Using Oxygen Gas Transfer Coefficients to Predict Carbon Dioxide Removal

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ABSTRACT

The purpose of this research was to determine if oxygen gas transfer coefficients, as reflected by overall mass transfer coefficient (K_La) values, could be used to predict carbon dioxide (CO_2) removal by degassing in aquaculture production systems. The motivation for this approach was that while there is ample literature related to oxygen gas transfer, there is limited information on CO_2 removal. A series of tests was conducted to determine the ratio (ϕ_E) of K_La for CO_2 to that of oxygen for two commonly used surface aerators and then compare ϕ_E to the theoretical

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ratio, ϕ_T, which is 0.90 based upon gas molecular diameters. Experiments were conducted in a 10,000 L circular tank aerated by means of two different surface agitators. The two aerators were selected to represent aeration patterns with high and moderate water to gas interface exposures or breakup patterns (photos supplied, Figures 2 and 3). The results showed that ϕ_E/ϕ_T ratios were 96% (for high air exposure) and 74% (for moderate air exposure) for water with an alkalinity of ~130 mg/L as $CaCO_3$. The ϕ_E/ϕ_T ratio decreased to 0.84 and 0.51 for the high and moderate air exposures, respectively, when higher alkalinity waters (~1,000 mg/L as $CaCO_3$) were used.

INTRODUCTION

Oxygen is essential for the production of fish in aquaculture systems. Adding oxygen or air to culture water can dramatically increase the system carrying capacity when dissolved oxygen is the limiting factor (Lawson 1995). Carbon dioxide (CO_2) can pose serious risks to fish health in intensive aquaculture and could be the limiting water quality factor in some cases. Increased CO_2 levels in water result in a lowering of culture water pH. Similarly, increased CO_2 decreases the pH of a fish's blood, which reduces the amount of oxygen their blood hemoglobin can carry (Eddy *et al*. 1977). Elevated levels of CO_2 in blood cause a drop in blood pH and produce a condition known as hypercapnia (Berg and Tandstat 1995). Despite the presence of adequate dissolved oxygen in the culture water, elevated blood CO_2 levels may result in respiratory distress due to a decrease in hemoglobin's affinity for oxygen (the Bohr effect) or a decrease in the maximum oxygen binding capacity of hemoglobin (the Root effect) (Lawson 1995, Wedemeyer 1996).

Fish densities in recirculating aquaculture systems (RAS) are often above 100 kg/m^3, which generally require the use of pure oxygen and active CO_2 stripping. There are various methods to remove CO_2, e.g., surface aerators (Boyd 1998), packed column aerators (Grace and Piedrahita 1994), and bubble columns or airlift pumps (Loyless and Malone 1998). While there is extensive literature that describes oxygen transfer and associated mass transfer coefficients, there is limited information on transfer coefficients for CO_2 removal. Therefore, the objective of this research was to determine if oxygen gas transfer rates as reflected by an overall mass transfer coefficient (K_La, time^{-1}; e.g. hr^{-1}) value could be used to predict CO_2 transfer in aquaculture production systems.

1.1. Gas transfer theory

The driving force for gas transfer is the difference in gas concentration (or pressure) between the air and water. The gas transfer rate is proportional to this gas pressure difference, the characteristics of the air-water interface, and gas diffusion and convective transport characteristics across the air-water interface. An overall mass transfer coefficient (K_La) is used to predict device performance as described by Equation 1 (Stenstrom 1979):

$$\frac{dC}{dt} = K_L a(C_s - C)V \qquad \text{(Equation 1)}$$

where:

dC/dt = gas transfer rate (mg hr^{-1})

C_s = saturation concentration of the gas (mg L^{-1})

C = measured gas concentration at time, t (mg L^{-1})

V = volume of water subjected to gas transfer (L)

1.2. Carbon dioxide removal

It is only as a dissolved gas, $CO_2(aq)$, that CO_2 is directly affected by aeration (Berg and Tandstad 1995). Unlike other important dissolved gases, such as nitrogen and oxygen, CO_2 exists as part of the carbonate chemical equilibrium system (carbon dioxide CO_2, carbonic acid H_2CO_3, bicarbonate HCO_3^-, and carbonate CO_3^{-2}) (Grace and Piedrahita 1994):

$$CO_2(gas) \leftrightarrow CO_2(aq) \qquad \text{(Equation 2)}$$

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \qquad \text{(Equation 3)}$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad \text{(Equation 4)}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{-2} \qquad \text{(Equation 5)}$$

