A Mass Transfer Experiment Using Deoxygenation and Aeration of Water

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Abstract

To demonstrate the phenomenon of mass transfer, an experiment was developed to measure the overall and individual mass transfer coefficients in the opposite processes of deoxygenation and aeration. Both these processes have practical applications in chemical, environmental and mechanical systems.

Streams of N₂ (deaeration/deoxygenation process) or Air (aeration/oxygenation process) were bubbled through a semi batch reactor containing water. The contents of the reactor were mixed using an external recirculating pump to provide uniform conditions of concentration in the reactor. The dissolved oxygen concentration in water can be reduced from the saturation limit of 8-9 mg/L at room temperature to 1-2 mg/L at the end of deoxygenation cycle. In the reverse process of aeration, dissolved oxygen concentration was raised from 1-2 mg/L to the saturation limit.

Dissolved oxygen concentration, volume of aqueous phase, and flow rate and composition of incoming gas stream were continuously measured. Using appropriate mass transfer relationships, experimental data are analyzed for the determination of individual (kₐ and k₈) and overall (Kₐ and K₈) mass transfer coefficients based on liquid (L) and gas (g) phase resistances. Two sets of four mass transfer coefficients (kₐ, k₈, Kₐ and K₈), determined for each process; aeration and deoxygenation, provide a basis for comparison and discussion of results.

The experiment, developed from the Masters’ thesis of one of the authors, offers the chemical and other engineering students an opportunity to understand the theory and application of mass transfer phenomenon and can be performed in one laboratory session of three hours. Only air, nitrogen and water are used in the experiment. Use of potentially harmful chemicals is avoided, resulting in increased safety and cost savings in the purchasing and disposal of chemicals. The experimental setup is simple and inexpensive, and can be developed in-house. In addition to determination of mass transfer parameters, the experiment can also be used for open-ended design problems based on the results from the experiment.
Background
The problem of corrosion due to dissolved oxygen is of major concern in the industrial systems using water. Deoxygenation of tap water is necessary to condition the water properly for industrial purposes such as cooling, steam production, etc. Nitrogen is an inert gas, while oxygen is corrosive to iron, zinc, brass and other metals. The presence of oxygen in the tap water is due to the physical forces and not because of chemical reaction. Dissolved oxygen hastens corrosion by a number of reactions depending on environmental conditions. Chemistry of the corrosion process involves the reaction between the metallic surface ion and oxygen, producing various oxides and hydroxides. Corrosion results in weakening of the material strength. Failure to control corrosion problems can result in high operating and equipment repair costs. Reduction in the influent oxygen concentration in the water stream not only prevents corrosion but also inhibits the growth of microorganisms in the circulation lines. Various methods are available to reduce oxygen content in water. They can be classified into two broad categories: chemical and physical methods. Each method has its own advantages and disadvantages which are widely discussed in the literature\textsuperscript{1,2}.

On the other hand, air (e.g., dissolved oxygen) is very important in the aeration processes of water and wastewater industries. Using oxygen in the aeration tanks prevents growth of anaerobic bacteria in the water treatment and growth of aerobic bacteria in the wastewater treatment plants. Therefore, a considerable amount of expense is involved in providing enough oxygen in both industries. Efficient distribution of oxygen in the treatment tanks is a major design criterion and requires a good understanding of the mass transfer mechanism.

Several mass transfer experiments are currently used in the unit operations laboratories of chemical engineering departments around the country. They vary from simple ‘in-house’ created setups to very sophisticated computer controlled systems. Some of the inexpensive and simple experiments in mass transfer have been reported in articles published in Chemical Engineering Education. Nirdosh and Baird\textsuperscript{3} along with their colleagues have described a series of low cost experiments in mass transfer. These articles have focused on exploring phenomena of liquid-liquid extraction, gas absorption, vapor diffusion and natural convection. Kwon \textit{et al.}\textsuperscript{4} have reported on a simple and inexpensive experiment to measure binary molecular diffusion. Mohammad\textsuperscript{5} has developed a simple mass transfer experiment using nanofiltration membranes which can be used to determine the mass transfer coefficient or diffusivity.

