow rate, temperature, and turbidity on the concentration of gas dissolved in pure water and its mass transfer coefficient is investigated using air as an aeration media with the assistance of the micro-bubble flow for a cost-effective and environmentally friendly aeration strategy.

MATERIALS AND METHOD

Material

The materials employed in the current work include analytical grade of hydrochloric acid (HCl 35–38% LR-grade, Thomas Baker) and sodium hydroxide (NaOH 0.1 M, Thomas Baker). These solutions were utilized without any treatment.

Method

The experiments involved using a bubble column (an acrylic vessel of 44 cm in length, 8 cm in width, and 30 cm in height with a wall thickness of 0.4 cm) fitted with a ceramic micro-porous diffuser (Point FourTM diffuser), with bubbling pressure of 1.7–2.4 bar at the base of the column. The column was equipped with an air generator/ compressor (Black/Decker BD 205/50, 8 bar and 2850 rpm/ P.R.C) and a flow meter (FLOWTECH Z-7002). Firstly, a specific volume of distilled water is introduced into a suitable container (via its open-top side) connected to a nitrogen cylinder. Nitrogen is delivered for 40 minutes to deoxygenate the water at the beginning of the experiments (Colombet et al., 2013; Muroyama et al., 2013). The deoxygenated water was then introduced into the column to a height of 20 cm. Next, the air was supplied to the column via the compressor with a constant pressure of 2 bar. After that, the bubbles were dispersed through the distributor and were monitored inside the water. The oxygen concentration was measured at a time interval of 1 min until the equilibrium was achieved where the concentration does not vary with time. The experimental setting of the current work is portrayed in Figure 1. To alternate the acidity of the water (pH values), the HCl and NaOH solutions were dropped carefully and the pH magnitude was measured via a pH-meter (LUTRON YK-21PH/ Taiwan) after an agitating time of 5 min. The practiced pH values were 4, 7, and 10. The oxygen concentration was measured by the O₂ meter (CRISON OXI-45P/EU). The effect of temperature on O2 concentration was studied. An electric thermocouple was employed as a heating source, while the cooling process occurred via a cooling system (HAAKE-EK12 220 V/Germany). The experimented temperatures were 7, 13, 16, 25, and 30 ± 1 °C. The turbidity of the solution was varied by using different amounts of natural kaolin with Nephelometric Turbidity Unit (NTU) values



Figure 1. Schematic diagram of the experimental setting

of 35, 65, and 95. The Turbidirct-Lovibond/Germany instrument facilitated the measurement of turbidity. The setting of the experimental work is sketched in Figure 1. Dissolving of oxygen in water without producing micro-bubbles (without the use of the diffuser) was separately performed on pure water for comparison at a constant temperature of 16°C, flow of 0.5 L min⁻¹, and pH 7. The maximum error of the experiments was in the range of about 4% measured by repeating an arbitrary test three times and calculating the error by the deviation from the average value.

Microbubble size measurement can be effectively conducted using the optical method with a setup consisting of several key components. Bubble size analysis using Point Four ceramic diffuser was conducted previously in another work (Abdulrazzaq, 2016). This diffuser generates microbubbles by dispersing air into the solution at a controlled rate of 1 L min⁻¹ with an operating air pressure of 2 bar. The system is set up in a glass rectangular tank ($21.5 \times 16 \times 30.5$ cm) filled with deionized water to create a stable medium for the bubbles. The process is illuminated by a 150W halogen lamp (Model no: HM-682 °C, Argos, UK) placed beside the camera to ensure clear visualization. A high-speed camera (Photron SA-3) captures the motion of the microbubbles at a rate of 2000 frames per second with a spatial resolution of 1024×1024 pixels, allowing for precise measurement and analysis of their sizes. The digital images are analyzed using digital image software (ImageJ).