The equilibrium concentration of CO_2(aq) in Equation 2 is a function of CO_2 gas pressure and a solubility constant (Henry's Law constant). The concentration of each component in Equations 2–5 depends on total carbonate carbon (C_T) and an ionization fraction:

$$C_T = [H_2CO_3] + [HCO_3^-] + [CO_3^{-2}] \qquad \text{(Equation 6)}$$

The magnitude of the ionization fraction depends upon pH, salinity, and temperature (Grace and Piedrahita 1994). Removal of CO_2 causes carbonic acid (H_2CO_3) to disassociate into more CO_2(aq) and H_2O. This in turn causes the concentration of the other constituents of the carbonate system to change. CO_2 removal causes a short-term depletion of CO_2 until a new equilibrium in the carbonate system is established (Grace and Piedrahita 1994). Alkalinity is conserved during the CO_2 removal process, where a simplified definition of alkalinity (ALK) is:

$$ALK = [HCO_3^-] + 2[CO_3^{-2}] + [OH^-] - [H^+] \qquad \text{(Equation 7)}$$

The temporary imbalance in the carbonate system caused by CO_2 removal will result in larger gas pressure differences for CO_2 removal existing through an aeration device than what would be predicted based upon equilibrium concentrations.

For practical reasons, the concentrations of CO_2(aq) and H_2CO_3 are combined and called H_2CO_3* or free CO_2 (Stumm and Morgan 1996).

The ratio of the two species $\frac{CO_2(aq)}{H_2CO_3}$ is ~ 650 and remains both constant and independent of pH (Stumm and Morgan 1996). Thus, from a practical perspective, essentially all measured CO_2 is CO_2(aq). For the remainder of this paper, CO_2 will be synonymous with H_2CO_3* when referring to dissolved CO_2 in the water column.

1.3. Diffusion Theory

Diffusion across the interface between a gas and a liquid represents the rate limiting factor to gas transfer (Tsivoglou *et al.* 1965). Although Einstein's law of diffusion usually is applied to gas transfer in a single, viscous medium, the gas-liquid interface in a turbulent system can also be considered a viscous resistance to diffusion. Therefore, applying Einstein's law of diffusion to the transfer of gases into or out of a liquid yields that K_La values and molecular diameters (d) are inversely proportional for any pair of gases (Tsivoglou *et al.* 1965). Using the molecular diameters of oxygen (d_{O_2} = 2.92 10^{-10} m) and CO_2 (d_{CO_2} = 3.23 10^{-10} m), the theoretical ratio of mass transfer coefficients (ϕ_T) for CO_2 relative to oxygen is (Lide 1992):

$$\phi_T = \frac{d_{O_2}}{d_{CO_2}} = \frac{2.92}{3.23} = 0.90 \qquad \text{(Equation 8)}$$

This same ratio, determined from physical experiments, can be defined as:

$$\phi_E = \frac{(K_L a)_{CO_2}}{(K_L a)_{O_2}} \qquad \text{(Equation 9)}$$

Given that the ϕ_T value for CO_2 relative to oxygen is 0.90, it can be assumed that the mass transfer coefficient for CO_2 could only be up to 90% of the oxygen mass transfer coefficient. Experimentally determined K_La ratios (ϕ_E) below the theoretical maximum (ϕ_T) would suggest that there are factors other than gas molecular diameter differences that are affecting the relative mass transfer.

MATERIALS AND METHODS

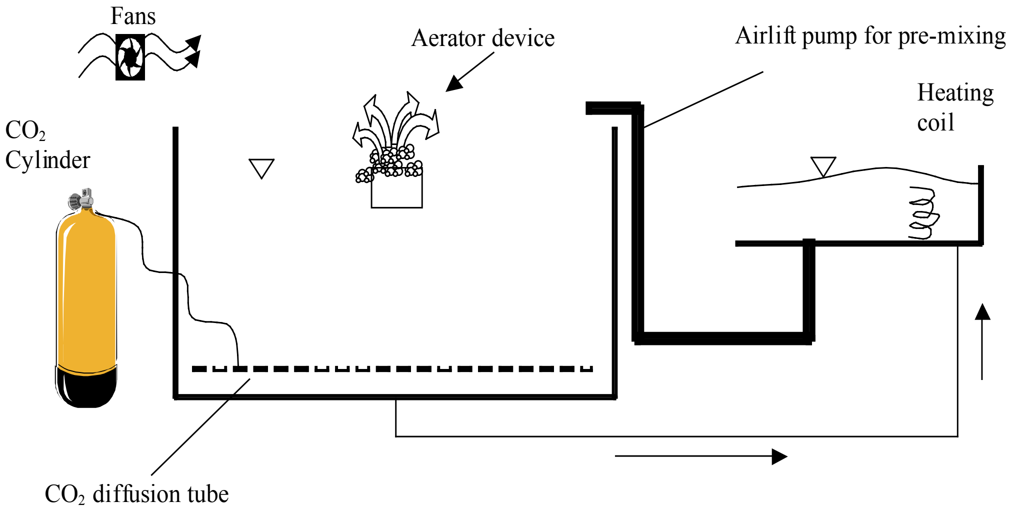
Oxygen and CO_2 mass transfer rates were measured using two types of mechanical aerators. The two aerators are commonly used in aquaculture systems, as described in section 2.2.

