

Gas Dissolution, Release, and Bubble Formation in Flotation Systems

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Abstract The theories and principles of gas dissolution, release, and bubble formation in gas flotation systems are introduced in detail for process design, optimization, and operation. Also introduced is a new instrument for real-time measurement of bubble content and size distribution in a typical flotation system consisting of gas bubbles (gas phase) and bulk water (liquid phase). Specific engineering topics included in this chapter are: gas dispersion principles, gas dispersion tester, bubble tester operation, gas dispersion example, gas transfer principles, Henry's Law constants, partial pressures, solubilities of various gases, gas dissolution and release, gas bubble formation and size distribution, bubble attachment, bubble rising and flotation, gas dissolution in water containing high dissolved solids or high salinity, and engineering design examples.

Key Words Adsorptive bubble separation processes • dissolved gas flotation • dispersed gas flotation • air flotation • gas dissolution • bubble formation • flotation systems • process design • gas dispersion tester • gas solubility • dissolved oxygen concentration • DO.

1. INTRODUCTION

Bubble dynamics is of great importance in optimizing the engineering design and operating parameters of various adsorptive bubble system operations, such as dissolved air flotation and dispersed air flotation, for the separation of solids from a liquid.

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The purpose of this chapter is to present a new instrument for real-time measurement of bubble content and size distribution in a typical bubble flow reactor where air bubbles and bulk water are the gas phase and liquid phase, respectively. This chapter introduces the operation of a newly developed air dispersion tester (or bubble generation tester), its theory, principles, operational procedures, analysis, typical examples, and design applications for air flotation systems.

2. BUBBLE SEPARATION PROCESSES

Adsorptive bubble separation processes are used to concentrate or separate materials that may be molecular, colloidal, or macroparticulate in size. The material is selectively adsorbed at the surfaces of bubbles rising through the liquid, and the efficiency of the separation process depends partly on differences in surface activity and, importantly, also on the number and size of the gas bubbles.

Adsorptive bubble separation processes (such as dissolved air flotation and dispersed air flotation) have many significant industrial applications including liquid industrial effluent treatment, water purification, activated sludge thickening, oil–water separation, cellulose fiber concentration, etc. (1–14). A 37.5 MGD flotation–filtration plant (14) and a 1.1 MGD flotation–filtration plant (3, 4) have been operating in Pittsfield, Massachusetts and Lenox, Massachusetts, respectively, for potable water production. A dissolved air flotation clarifier is operating for secondary clarification at an 18-MGD activated sludge plant in Texas (11). Here 1 MGD = one million gallons per day = 3.785 MLD = 3.785 million liters per day. Theoretical explorations and investigations of bubble dynamics and air dispersion mechanisms have become increasingly important to engineers in the design of such flotation systems.

The air pressure for generation of the air bubbles is the major parameter controlling air solubility in an air flotation unit and is an important factor in flotation operation. The total volume and size of air bubbles produced on depressurization is proportional to the pressure of the process stream, the rate of flow, and the pressure reducing mechanism. Large air bubbles produce a fast, turbulent rise rate resulting in reduced air–solids contact time and bubble surface area. More efficient solids removal is obtained with smaller air bubbles because of increased contact time and total bubble surface area.

An adequate air pressure generation system for optimum results in an adsorptive bubble separation process involving the use of dissolved air is needed to satisfy the requirements of air volumetric flow rate, bubble rising velocity, and power consumption. Usually, the amount of dissolved air is about 0.5–3.0% of the water volume. This amount should be adjustable and measurable. The optimum rising velocity of the air bubbles is about 12 in/min (30.5 cm/min) and should not be below 5 in/min (12.5 cm/min), nor over 20 in/min (50 cm/min). The air dispersion system must allow adjustment of the bubble rising velocity, and the proportion of the different rising velocities of the dispersed air bubbles. Power consumption is an important economic factor. For a dissolved air flotation system operated at full flow pressurization mode, the power consumption should be less than 13 Hp/m³/min (50 Hp/1,000 gpm). For DAF systems operated at partial flow pressurization mode, the power consumption should be less than 7 Hp/m³/min (27 Hp/1,000 gpm). Here 1 Hp = 1 horsepower = 746 watts = 0.746 kW. All the aforementioned parameters need to be optimized for a specific system. Additional references on various adsorptive bubble separation processes can be found from the literature elsewhere (15, 16).

3. GAS BUBBLE DISPERSION

3.1. Gas Dispersion Tester

A quick method for determining percent air, bubble size, and volume distribution would be useful for evaluating and improving the efficiency of air dissolving, power consumption, and bubble formation in an air flotation unit. An air dispersion tester (see Figs. 2.1 and 2.2) has

