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Estimation Model of K_La Constant Using Bubble Release Rate and Bubble Size

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Original Research Article

Abstract

Oxygen transfer efficacy highly depends on bubbles' size, bubbles' release rate, and bubbles' velocity while traveling toward the surface of the water. This work presents a mathematical modeling that correlates bubble release rate, bubble size, and bubble velocity to volumetric mass transfer coefficient, 1/hr (K_La). Multiple studies show models that correlate K_La to the concentration of oxygen for different flow patterns but this study focuses on a model that connects K_La to geometrical parameters. The model in this study was built on experimental data for a standard rubber membrane (SS2) manufactured by Xylem's Sanitaire company and tested with a new membrane, Sharp Nub, which was developed by Amano and Alkhalidi. The model was able to predict the experimental K_La20 values with slight variation. The proposed model can predict the K_La20 based on bubble release rate, bubble velocity, and bubble size. That makes it simpler to investigate the effects of changing any of these parameters without experimentation, thereby saving time and effort. By attaining the K_La20 values for a membrane, standard oxygen transfer efficacy (SOTE) can be easily found making it simpler to compare diffuser performances.
Keywords: Wastewater Treatment, Aeration, Mass Transfer.

INTRODUCTION

The aeration process constitutes a high proportion of energy consumption in the wastewater treatment process [1]. Since the energy crisis in the early 1970s, the world has switched from course bubble to fine bubble aeration. Fine pore diffusion is a subsurface form of aeration in which air is introduced in the form of very small bubbles to increase oxygen transfer efficacy (OTE) comparing to coarse bubble aeration. Smaller bubbles result in more bubble surface area per unit volume and longer bubble residency time that leads to a greater OTE.

Oxygen transfer in mixed bioreactors is investigated in the literature by several authors. Oxygen mass transfer in a stirred tank bioreactor was studied using different impeller configurations for environmental purposes [2]. In their study, a miniature stirred tank bioreactor was designed for treatment of the waste gas containing benzene, toluene, and xylene. The influence of volumetric oxygen transfer coefficient (K_La) on xylanases batch production by Aspergillus niger van Tieghem was studied in stirred tank and internal-loop airlift bioreactors [3]. In their study, batch fermentations in stirred tank bioreactor (STB) and airlift bioreactor (ALB) were operated under a range of K_La values. An investigation of new approaches to enhance pollutant removal in artificially aerated wastewater treatment systems [4] was carried out and this new aeration approach significantly improved pollutant removal efficiency compared to alternative aeration configurations, achieving >90% removal of the influent load for chemical oxygen demand (COD), biological oxygen demand (BOD), and computational fluid dynamics (CFD).

Standard oxygen transfer efficiency was achieved by applying the typical gassing-in and gassing-out method in a high-aspect ratio bubble column using both tap water and coalescence-inhibiting liquid mixtures that represent the coalescence behavior of biological media [5]. The liquid-side mass transfer coefficient K_La for high-density bubbles warm for a wide range of gas volume fraction was considered and a study was conducted for an air-water system in a square column [6]. The bubble size, shape, and velocity were measured for different gas flow rates with a high-speed camera. A dual-tip optical probe measured gas volume fraction and bubble velocity. The performance of fine-bubble diffused aeration systems using characteristic criteria such as specific standard oxygen transfer efficiency (SSOTE), transfer number (NT), and oxygen transfer coefficient (K_La_{20}) [7]; however, these criteria cannot directly show the variation of air demand with wastewater volume. All literature shown in this section discussed the SOTE for several conditions but none of discussed the dimensional effect of the bubble on SOTE

Nomenclature

C dissolved oxygen concentration, (mg/l)
C_∞ the steady state D.O. concentration as time approaches infinity, (mg/l)
C_0 D.O. concentration at time zero, (mg/l)
K_La volumetric mass transfer coefficient, (1/hr)
K_La_{20} K_La value corrected to 20 °C
W_{O2} mass flow of oxygen in the air stream, kg/hr

Subscripts

0 concentration at initial time.
∞ concentration at saturation.
20 at 20 °C
Aq Aqueous (dissolved in water)