The experiment based on the processes of aeration and deoxygenation, described above, offers the chemical engineering students an opportunity to understand the theory and application of mass transfer phenomenon, and can be performed in one laboratory session of three hours. This experiment has been used in our undergraduate unit operations laboratory for the last eighteen years and was developed from the Masters’ thesis of one of the authors (AP). Only air, nitrogen and water are used in the experiment. Thus, use of potentially harmful chemicals is avoided, resulting in increased safety and cost savings in the purchasing and disposal of chemicals.
Objectives

- **Deoxygenation:**
  1. Determine the overall mass transfer coefficient based on gas phase resistance, $K_g a$.
  2. Determine the individual mass transfer coefficients based on gas phase resistance, $k_{ga}$.
  3. Determine the relationship between mass transfer coefficients and the gas flow rate.

- **Aeration:**
  4. Determine the overall mass transfer coefficient based on liquid phase resistance, $K_L a$.
  5. Compare the results of overall mass transfer coefficient calculated for the two processes of deoxygenation and aeration.

Theory

Mechanism of the deoxygenation of tap water can be viewed as solute (oxygen) diffusing from the liquid phase (water) through the gas-liquid interface to the gas phase (nitrogen) due to a concentration gradient (driving force) existing between the two phases. In this study two-film theory was used to develop theoretical equations of mass transfer. This theory divides the total mass transfer resistances into two individual gas and liquid film resistances. Obviously the concentrations must have a continuous profile, and if the solute concentration were expressed in term of fugacities for the liquid and gas phases, the potential curve would be a continuous function, since the fugacity has the same significance and units for both phases. Since the measurement of diffusion distance (film thickness) is not possible and the transfer mechanism is a combination of molecular and turbulent processes whose relative effects can not be predicted, it is necessary to employ mass transfer coefficient concept which includes the combination of film thickness and diffusivity.

Concentration (partial pressure) gradient between bulk liquid and bulk gas phases is shown in Figure 1 commonly referred to as Two-Film Theory diagram. When the transfer rate through the film reaches a steady state value, the net mass transfer rate through the two films is the same:

$$N = k_g (P_g - P_{gi}) = k_L (C_{Li} - C_L)$$

(1)

The ratio of $k_L / k_g$ has been assumed constant for the above derivation of the rate equations. However, in actual practice surface effects, waves and other phenomena can complicate these relationships. Since the measurement of the interfacial partial pressure, $P_{gi}$ or concentration, $C_{Li}$ is a difficult task, a slight modification of Equation (1) is made by using Henry's law without changing the concept of the two film theory. The equilibrium values of the partial pressure or concentration, defined by $P^*$ and $C^*$ are related through Henry's law constant:
\[ H = \frac{P_g}{C_L^*} = \frac{P_g^*}{C_L} \quad (2) \]

where \( P_g \) and \( C_L \) are partial pressure and concentration of the solute, respectively. Thus the mass transfer rate can be expressed based on liquid or gas phase overall mass transfer coefficients as:

\[ \frac{dm}{dt} = \frac{(C_g^* - C_g)}{(1/K_g^a)} = \frac{(C_L^* - C_L)}{(1/K_L^a)} \quad (3) \]

where,

\[ \frac{1}{K_g} = \frac{1}{k_g} + \frac{H^*}{k_L} \quad (4) \]

\[ \frac{1}{K_L} = \frac{1}{H^* k_g + 1/k_L} \quad (5) \]

The resistance to mass transfer \((1/K_L^a)\) is a function of the gas phase Reynolds’ number and is described by Equation (6) below:

\[ \frac{1}{K_L^a} = f(N_{Re}\text{gas}) + \text{Constant} \quad (6) \]

**Methodology**

A schematic diagram of the experimental setup is shown in Figure 2 along with a photographic image in Figure 2A. The experimental apparatus consisted of a 7.3 liter Pyrex glass vessel with inside diameter of 13.5 cm and height of 51 cm. The tube from the gas cylinder is immersed in the column just one centimeter from the bottom of the reactor. In the deoxygenation process the nitrogen gas (air in aeration process) is sparged into water through a nozzle with 3 mm inside diameter. The gas stream from the cylinder is passed through the vessel via the rotameter, which ranges from 120 to 2600 ml/min. The measurement of the dissolved oxygen (DO) is facilitated by inserting an oxygen self-stirring probe which is connected to a Digital Dissolved Oxygen Meter (YSI Model 58). This meter reads oxygen concentration from 0 to 20 mg/l and measures temperature from 0 to 45°C. The DO meter is calibrated according to the manufacturer specifications on a daily basis.