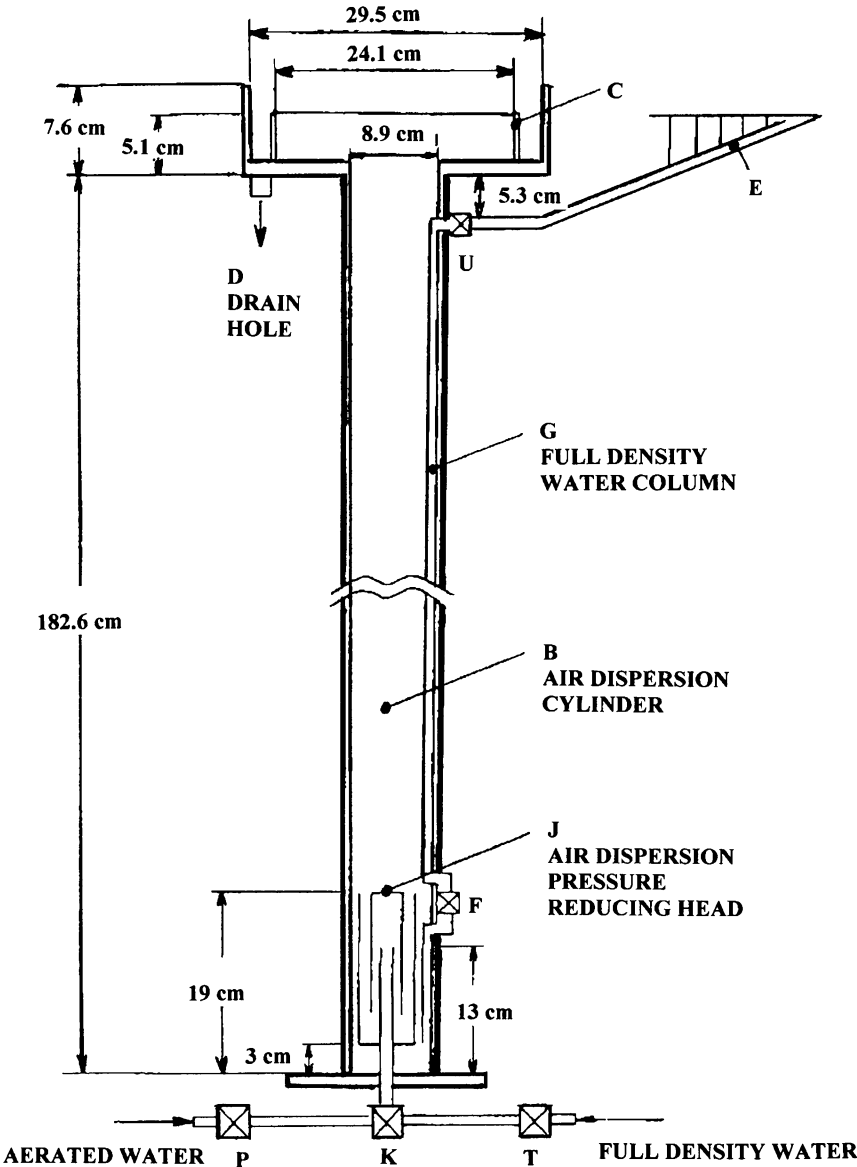


Fig. 2.1. Air dispersion tester.

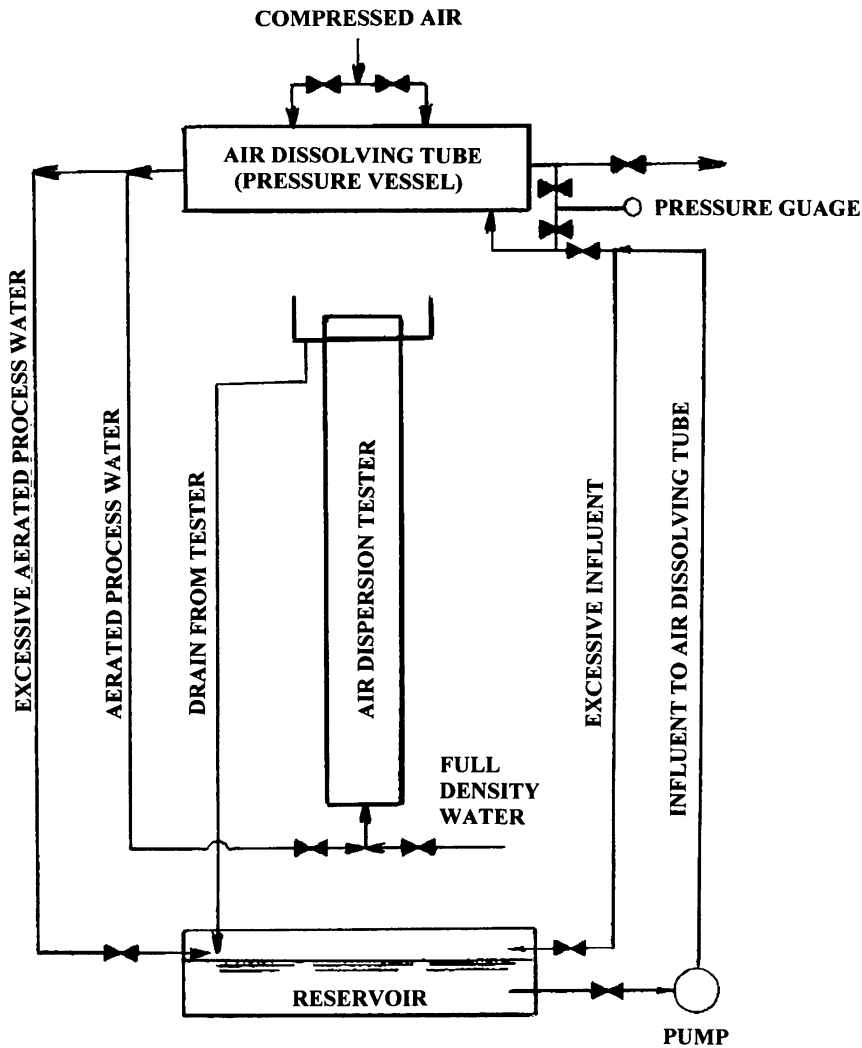


Fig. 2.2. Experimental system setup.

been developed to measure the percent air content in an air flotation process stream. A narrow Plexiglas cylinder is attached to a larger diameter Plexiglas air dispersion cylinder, and both are open to atmospheric pressure at the top. An overflow is provided with a drain to allow continuous feed through the tester. Separate inlet valves for water at atmospheric pressure and pressurized process flow are mounted at the bottom of the instrument. A small untreated water column is a few centimeters above the bottom plate and rises vertically to the bottom of the large, outside Plexiglas air dispersion cylinder. The untreated water column is then extended with a transparent plastic tube around the perimeter of the large cylinder stopping at the top level of the tester. The transparent plastic tube is calibrated in percent air volumes, and the slope of the tube is determined by the percent change in height. The difference in level