Calculation of volumetric mass transfer coefficient

Based on the two-film theory, oxygen molecules should diffuse from the gas phase (gas bubble) to the bulk liquid via gas and liquid films (Solecki, 2015). Due to its low solubility in water, the oxygen concentration difference over liquid film is slightly small, and its absorption is slow. This hypothesizes that the resistance of oxygen transferring through the liquid film is much greater than in the gas film, which proposes that the mass transfer resistance of oxygen in the gas film can be negligible. The mathematical formula that defines the mass transfer of oxygen in liquid water can be described by Equation 1 (Ratnawati et al., 2018).

$$\frac{dC}{dt} = k_L a \left(C^* - C \right) \tag{1}$$

where: K_{La} is the oxygen volumetric mass transfer coefficient, C and C* are the oxygen concentration at time t and equilibrium conditions, respectively. Equation 1 can be integrated to obtain Equation 2.

$$\ln(1 - C/C^*) = -k_L a t$$
 (2)

RESULTS AND DISCUSSION

The parameters used in the practical segment to replicate the conditions of local river water (Tigris River) were chosen.

Effect of temperature on the oxygen concentration

The influence of temperature on the concentration of the dissolved oxygen in water is depicted in Figure 2. The selected temperatures were 7, 13, 25, and 30 °C at a constant pH value of 7 and flow rate of 0.5 L min⁻¹.

It is obvious from Figure 2 that the concentration of dissolved oxygen is highly influenced by temperature. At a specific temperature, the dissolved oxygen sharply increases at the beginning of the dissolution process monitored after only 1 minute. Later, it slightly increases with time until equilibrium. Over the entire extent of temperatures applied in the current study, the



Figure 2. Effect of temperature on the oxygen concentration in water at a pH value of 7, gas flow rate of 0.5 L min⁻¹, and time extent of up to 10 min with an interval of 1 min



Figure 3. $\ln (1 - C/C^*)$ against time with the corresponding trendlines

oxygen concentration attains saturation between 6-8 min. However, the dissolution of oxygen decreases with temperature at an exact time. For example, it reaches around 12 ppm after only 1 minute when the temperature is 7 °C. This amount decreases with increasing temperature to become in the range of 8 ppm by elevating the temperature to 30 °C. The maximum dissolved oxygen at the temperature window under the present investigation (i.e., 7-30 °C) varies from 16.5 to 10.5 descending. To compare, the oxygen concentration in freshwater is around 14.6 ppm at 0 °C and declines to about 9.1, 8.3, and 7 ppm at 20, 25, 30 °C (Patel and Vashi, 2015). This shows that the micro-bubble flow technique has efficiently increased the level of oxygen content in water even at high temperatures.

By plotting Equation 2 (i.e., $\ln (1 - C/C^*)$ versus t) for each particular temperature as presented in Figure 3, the values of the oxygen mass transfer coefficient (K_{La}) can be obtained from the slope of the linearized data. The correlation coefficient (R2) for the experimented temperatures extends between 0.95–0.99.

The dependency of the mass transfer coefficient of oxygen gas on temperatures is represented in the following block chart (Figure 4).

The data in Figure 4 shows that the K_{La} of oxygen decreases with temperatures for pure water with a pH value of around 7 and a flow rate of 0.5 L min⁻¹. At a low temperature of 7 °C, the

 K_{La} is about 1.46×10^{-2} s⁻¹ and it considerably declines to around 1.14×10^{-2} s⁻¹ at 30 °C. The estimated values of the oxygen mass transfer coefficient corresponding with particular temperatures including errors are listed in Table 1.

Excessive temperatures can lead to bubble coalescence, reducing gas-liquid interfacial areas, which may limit the increase or even cause a decline in the values of K_{La} .

Effect of gas flow rate on the dissolved oxygen

The influence of the oxygen flow rate on the dissolved oxygen concentration is shown in Figure 5. The experimented flow rates were 0.5, 1, and 1.5 L min⁻¹ and the time scale was 0-12 min. The data were collected after bubbling the oxygen gas into the reactor at a constant temperature of 16 °C and pH value of 7.

