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CBE 140A: Aeration

## 1 Introduction

The transfer of gases into water is central to how water quality is ensured at industrial scales. Possible contaminants (such as organic matter, heavy metals, debris, and suspended solids) are given time in holding tanks to either settle out of the water or decay into less harmful byproducts. This process decreases the dissolved oxygen, which can harm fish and other wildlife if returned to the environment without restored the water's oxygen level. When sludge is present, certain biological agents are used to eat up these chemicals, requiring dissolved oxygen as fuel. For these and other reasons, aeration is a critical component of the wastewater treatment process. This experiment will characterize the aeration process and relate it to relevant topics from mass transfer.

## 2 Objective

In this experiment, a degassed volume of water will be aerated until saturated with oxygen. The rate of this process will be characterized. The effects of air volumetric flow rate, depth of water being treated, diffuser type, and stirring speed on the rate of aeration can all be explored.

## 3 Theory

Consider the water after completely deoxygenated, just as a flow of air has been reintroduced into the fluid. The relevant theory should describe the rate of mass transfer of oxygen from the air bubble, across the interface to water, and into the bulk of the water. Assuming binary, one-dimensional (radial, in the spherical direction) diffusion of oxygen, Fick's first law tells us:

$$N_A = J_A + x_A \sum N_i = -D \frac{dx_A}{dr} + x_A \sum N_i \quad (1)$$

where  $N$  and  $J$  are the total and diffusional molar fluxes, respectively, in units of moles per time per area,  $D$  is the diffusivity to be determined,  $x$  is the mole fraction, and  $r$  is the radial position in or outside the bubble. The subscript denotes the component of interest, oxygen, and the summation is over all components. Unfortunately, this approach to analysis is not feasible as the interfacial concentrations of oxygen are not known.

Considering the regions of mass transfer, from the bubble bulk to the interface, across the interface, and into the water bulk, we can see this system might be appropriately described by two-film theory. [1, 307] For this model of mass transfer, overall mass transfer coefficients are introduced:

$$N_A = K_G(p_{A,G} - p_A^*) = K_L(C_A^* - C_{A,L}) \quad (2)$$

where  $K_G$  = overall coefficient for driving force in units of pressure,

$p_{A,G}$  = the partial pressure of oxygen in the bubble bulk,

$p_A^*$  = the partial pressure of oxygen which would be in equilibrium with its concentration in the liquid bulk,

$K_L$  = overall coefficient for driving force in units of concentration,

$C_A^*$  = the concentration of oxygen which would be in equilibrium with its partial pressure in the bubble bulk, and

$C_{A,L}$  = the concentration of oxygen in the liquid bulk.

The overall coefficients can be represented by the appropriate function of its individual components. Since this mass transfer process involves steps occurring in series (from bubble bulk to liquid bulk), the resistances, or equivalently the reciprocal of the mass transfer coefficients, can be summed. This can also be shown by algebraic manipulation of the several flux equations, which is shown in [1]:

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{H}{k_L} \quad \text{and} \quad \frac{1}{K_L} = \frac{1}{Hk_G} + \frac{1}{k_L} \quad (3)$$

Here,  $k_G$  and  $k_L$  represent the mass transfer coefficients for only the gas or liquid film, respectively. The Henry's law constant,  $H$  allows for conformity of units and develops as a result of the equilibrium concentration and pressure terms in Equation 2.

For gases that are either highly or sparingly soluble, the value of  $H$  allows one of the terms to become negligible, resulting in either  $K_G = k_g$  or  $K_L = k_L$ . This is identical to stating that all the mass transfer resistance is either in the gas or the liquid phase, respectively.