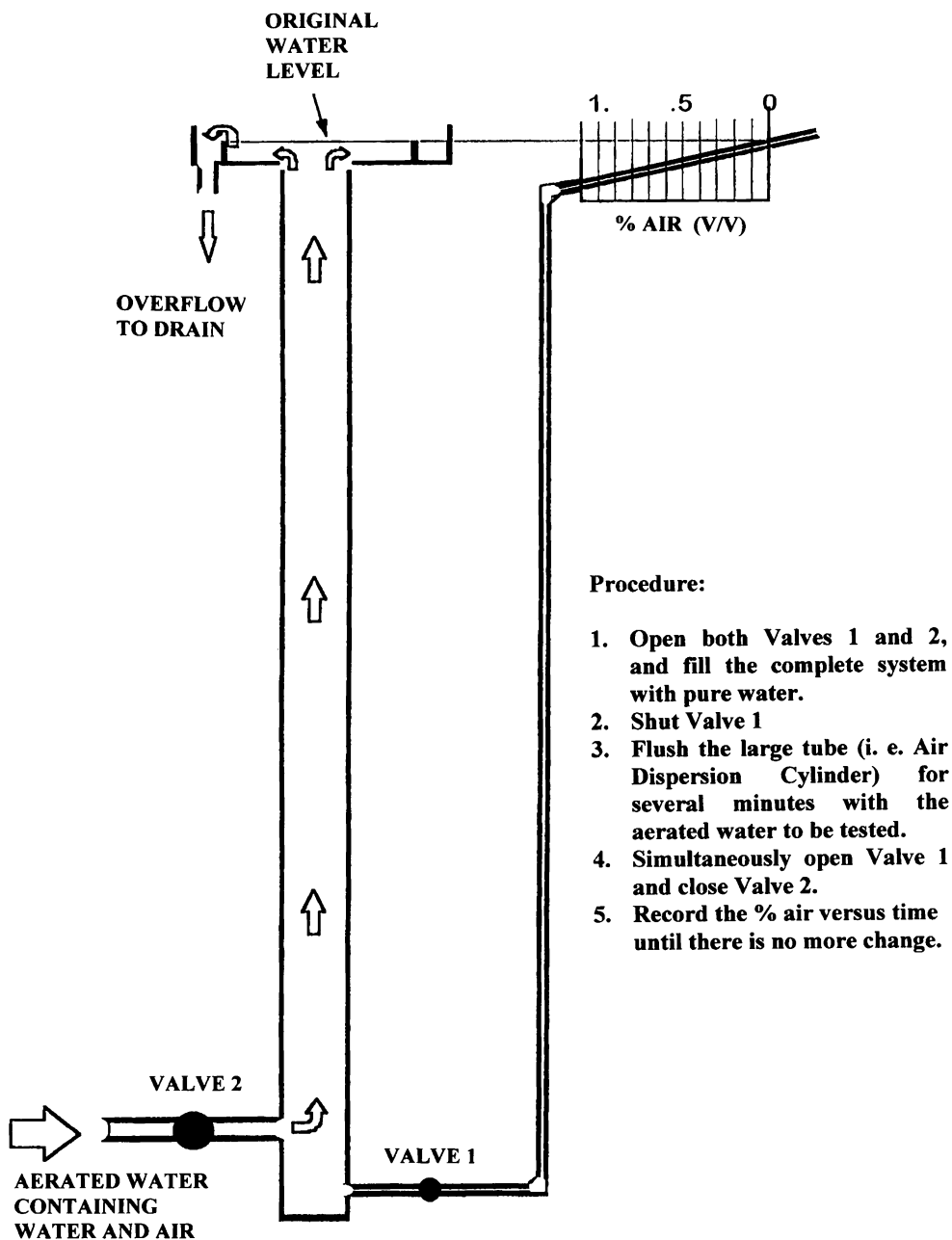


Fig. 2.3. Experimental procedure.

in the transparent tube expressed in percent of the total height of the tester is equal to the percent air content. Extending the tube on a horizontal incline over 7.6 cm in height facilitates in establishing a precise graduation for percent air readings.

Supersaturated process water from the air flotation unit enters through a pressure reducing valve into the main air dispersion cylinder for a period of a few minutes. The flow is stopped and the gate valves separating the aerated process water and untreated are opened (see Fig. 2.3). This causes the level in the small transparent tube to drop in proportion to the percent air content of the process water in the air dispersion cylinder. Calibrated readings are recorded at 30–120 s time intervals and graphically plotted vs. time. The curve can be approximated with a number of straight lines, each corresponding to fine, medium, or coarse bubble diameters and their respective rising velocities.

3.2. Gas Dispersion Principles

Discrete particle flotation in a bubble separation process unit under laminar flow conditions is given by Stoke's law: Stoke's law can be used to calculate the bubble rise rate, or the falling rate of a spherical object in a fluid, such as water. Such an object reaches a terminal velocity when the gravitational force, buoyancy, and the viscous drag reach a net equilibrium. For a gas bubble with essentially no mass, the terminal velocity is reached when the buoyancy force equals the drag force.

$$(3.14)(D^3)(d_W - d_B)g = 18(3.14)vDV_T, \quad (1a)$$

$$V_T = g(d_W - d_B)D^2/(18v), \quad (1b)$$

where D is the diameter of a spherical gas bubble, m; V_T is the terminal velocity of a spherical bubble diameter D , m/s; d_W is the density of water, kg/m³; d_B is the density of gas bubble, kg/m³; v is the water viscosity, Pa s; and g is the gravitational acceleration = 9.8 m/s².

The Reynolds number must be less than 1.0 for Stoke's law to apply. The spherical particle can be a bubble or an air–solid–oil floc having a specific gravity of less than 1, thus causing a negative terminal velocity, or a rising velocity. The bubble size is affected by the pressure in the bubble formation, viscosity, and surface tension of the fluid.

Free air is defined as air under the conditions prevailing at the air pump or air blower inlet. Standard air is defined in air blower work as air at a temperature of 68°F (20°C), a pressure of 14.7 psig (101.3 kPa), and a relative humidity of 36%. Standard air has a specific weight of 0.0750 lb/ft³ (1.20 g/L). The specific weight of air varies at sea level from 0.0776 lb/ft³ (1.24 g/L) at 50°F (10°C) to 0.0724 lb/ft³ (1.16 g/L) at 86°F (30°C). One standard atmosphere pressure = 10.333 m of water = 33.899 ft of water = 14.696 lb/in² = 101.325 kPa = 101.325 kN/m² = 1.013 bar.

3.3. Gas Dispersion Tester Operation

The installation of the newly developed air dispersion tester (or bubble generation tester) is described in Figs. 2.1 and 2.2. Figures 2.4 and 2.5 illustrate two different types of tester operations, types 1 and 2 consecutively.