Abbreviation

BOD biological oxygen demand
CFD computational fluid dynamics
COD chemical oxygen demand
DO dissolved oxygen
EPDM rubber(ethylene propylene diene Monomer (M-class) rubber
l/min liter per minute
m meter
mm millimeter
OTE oxygen transfer efficiency
PIV particle image velocimetry
SS2 standard membrane from ITT Company, flat punch
TOC total organic carbon
WWTP wastewater treatment plant

Improving energy efficiency in wastewater treatment was the core of our work for the last couple of years, in our previous work [8] we reviewed air bubble creation and the factors that affect it in a wastewater treatment system using both computational fluid dynamic (CFD) and experimental techniques. Our work established that the bubble size depended on several factors such as flow rate, inlet pressure, and the contact angle of the rubber membrane. Among those factors, it was concluded that the flow rate had the largest effect on the bubble size followed by the membrane material's contact angle. Additionally, we investigated wave generation in subsurface aeration system, these waves enhanced mixing in the aeration tank in wastewater treatment [9]. We also investigated Improving Mixing in Water Aeration Tanks Using Innovative Self-Powered Mixer and Power Reclamation from Aeration Tank and results showed a good improvement in SOTE [10-11]. A validation of a multi-phase plant-wide model described the aeration process in a wastewater treatment plant (WWTP); the mathematical model constructed was able to reproduce biological COD and nitrogen removal, liquid-gas transfer, and chemical reactions [12].

Recycled pressurized air effect on SOTE was investigated using a pilot plant that was constructed to study the effect of using recycled pressurized air within sequencing batch reactor (SBR) model; the results showed that the new technique comparing with the conventional SBR model improved standard oxygen transfer rate (SORT), standard oxygen transfer efficiency (SOTE) and standard aeration efficiency (SAE) [13]. The influence of full-scale plant wastewater characteristics on oxygen transfer efficiency (OTE) was studied and as expected increased alphas were observed for wastewater matrixes with increased water quality; during the dynamic batch test experiments a linear relationship between alpha and oxygen uptake rate (OUR) was detected [14].

Various authors have investigated the K_La_{20} based on the oxygen transfer rate. Bubble release rate and bubble size were never investigated. This work uses experimental data to develop a new mathematical model that can predict K_La_{20} based bubble size and bubble release rate. This model saves engineers time and cost required to execute SOTE analysis on water.

EXPERIMENTAL

The oxygen transfer analysis in this work was executed experimentally to generate a mathematical model built on data from standard rubber membrane (SS2) manufactured by Xylem's Sanitaire company specialized in wastewater aeration industry. An innovative membrane (Sharp Nub) developed by Amano and Alkhalidi [15] was used to test the model in this work. SS2 had a nozzle that increases the bubble release rate and decreases the bubble size.

Two experimental setups had been used: i) transparent rectangular tank with a high-speed camera, shown in **Fig-1**, for predicting bubble release rate and bubble size experimentally and ii) Dissolved Oxygen Experimental Setup.

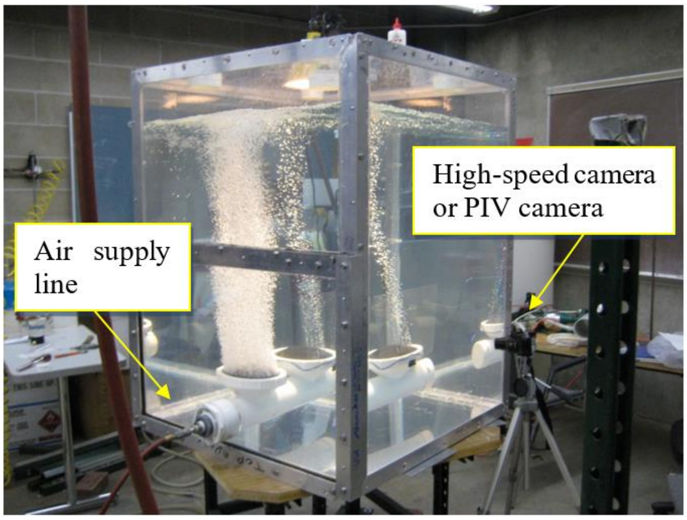

Fig-1: Air diffuser experimental setup

Fig-1 shows a clear plexiglass water tank fitted with submerged PVC air diffusers. The rectangular water tank shape was selected to insure best performance for the high-speed camera used. The experimental setup was fitted with a pressure regulator flow meter and pressure gauges to precisely control the experimental conditions.