2.1. Experimental setup

Oxygen and CO_2 mass transfer were measured in a 10,000 L (nominal volume) circular tank (3.7 m diameter by 1.2 m high). The water level was kept constant in the tank at 0.91 m. Well water (14°C) with a pH of

7.5 and an alkalinity of 130 mg L^{-1} as $CaCO_3$ was used for all tests. The well water was warmed to 22–25°C using a tank equipped with heating coils and an air lift pump to recirculate the water prior to any test being performed. The aerators were positioned in the center of the test tank. A schematic of the test system is shown in Figure 1. The elevation at the site was 375 m above sea level.

Figure 1. General schematic of experimental set up using a 10 m^3 tank.



2.2. Description of aeration devices

The aerators tested were a Kasco model KA751 and a Sweetwater model HS5 (both supplied by Aquatic Ecosystems, Inc., Apopka, Florida, USA). Both aerators were circular, surface-draw aerators. The Kasco unit was equipped with a continuous duty 0.56 kW (0.75 hp) motor and was supported on a polyethylene float. The manufacturer specified that the unit pumps approximately 41 L s^{-1} and draws 6.7 amps. During operation, water agitation in the tank was extremely violent with the entire water plume ejected into the air being whitewater (Figure 2). The pumped water was evenly distributed about the tank in a circular fashion and the aerator was deemed to have a “moderate air exposure” relative to the Sweetwater unit, as described next.

The Sweetwater unit was a much smaller unit designed for small ponds and tanks. It was powered by a 0.12 kW (0.17 hp) motor and was floated on top of the water by a Styrofoam collar. The manufacturer specified that the unit pumps 7.6 L s^{-1} and draws 1.8 amps. During operation, water agitation in the tank was less turbulent than with the Kasco unit, and the plume of water ejected into the air contained almost no whitewater and produced few bubbles on the water surface (Figure 3). However, the Sweetwater unit created a large air-water exposure during operation and was defined as having a "high air exposure" relative to the Kasco unit. These two units were chosen because they represented two levels of water breakup and air exposure. While the Kasco unit broke up more water, the air exposure of the water was not as complete as with the Sweetwater unit.

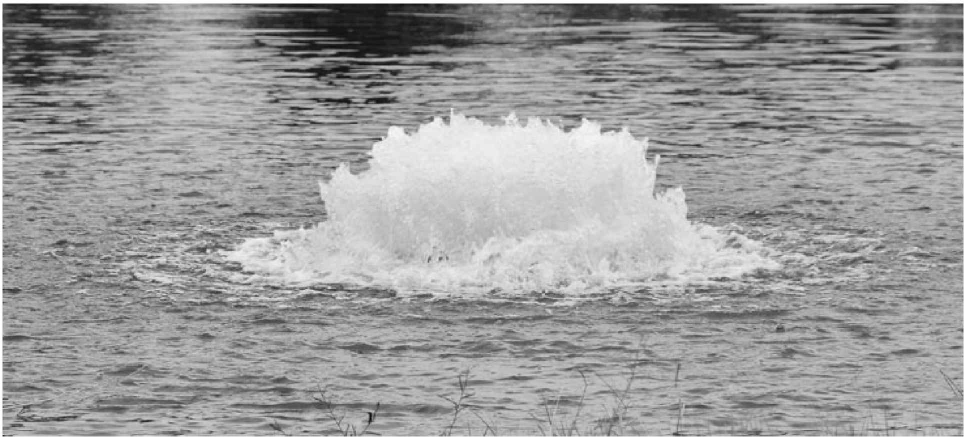


Figure 2. Water breakup pattern for Kasco Model KA 751 unit (moderate air exposure, MAE).

Figure 3. Water breakup pattern for Sweetwater Model HS5 unit (high air exposure, HAE).

2.3. Determination of oxygen transfer

Well water (130 mg L^{-1} as $CaCO_3$ alkalinity) was deoxygenated using sodium sulfite catalyzed with cobalt chloride (ASCE 1984). Cobalt chloride was added first to the test tank at a concentration of 0.5 mg L^{-1} with the aerator running to ensure uniform mixing. The sodium sulfite was then added at a concentration of 7.88 mg L^{-1} for every milligram per liter of dissolved oxygen to be removed. A sufficient quantity of sodium sulfite was added to drop the dissolved oxygen concentration below 0.5 mg L^{-1}. The dissolved oxygen content of the water was measured prior to beginning any test to prevent the addition of excess chemical and ensure that the starting concentration remained below 0.5 mg L^{-1}. During an oxygenation test, composite water samples were collected as a function of time (ASCE 1984). Four sample points were used for each water composite sample for measurements of dissolved oxygen: one shallow, one mid-depth, one deep, and one chosen by the researchers (ASCE 1984).