Contents of the vessel are well mixed by circulating water through a 4.5 mm ID plastic tube and a pump with a flow rate of 4.4 l/min. This helps in three ways: 1- allows sufficient mixing, 2- aids in breaking up the gas bubbles, and 3- eliminates the vortex formed at the surface. The experiment is carried out as follows:

The vessel is filled with tap water to the set height. The temperature of the water is recorded. The location of the dissolved oxygen probe is 2 cm below the water level. The water circulation pump is started and the initial reading for the dissolved oxygen concentration is read from the DO meter’s digital monitor. Once this is done, nitrogen gas is introduced at a known flow rate
and pressure, and the timer is started immediately. The nitrogen at steady state flow rate now begins to strip the dissolved oxygen, and the residual dissolved oxygen as read by the meter is recorded at a preselected time interval (e.g., one minute).

The aeration studies are conducted in the same manner, except air replaces nitrogen in the system and the process proceeds in a reverse manner. This step should immediately proceed after deoxygenation is completed by introducing air to the vessel. The process is continued until the oxygen concentration reaches the saturation level; the solubility of oxygen in water varies considerably with temperature. The concentration of dissolved oxygen is again measured over the entire time period.

**Results and Discussion**

Sample results from this experiment are shown in Figures 3-7. Oxygen elimination from the tap water by using nitrogen gas was one of the primary goals of this work. Concentration of DO in water versus time data were mathematically treated using theoretical equations to determine the mass transfer rate and coefficients. Various nitrogen flow rates ranging from 120 to 900 ml/min were applied and the instantaneous DO concentrations were determined (Figure 3). The final concentration of DO was about .05-.1 mg/L for all runs. As the N₂ flow rate increased from 120 to 900 mL/min, the time required to deplete DO reduced from 30 to 15 minutes. The experimental concentration data in conjunction with the proposed rate equation (Equation 3) gives the required mass transfer coefficients based on gas phase resistance. The proposed mass transfer equation suggests a linear relationship between the rate and concentration. The calculated rate using the experimental data is also graphically shown in Figure 4. The linear relationship between the rate of deoxygenation and oxygen concentration in the gas phase (N₂) was well satisfied. The slope of the lines present the overall mass transfer coefficients based on gas phase (OMTC). The relationship between the calculated OMTC and flow rate is presented as a Wilson plot in Figure 5, depicting the relationship between the mass transfer resistance and the inverse of gas flow rate according to Equation (6). The calculated OMTC in conjunction with Equations (5 & 6) were used and the individual mass transfer coefficients (k_g) were determined which ranged from 1.34 * 10⁻³ to 6.9 * 10⁻³ cm/sec for flow rates ranging from 120 to 900 mL/min, respectively.

The aeration process was primarily done to compare the results to the deoxygenation process. Similar methodology was followed and air instead of N₂ was used. The concentration profiles obtained for various air flow rates are shown in Figure 6. As expected the concentration of DO increased with increasing air flow rate. It took between 8-12 minutes to reach the saturation concentration. The experimental data were treated according to Equation (3) and the calculated values of mass transfer rate are graphically presented (Figure 7). Again, there was a direct relationship between the air flow rate and the overall mass transfer coefficients based on the liquid phase, which is presented in Figure 5.

Slopes of the lines representing K_{g,a} and K_{L,a} were determined according to Equation (3) from
plots of mass transfer rates, \( \frac{dm}{dt} \) vs. gas phase driving force \((C_g^* - C_g)\) and liquid phase driving force \((C_L^* - C_L)\), respectively. Equations (4) and (5) were then used to calculate individual mass transfer coefficients, \( k_g \) and \( k_L \). Typical values of these constants at various gas flow rates are given in Table 1.