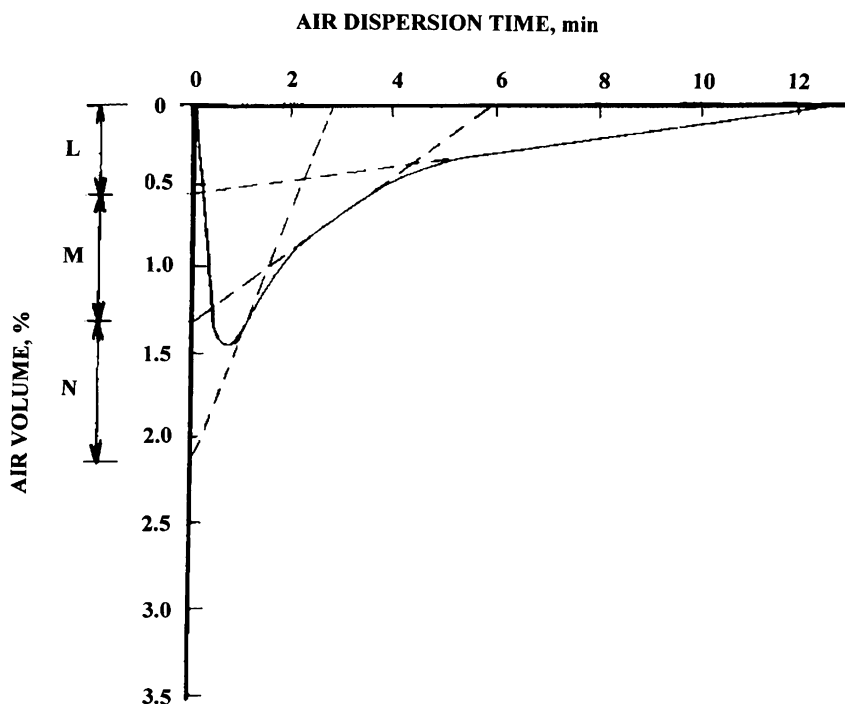


Fig. 2.4. Type I air dispersion test.

3.3.1. Type I Test

The air dispersion tester is initially filled with tap water or process water with valve P closed and valves T, F, and U open. After the tester is full, valves T and F are closed and valve P is opened for continuous and uniform feed of aerated process water. The aerated process stream is introduced through inlet valve P and is allowed to flow until it has filled the vertical air dispersion cylinder B and the larger open cylinder at the top C (exposed to atmospheric pressure) and has overflowed through drain D. The pipe connection between valve P and the inlet into the tester should be as short as possible. After a period of 2–5 min, valve P is closed and valve F is opened, timing is begun and the percent air level in the transparent tube E is measured in adequate time intervals. At this time, the water in tube E and column G (at least 80% smaller in diameter than cylinder B) is allowed to enter the main air dispersion cylinder B. The water from tube E replaces a portion of the aerated process stream in cylinder B in direct proportion to its greater density. The drop in level of water in tube E is determined by calibration markings on the tube and converted by a calibration curve (Fig. 2.1) to percent air in the aerated process stream. The change in density with time can be charted as shown in Fig. 2.4 for this testing (Type I Test). Tangents to the curve shown in Fig. 2.4 are denoted L, M, and N. Their intersection with the upper abscissa gives the average time, in min, for a bubble to rise through the height of cylinders B and C. The intersection of L tangent with the ordinate indicates the percent air in water for the L size bubbles. When the

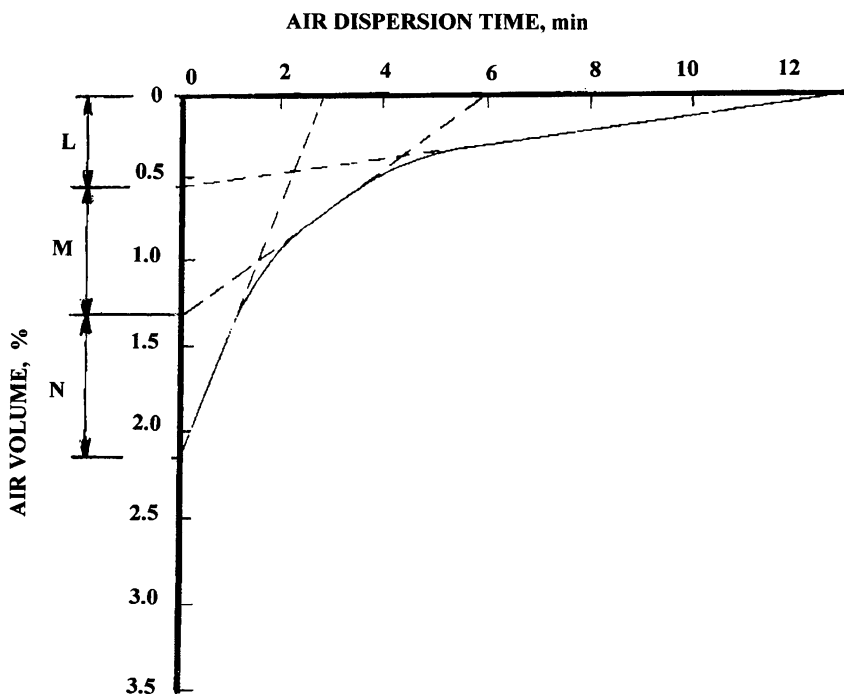


Fig. 2.5. Type II air dispersion test.

value is subtracted from the intersection point of the M tangent, the percent air in water is determined for the M size bubbles, etc. Thus the total volume of generated air for each size of bubbles may be determined.

3.3.2. Type II Test

The air dispersion tester is initially filled with tap water or process water with valve P closed and valves T, F, and U open. After the tester is full, valve T is closed and valve P is opened for continuous and uniform feed of aerated process water. After over 5 min and when a steady-state condition is reached, valve P is closed, timing is begun, and percent air vs. time is recorded. Figure 2.5 is explained in a typical example.

Application of Stokes law to the available data enables the bubble size distribution to be assessed. This can be accomplished automatically by interposing a pressure transducer to sense the pressure differential between column G and cylinder B. The transducer generates an electronic signal outputted to an appropriately programmed computer so that real-time bubble size distribution data can be displayed.

Tests should be carried out with water or wastewater with known characteristics. Results and conclusions should be reported of investigations that have been undertaken with the bubble generation instrument (air dispersion tester) to determine the effect on bubble size distribution under various operating conditions: air compressor pressure, dissolving tube pressure, pump pressure, rotameter levels, air flow rate, bubble rise rate, water and air

temperatures, surface tension and viscosity of water (bubble formation conditions), chemical addition (if any), and presence of various particulates (if any).

The tester should be carefully examined and all its dimensions (diameters, heights, tube volume, overflow volume, etc.) measured. A flow diagram illustrating the air dissolving tube and the air dispersion tester is presented in Fig. 2.2.

In actual operation, the bleed-off valve should be checked. The time of air input into the tester and the rise rate of air–water interface should be recorded.