For the Kasco unit, water samples in a given test were taken such that two-thirds of the values corresponded to the period during which dissolved oxygen concentration changed rapidly and one-third during the more stationary period as the water moved towards equilibrium oxygen concentration. For the Sweetwater unit, water samples were taken at equal time intervals between the first and last dissolved oxygen readings. Oxygen readings were taken using a dissolved oxygen meter (Model 54A, YSI, Yellow Springs, Ohio, USA) and polarographic oxygen probe (Model 5739, YSI, Yellow Springs, Ohio, USA). The oxygen meter was calibrated prior to each test according to the manufacturer's specifications. Oxygen tests were replicated three times for each of the two aerators and the oxygen K_La values were calculated as described in section 2.5.

2.4. Determination of carbon dioxide transfer

Three trials at low alkalinity (well water) were conducted for each aerator with three different initial levels of tank water CO_2. In addition, tests for both aerators were conducted at elevated levels of both alkalinity (~ 1,000 mg L^{-1} as $CaCO_3$) and CO_2 to see if there was a noticeable effect on measured K_La values. Initial CO_2 values were selected to cover an expected range of concentrations that would be experienced in commercial RAS. The high alkalinity levels were created by adding sodium bicarbonate directly to the water. Alkalinity was verified by titrating a 100 ml sample with 1.600 N sulfuric acid to a pH of 4.8. A Hach Co. (Loveland, CO, USA) titrator and reagents were used.

Compressed CO_2 gas ($CO_2 > 99\%$) was added to the main tank water using a tube-diffuser hose. The diffuser assembly was connected to a CO_2 tank with a flow meter to control the rate of application. For each test, after injection of CO_2 gas brought the dissolved level to the desired concentration, the water was allowed to equilibrate for five minutes. This procedure was repeated until the desired CO_2 level remained constant. Alkalinity does not change due to the addition or removal of CO_2 (APHA 1995, Stumm and Morgan 1996), hence it was measured prior to the beginning and at the end of each test and the average of these two values was used in all calculations of the CO_2 concentration for that particular run.

Concentrations of CO_2 were calculated from measurements of temperature, alkalinity and pH according to Standard Methods 4500-CO_2 D (APHA, 1995). The pH measurements were obtained using an Ion Analyzer (Model 250, Corning Inc., Corning, NY, USA) and a sealed, gel filled, combination pH probe (Model 910600, Orion Research, Beverly, MA, USA). The pH meter was calibrated using a two-point method prior to each test run with standard buffer solutions of pH 4.00 and pH 7.00.

Measurements of CO_2 for the Kasco unit were taken at four minute intervals for the first hour and at eight minute intervals thereafter. Measurements for the Sweetwater unit were taken at five minute intervals for one hour and at ten minute intervals thereafter. In all cases, a water sample of approximately 200 ml was taken from the test tank and immediately tested for pH. The pH meter stabilized in approximately 30 seconds for each reading. Water samples were taken from various positions and depths in the test tank using closed flasks and a siphon hose in order to reduce sampling position bias.

2.5. Determination of the Mass Transfer Coefficient, K_La

The overall mass transfer coefficient in Equation (1) was determined by using the log-deficit model in integrated form (Stenstrom 1979):

$$\ln\left|C_s - C\right| = -K_L a \cdot t + \ln\left|C_s - C_{t=0}\right| \qquad \text{(Equation 10)}$$

The equilibrium values (C_s) for oxygen and CO_2 were calculated using the gas solubility equations as presented by Weiss (1970, 1974) and ASHRAE (1972); effects of barometric pressure, gas partial pressures, and temperature were included in these calculations. A semi-log plot of the gas deficit versus time yields a straight line with a slope equal to K_La. A linear least squares regression of the data was performed using Microsoft® Excel to obtain K_La and R^2 values. The same log-deficit method was used to determine the K_La values for oxygen and CO_2. For ease of comparison, K_La values were standardized to a reference temperature of 20°C by (ASCE 1984):

$$(K_L a)_T = (K_L a)_{20}\,\Theta^{(T-20)} \qquad \text{(Equation 11)}$$

where :

$(K_La)_T$ = value from Equation 10

Θ = temperature correction factor, 1.024 in fresh water

T = temperature, °C

RESULTS

The results of the oxygen transfer tests for the Kasco and Sweetwater units yielded mean $(K_La)O_2{,}20$ values of 7.71 hr^{-1} (sd = 0.04) and 1.23 hr^{-1} (sd = 0.15), respectively. For the low alkalinity tests, the $(K_La)CO_2{,}20$ values for the Kasco and Sweetwater units yielded average values of 5.17 hr^{-1} (sd = 0.64) and 1.06 hr^{-1} (sd = 0.04), respectively. The K_La values for CO_2 in the high alkalinity water obtained from a single test for each aerator were 3.58 hr^{-1} and 0.93 hr^{-1} for the Kasco and Sweetwater units, respectively. All regression curves used to determine K_La values for either oxygen or CO_2 had R^2 values greater than 0.90 (Aitchison 1999).