To predict the rate of aeration, Equation 2 can be combined with a transient mass balance of the system. Assuming the gas is sparingly soluble, we can show:

$$V \frac{dC_A}{dt} = N_A A = K_L A (C_A^* - C_{A,L}) = k_L A \left( \frac{p_A}{H} - C_A \right) \quad (4)$$

Here,  $V$  is the volume of water and  $A$  is the area available for mass transfer, the surface area of all the bubbles. This is the type of differential equation we (or Wolfram Alpha) can solve, combined with an initial condition describing the dissolved oxygen concentration at the outset ( $C_{A,0}$ ). After some algebraic manipulation, the only value still unknown is  $k_L A$ , assuming  $p_A$  is constant:

$$\frac{C_A^* - C_A(t)}{C_A^* - C_{A,0}} = \exp \left[ - \frac{k_L A}{V} t \right] \quad (5)$$

Through introduction of a new variable  $a$ , representing the area for mass transfer per unit volume, the constant term in the exponential of Equation 5 becomes  $k_L a$ . The value of this quantity can be determined experimentally by plotting the logarithm of the left-hand side of Equation 5 as a function of time. After calculating the slope of the line for this plot,  $k_L a$  can be determined empirically. Moreover, correlations exist that can predict  $k_L a$  based on system geometry and components involved. A common option for bioreactors is the Van't Riet correlation, however this requires measurement of mixing power. Figure 18-29 in [2] illustrates the effect of superficial gas velocity and mixing power on  $k_L a$ . Another approach would be to estimate  $k_L$  by itself using empirical correlations of dimensionless groups, typically Sherwood, Reynolds, and Schmidt, requiring estimating the total bubble surface area. These correlations are available in many mass transfer texts and depend on the geometry and conditions of operation, for example, Table 5-17 in [2]. This parameter  $k_L a$  is occasionally referred to as the coefficient of absorption,  $K$ .

Another parameter of interest is the oxygenation capacity,  $R$ . This parameter estimates the amount of oxygen that can be dissolved into one cubic meter of water per unit time, starting with no dissolved oxygen. Temperature is typically removed as a confounding factor by adjusting the rate of mass transfer to its expected value at 10 °C:

$$R_{10} = (k_L a) F C_{A,10}^* V \quad (6)$$

The new variable,  $F$ , is a temperature correction factor if  $k_L a$  was not determined at 10 °C. The saturation concentration of oxygen is 11.3 mg·L<sup>-1</sup> at 10 °C. Temperature correction factors as a function of temperature is provided below.

Table 1: Temperature correction factors.

Temperature, °C	F
0	1.219
2	1.172
4	1.126
6	1.083
8	1.040
10	1.000
12	0.961
14	0.924
16	0.888
18	0.853
20	0.820
22	0.788
24	0.758
26	0.728
28	0.700
30	0.673

## 4 Experimental Apparatus

In Figure 1, the aeration apparatus is illustrated. A tank of water (1), whose depth can be recorded with ruler tape on its side (2), has its dissolved oxygen (D.O.) concentration and temperature recorded by a D.O. Vernier sensor (3). The probe can be connected via bluetooth to a computer for automatic data logging, with the appropriate software installed. Air is fed into the system by a compressor (4), with the volumetric flow rate controlled by a valve (5) and metered by a flow meter (6) before introduction into the water through a diffuser (7). The compressor is turned on by its switch (8). The water can be agitated by a motor-driven impeller (11), which is turned on by switch (9) and whose angular speed can be controlled by (10). An optical tachometer (not shown) can be used to measure the rate of rotation for the impeller shaft. A drain hose is connected to the bottom of the tank and includes a ball valve.