The data to be presented for discussion should include, but not be limited to: the percent total air content, percent of air bubbles in the water, air bubbles rise rates, and bubble sizes.

3.4. Gas Dispersion Example

3.4.1. Construction and Testing of an Air Dispersion Tester

A vertical transparent plastic air dispersion cylinder B, 8.9 cm ID, 182.6 cm long is closed at the base by a 1.59 cm thick plastic base (see Fig. 2.1). An inlet tube rises from the base to 13 cm above the interior base where there is an air dispersion head. This inlet may either admit fresh tap water (or process water) from valve T or water with dissolved and entrained air to be tested from valve P. There is an additional base valve K with two positions that determine this source selection. When the pipe that normally supplies untreated water is opened to the drain, the water in the cylinder may be drawn down to the level of the input tube, which rises through the base to approximately 13 cm above the base. Figures 2.1 and 2.2 show the entire system for air dispersion testing.

A copper tube called the raw water column G is inside the 8.9 cm ID air dispersion cylinder (for the sake of heat transfer). The top of the copper tube G which is 5.3 cm below the overflow drain hole is extended to a sloping transparent high-resolution volumetric level indicator, as shown in Fig. 2.1. The volumetric level indicator is made of transparent plastic tubing (74.3 cm effective length) and is calibrated for determination of “percent air in water.” Zero to 5% air volume is uniformly scaled on a 73.7 cm horizontal line. The slope of the transparent plastic tubing E is 7.6 cm/73.7 cm equal to 0.103. There is a valve U at the point where the copper tube exits the air dispersion cylinder B to fill the high-resolution volumetric level indicator.

At the top of the air dispersion cylinder there is a 24.1 cm diameter overflow dish 5.1 cm deep. This overflow dish is made level. The volumetric indicator shown in Fig. 2.1 is a board with the high-resolution sloping tube for the untreated water. A supplemental volumetric indicator is the periphery of the 29.5 cm ID dish that receives the overflow.

The air dispersion cylinder B that contains the water samples for testing is mounted vertically with valves P and T positioned to permit a short path of direct transfer of water sample to the cylinder. The air dispersion cylinder B is sufficiently long and large in diameter, in order to slow the flow rate of the sample transfer, increase the resolution with the larger sample volume, permit an internal graduated mark to be used for measuring the rising velocity of bubbles, and allow the stages of changing bubble velocity to be observed for a wide range of bubble sizes.

Table 2.1
Experimental conditions for Type II test

Measurement	Value
Air dissolving tube effluent flow to reservoir, L/min	19
Air dissolving tube effluent flow to tester, L/min	12
Air dissolving tube total flow, L/min	31
Air flow, std (Meter A), L/min	0.2
Air flow, std (Meter B), L/min	0.2
Air pressure, psig	80
Air dissolving tube water pressure, psig	60*
Air dissolving tube diameter, cm	11.4
Air dissolving tube length, cm	88.9
Wastewater source	Gray water
Wastewater temperature, °C	24

*60 psig = 413.7 kPa.

Table 2.2
Air dispersion data for Type II test

Time, min	Air volume, %
0	2.10
0.25	1.95
0.50	1.80
1.00	1.50
1.50	1.15
2.00	0.90
4.00	0.50
6.00	0.34
8.00	0.25
10.00	0.15
12.00	0.05
12.50	0

3.4.2. Experimental Results

As an example, the Type II Test was conducted for an aerated wastewater whose experimental conditions are shown in Table 2.1. The air dispersion data for the Type II Test were recoded as shown in Table 2.2.

The air dispersion data are plotted in Fig. 2.5 and the calculations are shown below:

Fine bubbles (L):

Fine air bubbles in water = 0.55%

Fine bubbles in all bubbles = 25.6%

Fine bubbles rising velocity = 14.4 cm/min

Medium bubbles (M):

Medium air bubbles in water = 0.8%
 Medium bubbles in all bubbles = 37.2%
 Medium bubbles rising velocity = 42.7 cm/min

Coarse bubbles (N):

Coarse air bubbles in water = 0.8%
 Coarse bubbles in all bubbles = 37.2%
 Coarse bubbles rising velocity = 125 cm/min

Total bubbles:

All air bubbles in water = 2.15%
 Sum of all bubbles = 100%

The air bubbles rising velocities were estimated by the following equation:

$$V_T = D_e/t, \quad (2)$$

where V_T is the bubbles vertical rising velocity, cm/min; D_e is the effective depth of air dispersion cylinder, cm; and t is the bubbles traveling time to water surface, min.

The aforementioned bubbles rising velocities were calculated as follows:

Fine bubbles rising velocity = $187.7/13 = 14.4$ cm/min
 Medium bubbles rising velocity = $187.7/4.4 = 42.7$ cm/min
 Coarse bubbles rising velocity = $187.7/1.5 = 125$ cm/min

This is an example of too much air (2.15% of air bubbles in water) and too coarse air dispersion (37.2% of air bubbles are coarse bubbles).

Knowing the water temperature, bubble terminal rising velocity, kinematic viscosity (from Table 2.3), specific gravity of air bubbles (from Table 2.4), and gravitational acceleration coefficient, one can then calculate the average diameter of spherical air bubbles using Eq. (1a). Application of Eq. (1a) for determination of the rise rate of a gas bubble is presented in Sect. 4.

4. GAS TRANSFER, DISSOLUTION, RELEASE, AND FLOTATION

4.1. Gas Transfer Principles

When a gas is in contact with the surface of a liquid, the amount of the gas that will go into solution is proportional to the partial pressure of that gas. A simple rationale for Henry's law is that if the partial pressure of a gas is twice as high, then on the average twice as many molecules will hit the liquid surface in a given time interval, and on the average twice as many will be captured and go into solution. For a gas mixture, Henry's law helps to predict the amount of each gas that will go into solution. However, different gases have different solubilities and this also affects the rate. The constant of proportionality in Henry's law must take this into account (17–25).

Table 2.3
Viscosity and specific weight of water

Temperature, °F	Specific wt, lb/ft ³	Absolute viscosity ^{a,c} , lb-s/ft ²	Kinematic viscosity ^{b,c} , ft ² /s
32	62.42	3.746	1.931
40	62.43	3.229	1.664
50	62.41	2.735	1.410
60	62.37	2.359	1.217
70	62.30	2.050	1.059
80	62.22	1.799	0.930
90	62.11	1.595	0.826
100	62.00	1.424	0.739
130	61.55	1.069	0.558

^aTo convert to centipoise, divide by 2.088×10^{-5} . 1 centipoise = 10^{-2} g/cm-s.