Mean values for ϕ_E were 0.67 (sd = 0.08) and 0.86 (sd = 0.03) for the Kasco (moderate air exposure) and Sweetwater (high air exposure) units, respectively, for the low alkalinity trials. For these trials, the ϕ_E/ϕ_T ratios were 0.74 and 0.96 for the Kasco and Sweetwater units, respectively. For the high alkalinity trials, ϕ_E/ϕ_T ratios were 0.51 and 0.84 for the Kasco and Sweetwater units, respectively. Mean K_La values for oxygen and CO_2 and associated ratios of ϕ_E and ϕ_E/ϕ_T are given in Tables 1 and 2. Representative graphs of the change in oxygen and CO_2 over time for the two aerators are shown in Figures 4 and 5.

DISCUSSION

The major objective of this research was to determine whether mass transfer coefficients (K_La) for oxygen could be used to predict CO_2 transfer for the same device by using the theoretical adjustment ϕ_T factor, which is based upon the ratio of gas molecular diameters. If the theoretical correction proved to be valid, then the K_La for CO_2 gas transfer

Table 1. Oxygen and carbon dioxide testing results for Kasco Model KA751 Aerator (Moderate Air Exposure, MAE)

	Trial #1	**Trial #2**	**Trial #3**	**Mean**	**Trial #4***
Water Temp (°C)	22.3	24.5	25.0	—	25.0
Initial CO_2 (mg L^{-1})	27	56	104	—	143
Alkalinity (mg L^{-1})	108	137	133	—	1,046
$(K_La)_{CO_2,20}$ (hr^{-1})	5.90	4.73	4.87	5.17	3.58
Mean $(K_La)_{O_2,20}$ (hr^{-1})**	—	—	—	7.71	—
ϕ_E	0.76	0.61	0.63	0.67	0.46
$\phi_E/(\phi_T = 0.90)$	0.84	0.68	0.70	0.74	0.51

* *Carbon dioxide stripping test at elevated alkalinity; results not averaged with other trials; K_La value for oxygen assumed to be the average of the low alkalinity trials.*

** *The oxygen K_La value is the mean of three separate tests and was used for all ϕ_E calculations.*

Table 2. Oxygen and Carbon Dioxide Testing Results for Sweetwater Model HS5 Aerator (High Air Exposure, HAE)

	Trial #1	**Trial #2**	**Trial #3**	**Mean**	**Trial #4***
Water Temp (°C)	26.0	25.8	25.1	—	25.0
Initial CO_2 (mg L^{-1})	28	59	102	—	121
Alkalinity (mg L^{-1})	128	128	125	—	920
$(K_La)_{CO_2,20}$ (hr $^{-1}$)	1.01	1.09	1.08	1.06	0.93
Mean $(K_La)_{O_2,20}$ (hr $^{-1}$)**	—	—	—	1.23	—
ϕ_E	0.83	0.89	0.88	0.86	0.76
$\phi_E/(\phi_T = 0.90)$	0.92	0.99	0.98	0.96	0.84

** Carbon dioxide stripping test at elevated alkalinity; results not averaged with other trials; K_La value for oxygen assumed to be the average of the low alkalinity trials.*

*** The oxygen K_La value is the mean of three separate tests and was used for all ϕ_E calculations.*

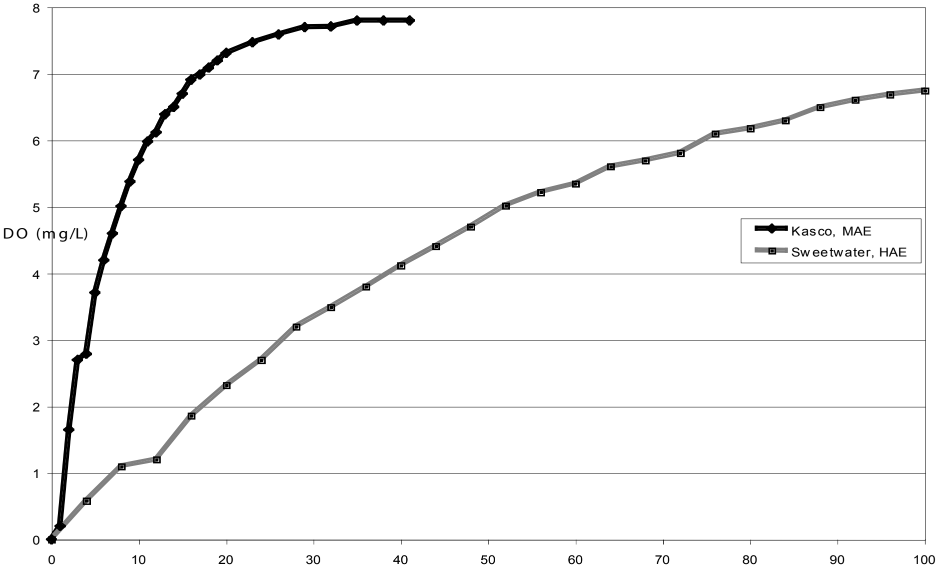


Figure 4. Representative data from an oxygen transfer trial for both aerators showing dissolved oxygen (DO) versus time (water temperature 22°C for both aerators).