The oxygenation process depends on several factors; chief among them are bubble release rates and bubble size that affect SOTE in aeration tank. The Dissolved Oxygen Experimental Setup was a cylindrical water tank. This geometry was used to avoid any dead zones in the body of the water, which could disturb the SOTE reading and to ensure symmetry around the diffuser. Tank dimensions were 0.9 m in diameter, 1.15 m in length above the diffuser, and a total length of 1.2 m of water was used. This tank was fitted with dissolved oxygen probes, three, connected to a data acquisition unit. The schematic and experimental setup is shown in

Fig-2. Dead zones could affect the results by producing sudden increases or decreases to the oxygenation level.

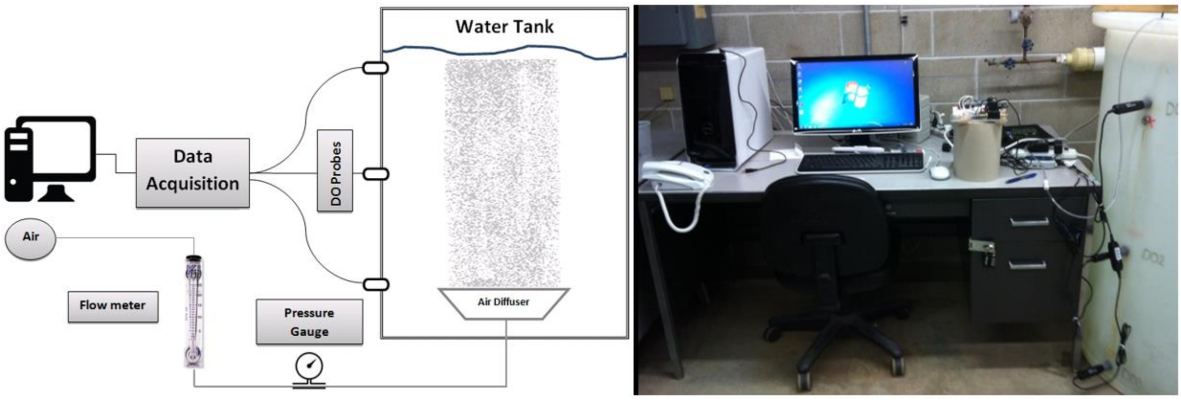

Fig-2: Dissolved Oxygen Experimental Setup Layout

Probes were used with a sampling rate of 1 Hz, ±0.2mg/l accuracy. Probes' readings showed a slight fluctuation due to water motion within the tank but this was solved by fitting the results with a fifth order polynomial to determine K_La_{20}.

A slit, made by a straight punch, in the diffuser membrane releases air to the water on the top of the membrane. This slit expands as the rubber membrane expands due to air pressure caused by airflow in the membrane creating an oval slit opening that released bubbles to the water. The oval opening closed after the airflow stopped and it returns to a straight-slit shape so no water can backflow inside the rubber membrane. This oval opining's dimensions were estimated experimentally resulting in 0.62 ± 0.09 mm major diameter and 0.14 ± 0.05 mm minor diameter for SS2 and Sharp nub membranes, respectively. Contact angle of 57 ± 0.5° for the rubber water air interface was measured by using Contact Angle Goniometer.