^bTo convert to centistokes, divide by 1.075×10^{-5} . 1 centistoke = 10^{-2} cm²/s.

^cValues, $\times 10^{-5}$.

Table 2.4
Typical values for the specific weight of ambient air at relative humidity of 36%

Elevation (ft)	Pressure (psi)	Temperature		
		10°C	20°C	30°C
		Specific weight of air		
0	14.7	0.0776	0.0750	0.0724
1,000	14.2	0.0750	0.0724	0.0701
2,000	13.7	0.0722	0.0697	0.0674
4,000	12.7	0.0670	0.0648	0.0625

All specific weights are in lb/ft³ (1 g/cm³ = 62.43 lb/ft³). 1 ft = 0.3048 m. 1 psi = 6.895 kPa.

Table 2.5 gives the Henry’s law constants for sparingly soluble gases, such as air, carbon dioxide, carbon monoxide, hydrogen, hydrogen sulfide, methane, nitrogen, and oxygen (23). The values in Table 2.5 should be multiplied by 10⁴ to obtain atm/mol fraction.

The partial pressure of gases at sea-level (i.e., 1.0 atm total pressure, or 0.0 m elevation above mean sea level) is given in Table 2.6. Specifically, Table 2.6 presents the partial pressures of the gases in air (nitrogen, oxygen, argon, carbon dioxide, methane, and carbon monoxide) in a natural atmosphere under 1 atm total pressure and dry air conditions. The same table also shows the percent volume of various gas components in dry air. For instance, the percent volumes of nitrogen, oxygen, argon, and carbon dioxide gases in dry air are 78.9%, 20.95%, 0.93%, and 0.032%, respectively.

When aquatic environmental systems are open to the atmosphere, there are two ways for gas transfer: (a) gases from the atmosphere are free to dissolve into the aqueous phase; and (b) gases from the aqueous phase are free to escape into the atmosphere. Equilibrium is defined as

Table 2.5
Henry's law constants for sparingly soluble gases

$T(^{\circ}\text{C})$	Air	CO_2	CO	H_2	H_2S	CH_4	N_2	O_2
0	4.32	0.073	3.52	5.79	0.0268	2.24	5.29	2.55
10	5.49	0.104	4.42	6.36	0.0367	2.97	6.68	3.27
20	6.64	0.142	5.36	6.83	0.0483	3.76	8.04	4.01
30	7.71	0.186	6.20	7.29	0.0609	4.49	9.24	4.75
40	8.70	0.233	6.96	7.51	0.0745	5.20	10.4	5.35
50	9.46	0.283	7.61	8.65	0.0884	5.77	11.3	5.88
60	10.1	0.341	8.21	7.65	0.1030	6.26	12.0	6.29

Multiply values in the table by 10^4 to obtain atm/mol fraction.

Table 2.6
Partial pressure of gases in a natural atmosphere (23)

Gas	$p_{i,h}$
N_2	0.7809
O_2	0.2095
Ar	0.0093
CO_2	0.00032
CH_4	0.0000015
CO	0.0000001

1 atm total pressure and dry air conditions.

the conditions when the number of gas molecules that enter the aqueous phase is equal to the number escaping into the gas phase. Equilibrium conditions represent the maximum (i.e., saturation) concentration of a dissolved gas in solution (26, 27).

4.2. Henry's Law Constants, Partial Pressures, and Solubilities of Various Gases

Gas solubility in fresh water depends mainly on: (a) temperature; (b) type of gas; and (c) partial pressure of the gas. In addition to the above three parameters, the gas solubility in saline water also depends upon the salinity.

One may use Henry's law to compute dissolved gas mole fraction of any gas, X_i , at equilibrium conditions:

$$X_i = P_{i,h}/H_i, \quad (3)$$

where X_i is the dissolved gas mole fraction of any gas; $P_{i,h}$ is the partial pressure of the gas, i , at an elevation h ($h = 1.0$ if elevation = 1000 m); i is a gas; h is an elevation; and H_i is the Henry's law constant for the particular gas, i .

Since barometric pressure decreases with elevation, or lower atmospheric pressure, the partial pressure of gases in Table 2.6 must be corrected for elevation or any atmospheric pressure. The following equation is used to correct the partial pressures in Table 2.6 to take into account elevation effects.

$$P_{i,h} = P_{i,0}e^{-0.121h}, \quad (4)$$

where H is the elevation above sea level in thousands of meters and $P_{i,0}$ is the partial pressure of the gas, i , at sea level where h is 0 m. e value is 2.71828.

The concentration of dissolved gas (mole/L) can be calculated using the following approximation:

$$C_i = X_i C_{\text{water}}, \quad (5a)$$

where C_i is the concentration of dissolved gas, mole/L; X_i is the dissolved gas mole fraction of any gas; and C_{water} is the molar concentration of water.

$$C_{\text{water}} = (1,000 \text{ g/L}) / (18 \text{ g/M}) = 55.56 \text{ M/L}. \quad (5b)$$

The following example shows how the saturation concentration of dissolved oxygen in Las Cruces, New Mexico (elevation = 1,160 m; temperature = 30°C) can be calculated.

According to Table 2.6, the partial pressure of oxygen at sea level is 0.2095 atm. At the elevation of 1,160 m ($h = 1.160$), the atmospheric pressure decreases to 87% of sea level conditions.

$$\begin{aligned} P_{\text{oxygen},1.1} &= P_{i,0}e^{-0.121h} \\ &= 0.2095 e^{-0.121(1.160)} \\ &= 0.2095(0.87) \\ &= 0.182 \text{ atm}. \end{aligned} \quad (4)$$

Using Henry's constant corresponding to oxygen at 30°C, from Table 2.5 one obtains the mol fraction of oxygen in water using Eq. (3):

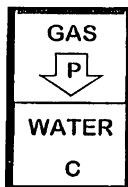
$$\begin{aligned} X_i &= P_{i,h} / H_i, \\ X_i = X_{\text{oxygen}} &= P_{\text{oxygen},1.1} / (4.75 \times 10^4 \text{ atm/mole fraction}) \\ &= 0.182 \text{ atm} / (4.75 \times 10^4 \text{ atm/mole fraction}) \\ &= 3.83 \times 10^{-6} \text{ mole fraction}. \end{aligned} \quad (3)$$

The molar concentration of dissolved oxygen at saturation can then be calculated:

$$\begin{aligned} C_i &= X_i C_{\text{water}}, \\ C_{\text{oxygen}} &= (3.83 \times 10^{-6} \text{ mole fraction})(55.56 \text{ M/L}) \\ &= 2.13 \times 10^{-4} \text{ M/L} \\ &= (2.13 \times 10^{-4} \text{ M/L})(32,000 \text{ mg/M}) \\ &= 6.8 \text{ mg/L}. \end{aligned} \quad (5)$$

Table 2.7

Solubilities of air, oxygen, nitrogen, hydrogen, and carbon dioxide in water at 1 atm and various temperatures (22).