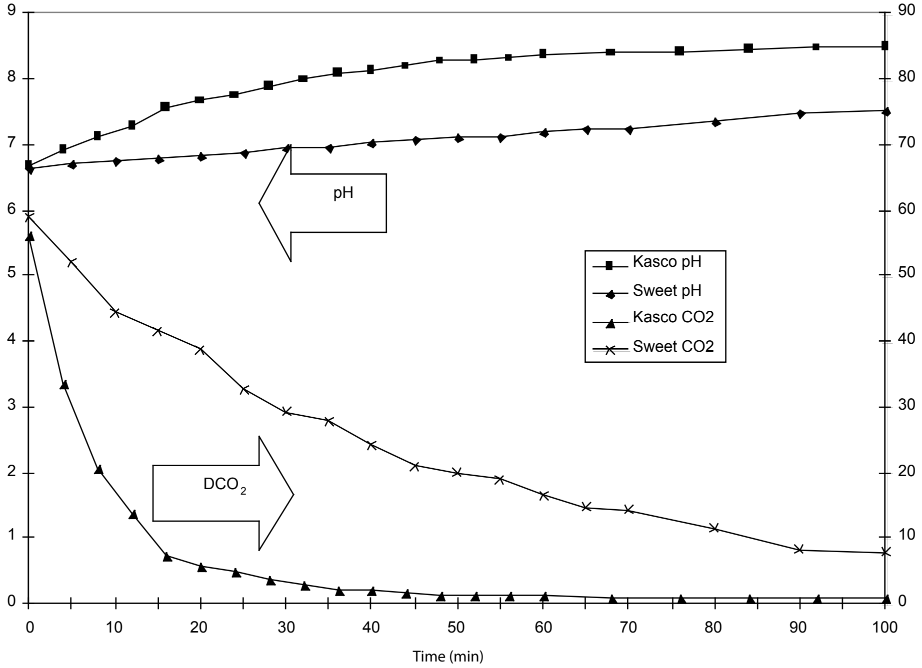


Figure 5. Representative data from a carbon dioxide transfer trial for both aerators showing dissolved (free) carbon dioxide (DCO_2) and pH versus time; water temperature 22°C and alkalinity of 137 mg L^{-1} as $CaCO_3$ for Kasco (MAE) unit and water temperature of 25°C and 127 mg L^{-1} alkalinity as $CaCO_3$ for Sweetwater (HAE) unit.

would be 90% of the K_La for oxygen in all cases. The experiments described here were performed using two types of surface aerators, one representing a moderate (Figure 2, Kasco Unit) and one a high air exposure pattern (Figure 3, Sweetwater Unit). The data for the Sweetwater unit (high air exposure) indicates that the ϕ_T correction (0.90) may be used ($\phi_E/\phi_T = 0.96$) in waters with low alkalinity (~130 mg L^{-1} as $CaCO_3$) and a broad range of dissolved CO_2 concentrations (~ 30-100 mg L^{-1}). However, results for the Kasco unit (moderate air exposure) showed that the ϕ_E/ϕ_T ratio was only 0.74 for the same water quality conditions.

The photographs of the water breakup caused by the two aerators (Figures 2 and 3) show that even though the Kasco unit creates a large degree of turbulence there is less exposure of the water to air than in the Sweetwater unit. The Kasco unit churns and bubbles water up, but does not create a fountain-like pattern, as does the Sweetwater unit. There is no visible airspace behind the plume of water created by the Kasco unit while the Sweetwater unit created more of a fountain-type spray. A fountain-type spray may result in a higher renewal rate of the gas phase around the aerator, resulting in an effect analogous to the high gas flow to liquid flow (G/L) that is necessary for effective CO_2 removal in a packed column aerator (Grace and Piedrahita 1994). Other aerator types, such as true fountain aerators, may create a higher exposure of the water to air than the Sweetwater unit. However, that degree of water breakup may not be necessary to achieve effective CO_2 removal, as the Sweetwater unit achieved nearly 100% of the ϕ_E/ϕ_T ratio. Eschar *et al*. (2003) presented K_La values for a paddle wheel aerator and a submerged aerator. As in the present research, these two devices created very different water-breakup and air exposure patterns. Using the data presented by Eschar *et al*. (2003), the ϕ_E/ϕ_T ratios were 0.89 and 0.65 for the paddle wheel and submerged aerator, respectively. This supports the results observed in this research.