Figure 5 indicates that at a gas flow rate of 0.5 L min⁻¹, the dissolved oxygen in water is around 10 ppm in 1 min. The concentration increases to about 13 ppm after only time 2 min. This increase continues slightly to attain the equilibrium at around 7 min with a maximum oxygen concentration of about 14.5 ppm. Amplifying the flow rate to 1 and 1.5 L min⁻¹ does not enhance the dissolution of oxygen in water. Despite the oxygen concentration being relatively higher at 1 and 2 min at these flow rates, it reaches the



Figure 4. Effect of temperature on the oxygen mass transfer coefficient in water at a pH value of 7, gas flow rate of 0.5 L min⁻¹, and time extent of up to 10 min with an interval of 1 min



Figure 5. Effect of gas flow rate on the concentration of dissolved oxygen in water at $16 \pm ^{\circ}C$, pH = 7, and time extent of up to 10 min with an interval of 1 min

Temperature °C	K _{La} × 102 s ⁻¹
7 ± 1	1.46 ± 0.06
13 ± 1	1.34 ± 0.05
16 ± 1	1.23 ± 0.05
25 ± 1	1.17 ± 0.05
30 ± 1	1.14 ± 0.05

 Table 1. The mass transfer coefficient of oxygen with the corresponding temperatures

equilibrium faster (i.e., after only 4 min) and its highest value remains at around 14 ppm. The data of the three curves reflects no significant effect of the oxygen gas flow rate for augmenting its concentration in water. The estimated mass transfer coefficient was about 2.25×10^{-2} and 2.75×10^{-2} s⁻¹ for both flow rates of 1 and 1.5 L min⁻¹ compared with 1.23×10^{-2} s⁻¹ in the case of the flow rate 0.5 L min⁻¹, reflecting faster dissolution. In the current work, the flow rate of 0.5 L min⁻¹ was considered the best gas flow rate, and it will be used for the next sections.

Effect of PH on the oxygen concentration

Variation of oxygen concentration with pH is presented in Figure 6. The tested pH values were 4, 7, and 10. The time window was 0 - 10 min at a constant flow rate of 0.5 L min⁻¹ and temperature of 16 ± 1 °C.

From Figure 6, the dissolved oxygen concentration of the pure water shows low dependency on the acidity where no significant change is monitored with increasing or decreasing the pH value from the neutral water of pH = 7. The obtained values of K_{La} are 1.22, 1.23, and 1.25 × 10^{-2} s⁻¹ which should be included in the range of examined pH of about $1.23 \pm 0.05 \times 10^{-2}$ s⁻¹ by considering the experimental errors.

Effect of turbidity on the oxygen concentration

The effect of turbidity is reflected in Figure 7. The practiced turbidities varied by 0.2, 35. 65, and 95 NTU. The oxygen concentration was measured at a constant temperature of 16 °C, flow rate of 0.5 L min⁻¹, and pH magnitude of 7.

The data in Figure 7 indicates that the variation of the dissolved oxygen concentration of the contaminated water by natural kaolin with time has a similar tendency to neutral water. Noticeably, the amount of dissolved oxygen decreases with increasing turbidity at any particular time. For example, after 2 min, it decreases from around 10.2 ± 0.4 ppm of the pure water of 0.2 NTU to 9 ± 0.4 ppm for the turbid water of 95 NTU. The highest monitored concentrations of oxygen gas in the water that were measured with the above conditions are presented in Table 2.



Figure 6. Effect of pH on the dissolved oxygen concentration in water at 16 ± 1 °C, gas flow rate of 0.5 L min⁻¹, and time extent of up to 10 min with an interval of 1 min



Figure 7. Effect of turbidity on the dissolved oxygen concentration in water at 16 ± 1 °C, gas flow rate of 0.5 L min⁻¹, pH = 7, and time extent of up to 10 min with an interval of 1 min

As demonstrated in Table 2, the last three values of oxygen concentrations are almost the same when considering the maximum error of the experimental measurements. The presence of kaolin slightly decreases the oxygen content in the pure water of 0.2 NTU. The turbidity can obstruct oxygen transfer by increasing viscosity, reducing the gas-liquid interface, and promoting bubble coalescence. However, the effect of adding kaolin in the range of what has been tested in the current work (less than 0.004% of the total water volume of 5 L) resulted in decreasing the oxygen concentration by only about 7.5% at the highest turbidity of 95 NTU. The saturation of dissolved oxygen in water alters between 7–8 min and the variation of its mass transfer coefficient is exhibited in Figure 8.