P = Pressure of the the gas

Note: 1 atm = 1.01 Bar = 14.7 psi

C = Concentration of the gas in a saturated solution

Solubilities of gas in water at 1 atm*

Temp °C	Air	Oxygen	Nitrogen	Hydrogen	CO ₂
4	2.63	4.40	2.14	0.206	14.7
20	1.87	3.10	1.54	0.182	8.78
50	1.30	2.09	1.09	0.161	4.36

*% v/v = % gas volume/water volume = solubilities of gas in water at 1 atm.

4.3. Gas Dissolution and Release

Table 2.7 presents the solubilities (% v/v = % gas volume/water volume) of some common gases, (air, oxygen, nitrogen, hydrogen, and carbon dioxide) under normal atmospheric pressure ($P = 1 \text{ atm} = 1.01 \text{ Bar} = 14.7 \text{ psi}$) at various water temperatures (4–50°C). Table 2.7 also shows how a gas can be pressurized and dissolved in water. P is the pressure of a gas over the water, and C is the concentration of the gas in a saturated solution (22).

At constant temperature the solubility of a gas in a liquid is directly proportional to the pressure of the gas above the solution, as shown in the small diagram in Table 2.7.

$$C_1 = f \times P_1, \quad (6)$$

$$C_2 = f \times P_2, \quad (7)$$

$$f = C_2/P_2 = C_1/P_1, \quad (8)$$

$$C_2 = C_1(P_2)/P_1, \quad (9)$$

where C_1 is the solubility of a gas in water (% v/v) under pressure P_1 (atm), C_2 is the solubility of a gas in water (% v/v) under pressure P_2 (atm), P_1 is the normal atmospheric pressure = 1 atm (which may be corrected by elevation), P_2 is the pressure of a gas above the water, atm, and F is a constant.

The percent volume of gas bubbles released due to pressure change can be calculated by the following equation:

$$V_{br} = C_2 - C_1, \quad (10)$$

where V_{br} is the percent volume of gas bubble released from a previously pressurized water, %.

It should be noted that Table 2.7 presents the technical data for air and pure gases, such as oxygen, nitrogen, hydrogen, and carbon dioxide. When evaluating an environmental system, we are neither dealing with pure oxygen nor with pure nitrogen gases. Oxygen and nitrogen and others are the gas components of air. Actual concentration of a gas component, $C_{\text{gas-a}}$, which is only a fraction of the gas solubility shown in Table 2.7, can be calculated by Eqs. (11a) to (11d).

$$C_{\text{gas-a}} = P_{i,h} \times C_{\text{gas}}, \quad (11a)$$

$$C_{\text{oxygen-a}} = 0.2095 \times C_{\text{oxygen}}, \quad (11b)$$

$$C_{\text{nitrogen-a}} = 0.7809 \times C_{\text{nitrogen}}, \quad (11c)$$

$$C_{\text{carbondioxide-a}} = 0.00032 \times C_{\text{carbondioxide}}, \quad (11d)$$

where $C_{\text{gas-a}}$ is the actual concentration or solubility of a gas component in water, % v/v (% gas volume/water volume); C_{gas} is the concentration or solubility of a pure gas in water, % v/v (% gas volume/water volume = mL gas/100 mL water); $C_{\text{oxygen-a}}$ is the actual concentration or solubility of oxygen component in water, % v/v (% oxygen volume/water volume); C_{oxygen} is the concentration or solubility of pure oxygen in water, % v/v (% oxygen volume/water volume); $C_{\text{nitrogen-a}}$ is the actual concentration or solubility of nitrogen component in water, % v/v (% nitrogen volume/water volume); C_{nitrogen} is the concentration or solubility of pure nitrogen in water, % v/v (% nitrogen volume/water volume); $C_{\text{carbondioxide-a}}$ is the actual concentration or solubility of carbon dioxide component in water, % v/v (% carbon dioxide volume/water volume); $C_{\text{carbondioxide}}$ is the concentration or solubility of pure carbon dioxide in water, % v/v (% carbon dioxide volume/water volume); and $P_{i,h}$ is the partial pressure of the gas, i , at an elevation h .

Actual percentage of a gas component in water can be calculated by Eq. (12a):

$$\text{PCT}_{\text{gas}} = (100)(C_{\text{gas-a}})/(C_{\text{air}}), \quad (12a)$$

$$\text{PCT}_{\text{oxygen}} = (100)(C_{\text{oxygen-a}})/(C_{\text{air}}), \quad (12b)$$

$$\text{PCT}_{\text{nitrogen}} = (100)(C_{\text{nitrogen-a}})/(C_{\text{air}}), \quad (12c)$$

where PCT_{gas} is the actual percentage of a gas component, %; $\text{PCT}_{\text{oxygen}}$ is the actual percentage of oxygen component, %; $\text{PCT}_{\text{nitrogen}}$ is the actual percentage of nitrogen component, %; $C_{\text{gas-a}}$ is the actual concentration or solubility of a gas component in water, % v/v (% gas volume/water volume); $C_{\text{oxygen-a}}$ is the actual concentration or solubility of oxygen component in water, % v/v (% oxygen volume/water volume); $C_{\text{nitrogen-a}}$ is the actual concentration or solubility of nitrogen component in water, % v/v (% nitrogen volume/water volume); and C_{air} is the concentration or solubility of air in water, % v/v (% air volume/water volume).

The following are examples on engineering calculations for gas pressurization, dissolution, and bubble release (22).

4.3.1. Example 1

What is the solubility of air in water at 4°C and 5 atm pressure?