Results from the tests conducted at high alkalinity (alkalinity ~ 1,000 mg L^{-1} as $CaCO_3$), showed that the K_La coefficient was reduced 31% in the Kasco unit from the average K_La value obtained for the low alkalinity tests and 12% in the Sweetwater unit. These results highlight the difference between oxygen and CO_2 removal as CO_2 concentrations are dependent upon the carbonate chemical equilibrium system (see Equations 2–5), which is pH driven, while oxygen concentrations are not. In short, removal of CO_2 causes changes in the concentrations of the other components of the carbonate system such that a chemical equilibrium is re-established. Whereas some of the carbonate system reaction rates are essentially instantaneous, the dissociation of H_2CO_3 and HCO_3^- to CO_2 is not, resulting in a lag in the re-establishment of chemical equilibrium. As a result, the CO_2 concentrations used to determine K_La coefficients, which are measured in samples in which equilibrium has been reached after collection from the aeration tank, overestimate the instantaneous CO_2 concentration in the aeration tank. The consequence is that the mass of CO_2 gas removed from the water due to gas transfer is larger than the mass change that is reflected by a change in dissolved CO_2 concentration (Grace and Piedrahita 1994, Summerfelt *et al*. 2000). The magnitude of the consequence increases as alkalinity increases, and hence would be more noticeable in high alkalinity waters.

Given that the purpose of this paper is to provide a practical means of predicting CO_2 transfer based on oxygen transfer data for fish culture applications, the equilibrium dissolved CO_2 concentration in the water column is the more relevant parameter, because the equilibrium concentration is what impacts a fish physiologically. Thus, from an engineering perspective, K_La coefficients for CO_2 removal should be based upon equilibrium concentrations of CO_2 as well. Caution should be applied when using K_La values determined from oxygen transfer experiments to predict CO_2 mass transfer coefficients, as the ϕ_E/ϕ_T ratio is lower at high alkalinities (~ 1,000 mg L^{-1}) or as air exposure becomes less complete. For low and moderate alkalinities (< 150 mg L^{-1}), K_La values for CO_2 mass transfer can be assumed to be 0.90 of an established K_La value for oxygen transfer for a specific device when the device causes high air exposure as depicted by Figure 3. Lower values for the K_La for CO_2 relative to that for oxygen should be used for high alkalinity waters and for aerators with moderate air exposure as shown in Figure 2.

$$\phi_E = \frac{(K_L a)_{CO_2}}{(K_L a)_{O_2}} \qquad \text{(Equation 9)}$$

Example Problem

A recirculating tank system has a volume of 100 m^3. Culture tank water is maintained at 20°C and the maximum dissolved carbon dioxide concentration is 30 mg/L. The CO_2 saturation concentration ($Cs_{,CO2}$) is 0.5 mg/L. The following two surface aerators are proposed to maintain the target maximum dissolved carbon dioxide concentration in the culture tank:

	Moderate Air Exposure (MAE) Aerator	**High Air Exposure (HAE) Aerator**
Mean (K_La) $O_2$20 (hr^{-1})	7.71	1.23
Estimated ϕ_E	0.67	0.86
Power, kW	0.60	0.12
Capital Cost	$930	$670

Mass balance analysis shows that the aerators must remove 100 kg/d dissolved carbon dioxide. Calculate the number of aerators required for each choice and the cost effectiveness of the two aerators over their expected life cycle.

Step 1. Calculate the carbon dioxide transfer rate under operating conditions (CTR):

$$\mathrm{CTR} = \frac{(K_L a)_{CO_2} \cdot (C_{tank} - C_s) \cdot Vol_{tank}}{1{,}000}$$

Solving the CTR equation for the moderate air exposure (MAE) aerator:

$$\mathrm{CTR}_{MAE} = \frac{(7.71 \cdot 0.67)\mathrm{hr}^{-1} \cdot (30 - 0.5)\mathrm{mg/L} \cdot 100\mathrm{m}^3}{1{,}000} = 15.2\mathrm{kgCO_2} \cdot \mathrm{hr}^{-1}$$

Solving the CTR equation for the high air exposure (HAE) aerator:

$$\mathrm{CTR}_{HAE} = \frac{(1.23 \cdot 0.86)\mathrm{hr}^{-1} \cdot (30 - 0.5)\mathrm{mg/L} \cdot 100\mathrm{m}^3}{1{,}000} = 3.12\mathrm{kgCO_2} \cdot \mathrm{hr}^{-1}$$

Step 2. Calculate the number of aerators (n) that would be needed for the two aerator choices:

$$n_{MAE} = \frac{100\mathrm{kgCO_2} \cdot \mathrm{day}^{-1}}{(15.2\mathrm{kgCO_2} \cdot \mathrm{hr}^{-1} \cdot 24\mathrm{hr} \cdot \mathrm{day}^{-1})\mathrm{unit}^{-1}} = 0.27 \ \text{units}$$

$$n_{HAE} = \frac{100\mathrm{kgCO_2} \cdot \mathrm{day}^{-1}}{(3.12\mathrm{kgCO_2} \cdot \mathrm{hr}^{-1} \cdot 24\mathrm{hr} \cdot \mathrm{day}^{-1})\mathrm{unit}^{-1}} = 1.34 \ \text{units}$$

In practice, a designer must choose in unit increments and not by fractional units as the above example has shown. Obviously, the choice of 100 kg/d of dissolved carbon dioxide removal was arbitrary and hence, the resulting fractional unit result. The number of units selected then becomes a design choice but typically will be rounded up (to one MAE unit or two HAE units in this case) to ensure that the dissolved carbon dioxide concentration goal is met as a minimum criteria.