## 5 Safety

The major hazards associated with this experiment are the following: The compressor, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the

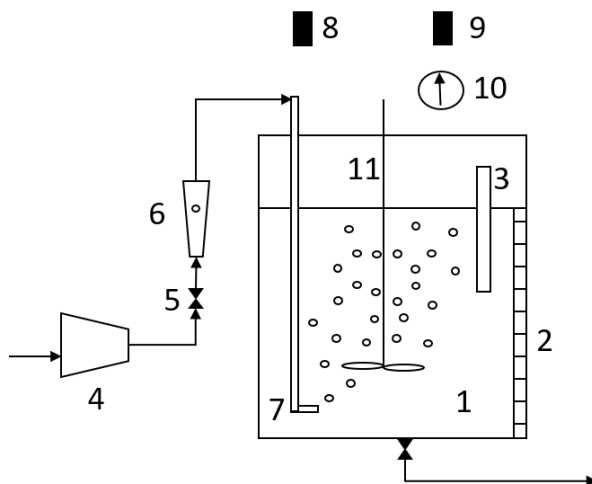


Figure 1: Experiment 6: aeration apparatus.

pump power cord does not become submerged and is not touched when in operation. Through accumulation of biological contaminants in the water, there is also a risk of infection. Contact the instructional staff if you believe the tubing needs cleaned or replaced. If water splashes out of the apparatus, there are risks to clothing damage, slips, and falls. Avoid this by carefully considering the impact of opening or closing of valves prior to acting, and clean spills immediately if they do occur. The stirring impeller shaft introduces a risk of injury if anything is caught by it. Mitigate this risk by ensuring any long hair is tied up and secured. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

## 6 Experimental Procedure

In order to aerate water, it must first be deoxygenated. This is accomplished by chemical means through addition of a 10% sodium sulfite solution and a 1% cobaltous chloride hexahydrate solution. If stock solutions are not available, prepare one liter of each by mixing 111.1 g of sodium sulfite in one liter of deionized water, and dissolve 10.1 g of cobaltous chloride hexahydrate in one liter of deionized water to prepare its solution.

Fill the water tank with roughly 20 liters of water, noting its settled height. Install a single-stone diffuser on the air line. Keep the air compressor off at this time. Add 1.5 mL of the 10% sodium sulfite solution and 0.5 mL of the 1% cobaltous chloride hexahydrate solution to the tank per liter of water to be deoxygenated. Set the stirring rate at a high value to expedite this process. Connect the Vernier D.O. probe to a computer and begin collecting oxygen concentration and temperature data. When the D.O. content reaches a minimum, at most 10% of its initial value, the trial can begin. If this does not occur, increase the stirring rate or add more of the deoxygenating solutions.

When ready to begin, be sure the Vernier D.O. probe is still collecting data. Turn on the air compressor and set the flow rate to 5 liters per minute. Lower the stirring speed as much as possible while still maintaining adequate mixing—note the angular speed with the optical tachometer. Continue to allow the software to periodically record the D.O. content over time until the oxygen concentration begins to approach saturation. Depending on the experimental conditions, this could take up to half an hour.

After a trial is complete, you can either deoxygenate the same water again or drain the tank to the sink and refill with fresh water, as preferred.

For subsequent trials, explore different settings of stirrer speed, air flow rate, type of diffuser, and depth of water.

## 7 Data Analysis

For each trial, characterize the water's aeration by: plotting dissolved oxygen concentration as a function of time; plotting the linearized form of Equation 5, by evaluating the logarithm of each side; calculating  $k_La$  (the coefficient of absorption) and the oxygenation capacity. Compare these charts and values to their expected shapes and values—if there is disagreement, what might be the cause, and is there evidence for it?

Based on the trials you were able to complete, investigate the effect of stirrer speed, air flow rate, type of diffuser, and depth of water on  $k_La$  (the coefficient of absorption) and the oxygenation capacity. Note this is combinatorial, allowing eight methods of analysis. Comment on significant results. Do they agree with the predicted relationships between these parameters? If not, what might be the cause, and is there evidence for it? Is there an optimal combination of settings for a maximum rate of aeration?

## References

- [1] Stanley Middleman. *An introduction to mass and heat transfer*. John Wiley and Sons, Inc., 09 1998.
- [2] Don W. Green, editor. *Perry's chemical engineers' handbook*. McGraw-Hill, eighth edition, 2008.