Turbidity NTU	Oxygen conc. ppm
0.2	14.62 ± 0.6
35	14.0 ± 0.6
65	13.7 ± 0.5
95	13.5 ± 0.5

 Table 2. Concentrations of oxygen verses the turbidity content

The estimated K_{La} values reflect that the mass transfer coefficient of oxygen slightly decreases with increasing turbidity. The K_{La} of the pure water (0.2 NTU) drops to $1.2 \times 10^{-2} \pm 0.05 \text{ s}^{-1}$ at 35 NTU before it declines to 1.16×10^{-2} and $1.14 \times 10^{-2} \pm 0.05$ at 65 and 95 NTU respectively. However, these magnitudes should be set in a very close range by including errors. This means that contaminating water with natural kaolin in a turbidity scale experimented in the current study has not considerably affected the mass transfer coefficient of oxygen might effectively help to maintain the K_{La} in its pure water limitations.

Bubble size analysis

The bubble size distribution for the Point Four diffuser, which is used in the current study, is shown in Figure 9 where the majority of bubble sizes is below 1000 μ m and the most frequent bubble diameters are in the range of 300–400 μ m as reported in our previous work conducted using deionized water (Abdulrazzaq, 2016).

Conventional bubbles have a decreased mass transfer coefficient owing to their increased size and reduced surface area-to-volume ratio, hence constraining gas exchange efficiency. Conversely, microbubbles have a significantly elevated surface area-to-volume ratio, hence improving the mass transfer coefficient and facilitating more efficient gas-liquid interaction. Conventional bubbles have less oxygen solubility because to their rapid ascent, which allows them to depart the liquid and decreases the duration available for oxygen to dissolve. Microbubbles, conversely, maintain suspension in the liquid for an extended duration, so enhancing the time for oxygen dissolution and yielding more oxygen solubility. Consequently, microbubbles are often more efficacious than traditional bubbles in applications necessitating improved oxygenation. In the practical experiment, the maximum efficiency of oxygen solubility was seen in the microbubbles, reaching 14.71 ppm, in contrast to the conventional bubbles, which achieved 6.04 ppm throughout the same duration. As shown in Figure 10.



Figure 8. Effect of turbidity on the oxygen mass transfer coefficient in water at a pH value of 7, gas flow rate of 0.5 L min⁻¹, and time extent of up to 10 min with an interval of 1 min



Figure 9. Distribution of bubble diameter versus the relative frequency of the generated bubbles in the utilized deionized water at air flowrate of 1 L min⁻¹



Figure 10. Comparison between the effectiveness of microbubbles and traditional bubbles at a pH value of 7, gas flow rate of 0.5 L min-1, and at $16 \pm {}^{\circ}\text{C}$

CONCLUSIONS

The micro-bubble flow was used to improve the dissolution of oxygen in water to maximize its concentration for organisms. The results showed that the dissolved oxygen increased with time. The oxygen concentration attained saturation after 6–8 min at the low flow rate of 0.5 L min⁻¹ at maximum. According to the conditions employed in the current work, the oxygen concentration and its mass transfer coefficient (K_{La}) are influenced by temperature and flow rates in different ways. However, their dependency on pH and turbidity of tested values was nearly negligible. The oxygen concentration in water increased with decreasing temperature where the highest oxygen content reached 16.5 ppm at 7 ± 1 °C, while the best concentration monitored at 30 ± 1 °C was around 11 ppm. At the same temperatures, the K_{La} declined from 1.46 to 1.14 × 10⁻² s⁻¹ respectively. Increasing the flow rate exhibited almost no considerable change of the dissolved oxygen, but it accelerated equilibrium to about 4 min. The decrease in the time to reach saturation time was reflected as an increase in the K_{La} to around 2.75 × 10⁻² s⁻¹. In all experiments, the maximal values of dissolved oxygen were obtained at the neutral conditions at pH 7.

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