Step 3. Calculate the aeration efficiency for each aerator unit, AE_{CO2}:

$$AE_{CO2,\,MAE} = \frac{15.2\mathrm{kgCO_2} \cdot \mathrm{hr}^{-1}}{0.6\mathrm{kW}} = \frac{25.3\mathrm{kgCO_2}}{\mathrm{hr} \cdot \mathrm{kW}}$$

$$AE_{CO2,\,HAE} = \frac{3.12\mathrm{kgCO_2} \cdot \mathrm{hr}^{-1}}{0.12\mathrm{kW}} = \frac{26.0\mathrm{kgCO_2}}{\mathrm{hr} \cdot \mathrm{kW}}$$

Although the HAE aerator has a much lower mass removal rate for dissolved carbon dioxide, both aerators operate at similar energy efficiency per unit mass of dissolved carbon dioxide removed. Energy efficiency may be a key factor in a designer's final choice of aerators as well as the initial capital cost. Both must be considered to make a rational selection.

Step 4. Calculate the life cycle cost of the aerators assuming the aerators operate continuously over the life cycle, which is assumed to be 5 years.

Total Cost = Capital Cost + Operating Cost

To keep the example simple, work with the fractional aerator units required to remove the 100 kg/d of dissolved carbon dioxide. Assume electrical energy cost is $0.10 per kWh.

$$\text{Operating Cost}_{\text{MAE}} = 0.27\text{units}\cdot\frac{0.60\text{kW}}{\text{unit}}\cdot\frac{24\text{hr}\cdot 365\text{day}\cdot 5\text{yr}}{\text{day}\cdot\text{yr}\cdot\text{cycle}}\cdot\frac{\$0.10}{\text{kWh}}=\frac{\$709}{\text{cycle}}$$

$$\text{Operating Cost}_{\text{HAE}} = 1.34\text{units}\cdot\frac{0.12\text{kW}}{\text{unit}}\cdot\frac{24\text{hr}\cdot 365\text{day}\cdot 5\text{yr}}{\text{day}\cdot\text{yr}\cdot\text{cycle}}\cdot\frac{\$0.10}{\text{kWh}}=\frac{\$704}{\text{cycle}}$$

$$\text{Total Cost}_{\text{MAE}} = 0.27\text{units}\cdot\frac{\$930}{\text{unit}} + \$709 = \$960$$

$$\text{Total Cost}_{\text{HAE}} = 1.34\text{units}\cdot\frac{\$670}{\text{unit}} + \$704 = \$1{,}602$$

In the above example, when fractional aerators are used for the calculations, the MAE unit was more cost effective over the 5 year assumed life of the aerator. If the number of aerators is rounded up to one MAE aerator or two HAE aerators instead of using the fractional aerators (since you cannot purchase a fractional aerator), operating costs (if you chose to run the aerators continuously) and total costs become:

$$\text{Operating Cost}_{\text{MAE}} = 1\text{unit}\cdot\frac{0.60\text{kW}}{\text{unit}}\cdot\frac{24\text{hr}\cdot 365\text{day}\cdot 5\text{yr}}{\text{day}\cdot\text{yr}\cdot\text{cycle}}\cdot\frac{\$0.10}{\text{kWh}}=\frac{\$2{,}628}{\text{cycle}}$$

$$\text{Operating Cost}_{\text{HAE}} = 2\text{units}\cdot\frac{0.12\text{kW}}{\text{unit}}\cdot\frac{24\text{hr}\cdot 365\text{day}\cdot 5\text{yr}}{\text{day}\cdot\text{yr}\cdot\text{cycle}}\cdot\frac{\$0.10}{\text{kWh}}=\frac{\$1{,}051}{\text{cycle}}$$

$$\text{Total Cost}_{\text{MAE}} = 1\text{unit}\cdot\frac{\$930}{\text{unit}} + \$2{,}638 = \$3{,}558$$

$$\text{Total Cost}_{\text{HAE}} = 2\text{units}\cdot\frac{\$670}{\text{unit}} + \$1{,}051 = \$2{,}391$$

When the number of aerators is rounded up, the relative costs are reversed and the HAE aerator option has a lower total cost, even though its initial capital cost is higher due to the need to purchase two aerators. As indicated previously, the choice of equipment depends on technical and economic factors that are specific to a particular operation.

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