Standard oxygen transfer efficiency (SOTE)

Clean water oxygen transfer tests were based on the dissolved oxygen removed from the water by sodium sulfite addition, followed by reaeration to within 2% of the predetermined oxygen concentration saturation level. The reaction for removing oxygen is:

$$2Na_2SO_{3\ (aq)} + O_{2\ (aq)} \xrightarrow{Cobalt} 2Na_2SO_{4\ (aq)} \qquad (1)$$

Water's dissolved oxygen content was monitored during the reaeration process by three probes at three different elevations: top, middle, and bottom of the tank. A simplified mass transfer model used to accurately estimate the mass transfer coefficient, K_La, analyzed the obtained data at each probe and the steady state dissolved oxygen concentration, C_∞. The model was defined as:

$$C = C_\infty - (C_\infty - C_0) \times exp(-K_Lat) \qquad (2)$$

Where C is dissolved oxygen concentration (mg/l), C_∞ is the steady state dissolved oxygen concentration as time approaches infinity (mg/l), C_0 is the dissolved oxygen concentration at time zero (mg/l), and K_La is the volumetric mass transfer coefficient (1/hr).

The standard oxygen transfer rate (SOTR) was obtained as the average of the products of the adjusted K_La_{20} values for each probe, the corresponding adjusted C_∞ values for each probe, and the tank's volume, as shown in the equation below:

$$SOTR = -K_La_{20}C_\infty Vt \qquad (3)$$

Where K_La_{20} is K_La value corrected to 20 °C, $C_{\infty 20}$ is value of steady-state D.O. concentration corrected to 20°C and 1 atm, and V_t = liquid volume of test water in the test tank when aerator(s) are off.

Oxygen transfer efficiency (OTE) refers to the fraction of the mass of oxygen in an injected air stream that actually dissolves into the test fluid under the specified conditions. The standard oxygen transfer efficiency (SOTE) is the OTE corrected to 20 °C, 0 mg/l D.O. and 1 atm of pressure.

$$SOTE = \frac{SOTR}{W_{O_2}} \qquad (4)$$

Where W_{O2} is the mass flow of oxygen in the air stream, kg/hr.

Results and Discussion

A high-speed camera was used to measure the bubble size and Particle Image Velocimetry (PIV) technique was used to measure the bubble velocity.

Bubble Release Rate and Bubble Size

The new model proposed in this work was built on a commercially used membrane, SS2, which was simply a flat rubber membrane containing slits that open in an oval shape to release air consisting of ethylene propylene diene Monomer (M-class) rubber (EPDM). The proposed model was tested on a sharp nub membrane that was designed and built by in this work; the membrane was equipped with a nozzle on the top of the slit to force the bubble to split into three bubbles as shown in Fig-3 to improve efficiency.

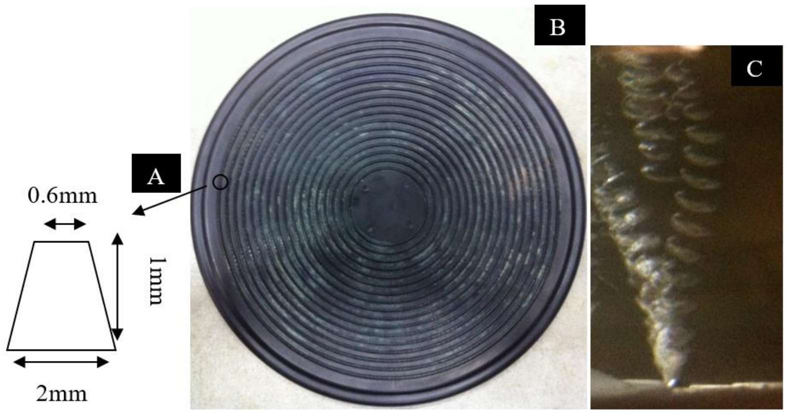

Fig-3 (a): Nozzle design and dimension; (b) sharp nub membrane; (c) bubbles splitting due to nozzle effect

Bubble release rate and bubble size were investigated using a clear tank. This was achieved by fitting two diffusers: one was the SS2 standard membrane with 5500 punches and the other SS2 had 3-5 punches. This was done to enable the high-speed camera of capturing bubbles clearly. A steel grid 5.5 cm × 5.5 cm was placed in the bubble bath, it was used to estimate the bubble size and compare it to the grid spacing. The high-speed camera was used in high speed video mode at a rate of 420 frames per second to estimate the bubble release rate. The bubbles were counted three times for accuracy. Averaged results are presented in Table-1.