### Table 1: Overall Mass Transfer Coefficients (\( K_L a \) & \( K_g a \)) and Individual Film Resistances (\( 1/k_a \)) for Various Nitrogen Flow Rates

<table>
<thead>
<tr>
<th>Nitrogen Flow Rate (L/min)</th>
<th>( K_L a ) (L/min)</th>
<th>( K_g a ) (L/min)</th>
<th>( 1/k_g a ) (min/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>0.43</td>
<td>0.018</td>
<td>44</td>
</tr>
<tr>
<td>0.29</td>
<td>0.66</td>
<td>0.024</td>
<td>30</td>
</tr>
<tr>
<td>0.56</td>
<td>0.82</td>
<td>0.033</td>
<td>19</td>
</tr>
<tr>
<td>0.90</td>
<td>1.33</td>
<td>0.042</td>
<td>12</td>
</tr>
</tbody>
</table>

**Summary**

An experiment based on this paper can provide useful training in the area of mass transfer operations to undergraduate students in the Chemical, Mechanical, Civil and Environmental Engineering disciplines. Besides general laboratory supplies and recirculating pump, together costing about $200-$300, the only major piece of equipment needed is the Dissolved Oxygen Monitor, which costs about $1,000-$1,200. Thus the total cost of the experiment is under $1,500. A PC-based data acquisition system can be easily integrated to the apparatus, making data analysis and calculations easier. By the addition of a Monsanto Prism Separator, upstream of the bubble reactor, mixtures of \( N_2/O_2 \) over a wide composition range can be obtained adding versatility to the experiment.

**Nomenclature**

- \( C_L \): solute concentration in the liquid phase, mass/volume,
- \( C_{Li} \): solute concentration at the gas-liquid interface, mass/volume,
- \( H \): Henry's law constant, partial pressure/concentration.
- \( k_{La} \): individual mass transfer coefficient based on liquid phase, \((IMTC)_{L}\),
- \( k_{Ga} \): individual mass transfer coefficient based on gas phase, \((IMTC)_{g}\),
- \( K_{La} \): overall mass transfer coefficient based on liquid phase, \((OMTC)_{L}\),
- \( K_{Ga} \): overall mass transfer coefficient based on gas phase, \((OMTC)_{g}\),
- \( N_A \): flux, mass/(area)(time),
- \( P_g \): solute (oxygen) partial pressure in the gas phase,
- \( P_{gi} \): solute (oxygen) partial pressure at the gas-liquid interface.
References

BIOGRAPHICAL INFORMATION

Dr. RAMESH C. CHAWLA is a professor of chemical engineering at Howard University. He has over thirty years of experience in teaching, research and industrial consulting in the fields of chemical and environmental engineering. His research and teaching interests include reaction engineering, separation processes, environmental engineering, and physical, chemical and biological treatment of hazardous wastes.

Dr. ALI POURHASHEMI is the Chairman of Chemical and Biochemical Engineering Department at Christian Brothers University in Memphis, TN. He has taught various courses in chemical engineering and has been very instrumental in upgrading and developing new experiments in the unit operations laboratory courses. His research interests are in the areas of the heat and mass transfer.
Figure 1. Concentration (Partial Pressure) Gradient between Bulk Liquid and Bulk Gas Phase

Figure 2. Schematic Diagram for Experimental Setup
Figure 2A. A Photographic Image of the Experimental Setup

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Figure 3. Dissolved Oxygen Concentration in Water for Various N2 Flow Rates

Figure 4. Rate of Deoxygenation as a Function of the Gas Phase Concentration
Figure 5. Relationship between Overall Mass Transfer Resistance and Gas Flow Rate for Deoxygenation & Aeration Systems

1/(Gas Flow Rate)^0.8

System
- Aeration
- Deoxygenation

$1/K_g^a \& 1/K_L^a, \text{min/cm}^3$
Figure 6. Dissolved Oxygen Concentration in Water at Various Air Flow Rates

Figure 7. Rate of Aeration as a Function of Liquid Phase Concentration at Various Air Flow Rates