Table-1: Bubble release rate

Flow Rate(l/min)	SS2	Sharp Nub
14	39	56
28	49	66
42	63	98
56	69	148
70	76	171
84	99	211
98	126	244

Sharp Nub membrane showed a higher bubble release rate than SS2 membrane. This could be attributed to the nature of the membrane where the nozzle forces the bubble to split into three bubbles. To investigate the bubble size, the same camera was used to film videos and capture images; the same steel grid sized 5.5 cm × 5.5 cm was used. Each experiment was repeated three times.

Table-2: Bubble size

Standard SS2				Sharp Nub			
Flow Rate (l/min)	Major (mm)	Minor (mm)	Average (mm)	Flow Rate (l/min)	Major (mm)	Minor (mm)	Average (mm)
14	2.8	1.9	2.3	14	2.6	1.9	2.3
28	2.9	2.1	2.5	28	2.8	2.0	2.4
42	3.3	2.5	2.9	42	2.9	2.3	2.6
56	3.5	2.8	3.1	56	2.6	2.1	2.3
70	3.8	2.9	3.3	70	2.8	2.1	2.4
84	3.9	2.9	3.4	84	2.9	2.2	2.6
98	4.1	2.8	3.4	98	3.1	2.3	2.7

Table-2 presents the bubble size measurements. The nozzle added to sharp nub membrane caused a significant reduction in bubble size at 56 l/min flow rate.

Average Bubble Velocity

The average bubble velocity was measured using PIV at different elevations. First at the top of the diffuser, then at 140 mm, and finally at 280 mm just before the surface of the water. The bubble velocity measurements are shown in

Table-3.

Table-3: Average bubble velocity

Flow rate (l/min)	SS2 (m/s)	Sharp Nub (m/s)
14	0.34	0.40
28	0.41	0.43
42	0.49	0.44
56	0.45	0.45
70	0.45	0.44
84	0.40	0.45
98	0.43	0.46

Relationship Between K_La_{20}, Bubble Size, and Bubble Release Rate

K_La_{20} could be defined as the volumetric mass transfer and it has a unit of 1/hr, it could be used to estimate the SOTE or it could be used to estimate the required time to achieve saturation. Experimental and model K_La_{20} results were plotted in **Fig-4** for flow rates 14 l/min to 98 l/min for the SS2 membrane.

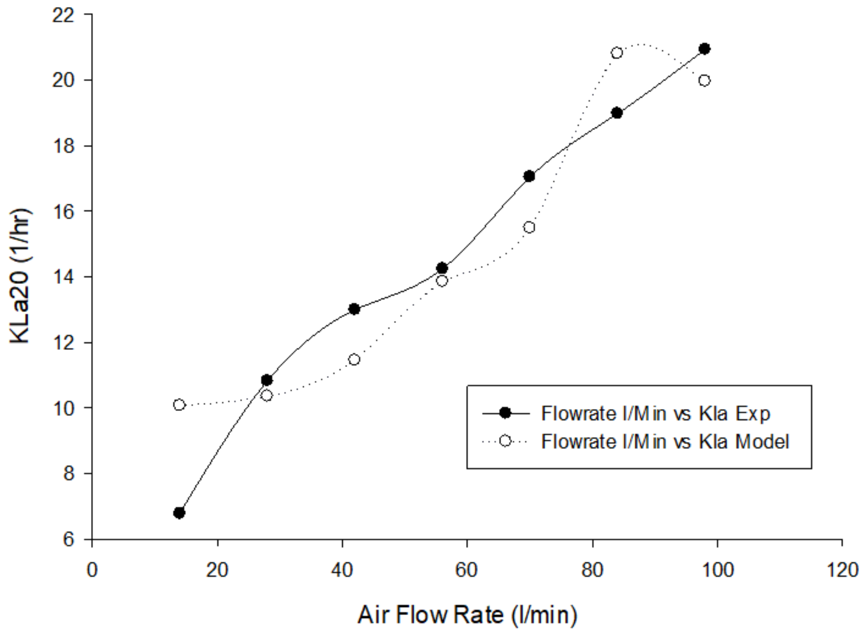

Fig-4: K_{La20} versus airflow rate

The experimental data presented in
Table-1,
Table-2, and

Table-3 were combined in the form of two non-dimensional parameters x and y where:

$$x = \left(\frac{\dot{N} * L}{V}\right) \quad (5)$$

$$y = \left(\frac{D_b}{D_P}\right) \quad (6)$$

Where $\dot{N}$ is the bubble release rate per second, L is the length of water column (1.15 m), V is the average velocity found by PIV (m/s), D_b is the average bubble diameter (mm), and D_p is the average Punch diameter (1.4 mm).

A mathematical model was created using Gaussian model for Nonlinear Regression - Dynamic Fitting:

$$K_L a_{20} = a \times exp\left(-0.5 * \left(\left(\frac{(x-x_o)}{b}\right)^2 + \left(\frac{(y-y_o)}{c}\right)^2\right)\right) \quad (7)$$

Where the coefficient is defined as shown in

Table-4.

Table-4: Coefficient for the Gaussian model

K_La_{20} (1/hr)	Volumetric mass transfer coefficient
x_0	1489491.291
y_0	1345539.057
a	2.87×10^7
b	685461.2139
c	-2.53×10^5

Model validation

The Sharp Nub membrane was tested to obtain K_La_{20} values using the proposed model and was compared to experimental data; results are presented in Fig-5. K_La_{20} model values showed a slight variation that could be attributed to the fact that the nozzle in the sharp nub model had significant effects on bubble release rate and the bubble size, these changes cause of the variation between both results.

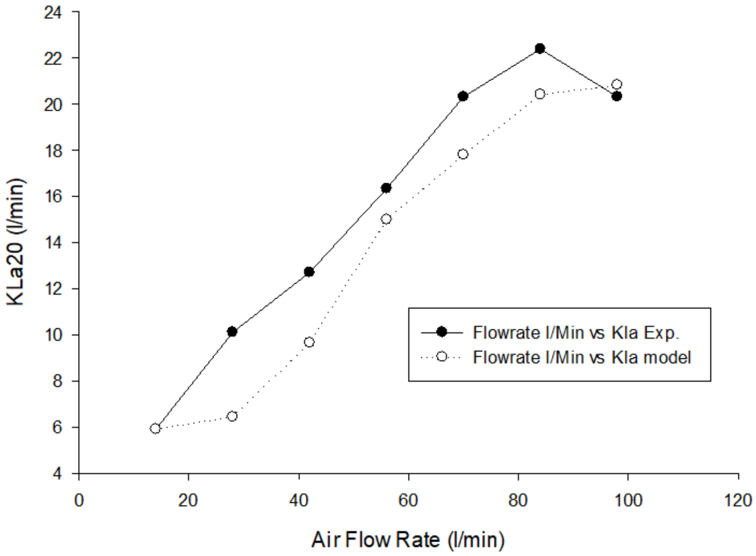

Fig-5: Sharp Nub membrane K_La_{20} values using the proposed model and experimental results

Conclusions

A new mathematical model was created based on K_La_{20} measured data for the rubber membrane, SS2, used for aeration of wastewater. By using the proposed model, K_La_{20} can be estimated by attaining the bubbles' geometry, bubbles' velocity, and bubbles' released rate. This model was tested for an innovative membrane design with a nozzle to force the bubbles to split imposing large changes on bubbles' shape and bubbles' release rate. The proposed K_La_{20} model's results for both membranes correspond well to experimental results.

The proposed model used the geometrical data for the bubble to investigate the K_La_{20} value that saves time and effort required for K_La_{20} testing based on the oxygen concentration, as it requires a long time and oxygen sensors that may not be available.

Author Contributions

Ammar A. T. Alkhalidi carried out the data curation, analysis of results, and validation of the proposed model. Ryo S. Amano provided the methodology of this work as well as the resources, project administration and supervision. Mohamad K. Khawaja was fundamental in the writing, reviewing, and editing of the work in this study.

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Conflicts of Interest

The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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