Solution

Select $C_1 = 2.63\%$ v/v for air from Table 2.7, and adopt Eq. (9).

$$C_2 = C_1(P_2)/P_1, \quad (9)$$

$$C_2 = (2.63\% \text{ v/v})(5 \text{ atm})/(1 \text{ atm}) = 13.15\% \text{ v/v}.$$

Therefore, the solubility of air in water at 4°C and 5 atm pressure is equal to 13.15 mL of air per 100 mL of water.

4.3.2. Example 2

The pressure of air is approximately 0.21 atm oxygen and 0.79 atm nitrogen. What is the concentration of oxygen and nitrogen in water at 4°C with 1 atm of air above it?

Solution

Select both $C_{\text{oxygen}} = 4.40$ and $C_{\text{nitrogen}} = 2.14$ from Table 2.7, and adopt Eqs. (11b), (11c), (12b), and (12c) for calculations:

$$\begin{aligned} C_{\text{oxygen-a}} &= 0.2095 \times C_{\text{oxygen}} \\ &= 0.2095 \times 4.40 = 0.924\% \text{ v/v}, \end{aligned} \quad (11b)$$

$$\begin{aligned} C_{\text{nitrogen-a}} &= 0.7809 \times C_{\text{nitrogen}} \\ &= 0.7809 \times 2.14 = 1.69\% \text{ v/v}, \end{aligned} \quad (11c)$$

$$\begin{aligned} \text{PCT}_{\text{oxygen}} &= (100)(C_{\text{oxygen-a}})/(C_{\text{air}}) \\ &= (100)(0.924)/(2.63) \\ &= 35.13\% \text{ oxygen}. \end{aligned} \quad (12b)$$

It is important to note that the air above this solution contains only 21% oxygen.

$$\begin{aligned} \text{PCT}_{\text{nitrogen}} &= (100)(C_{\text{nitrogen-a}})/(C_{\text{air}}) \\ &= (100)(1.69)/(2.63) \\ &= 64.28\% \text{ nitrogen}. \end{aligned} \quad (12c)$$

4.3.3. Example 3

Air is dissolved in water at 20°C and 80 psi. What will be the % volume of air bubbles released when the pressure is reduced to 14.7 psi? What will be the % volume of air bubbles released?

Solution

$$(80 \text{ psi})(1 \text{ atm}/14.7 \text{ psi}) = 5.4 \text{ atm}.$$

Table 2.8
Concentration of air dissolved in water (22)

Temp °C	Pressure of air above the water in atmospheres							
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Concentration of air dissolved in water in mg/L								
0	37.27	74.55	111.82	149.09	186.37	223.64	260.92	298.19
5	33.00	65.99	98.99	131.99	164.98	197.98	230.97	263.97
10	29.33	58.66	87.99	117.32	146.65	175.98	205.31	234.64
15	26.53	53.06	79.58	106.11	132.64	159.17	185.69	212.22
20	24.25	48.50	72.75	97.00	121.25	145.50	169.75	194.00
25	22.36	44.73	67.09	89.46	111.82	134.19	156.55	178.91
30	20.88	41.77	62.65	83.54	104.42	125.31	146.19	167.08
40	18.51	37.02	55.53	74.03	92.54	111.05	129.56	148.07
50	17.02	34.04	51.06	68.09	85.11	102.13	119.15	136.17
60	15.94	31.89	47.83	63.77	79.71	95.66	111.60	127.54
80	15.05	30.10	45.15	60.20	75.24	90.29	105.34	120.39
100	15.05	30.10	45.15	60.20	75.24	90.29	105.34	120.39

All concentrations are in mg/L. 1 atm = 101.325 kPa = 101.325 kN/m² = 1.013 bar.

Select $C_1 = 1.87\%$ v/v for air from Table 2.7, and adopt Eq. (9):

$$\begin{aligned}
 C_2 &= C_1(P_2)/P_1 \\
 &= (1.87\% \text{ v/v})(5.4 \text{ atm})/(1 \text{ atm}) \\
 &= 10.10\% \text{ v/v.}
 \end{aligned} \tag{9}$$

Therefore, the solubility of air in water at 20°C and 5.4 atm is equal to 10.10 mL of air per 100 mL of pressurized water.

The percent volume of gas bubbles released due to pressure change can be calculated by Eq. (10):

$$\begin{aligned}
 V_{\text{br}} &= C_2 - C_1 \\
 &= 10.10 - 1.87 \\
 &= 8.23\% \text{ v/v.}
 \end{aligned} \tag{10}$$

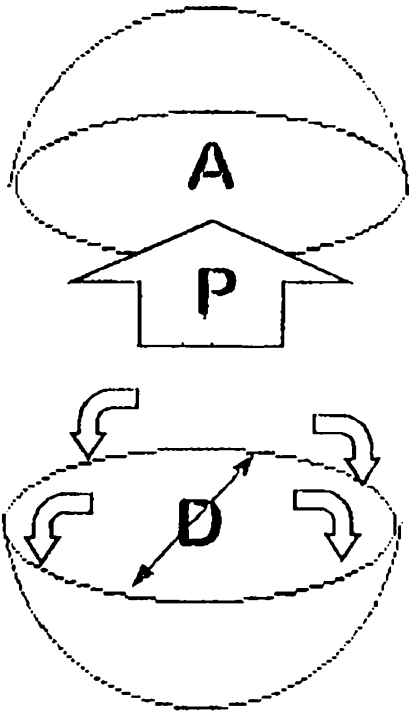
For every 100 mL of pressurized water at 5.4 atm, 8.23 mL of air bubbles will be released to the environment at 1 atm. This is the theoretical maximum. In actual engineering practice, there will be less volume of useful air bubbles due to the following factors: (a) efficiency of equipment for gas dissolution; (b) pressure losses; (c) bleed-off of excess gases; (d) distribution of air bubbles, and (e) pressurized water recycle.

For ease of engineering planning and design, much technical information has been precalculated or gathered (22). Table 2.8 predicts the concentration of air dissolved in water (mg/L) under various water temperatures (°C) and various air pressures above the water (atm). Table 2.9 presents the percent volume data of air bubbles released when the pressure is reduced from various air pressures to normal atmospheric pressure ($P = 1 \text{ atm}$) over the water.

Table 2.9
Percent volume of bubbles released when pressure is reduced to 1 atm (22)

Temp °C	Original pressure of air above the water in atmospheres							
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
0	0.00	2.88	5.76	8.64	11.52	14.40	17.28	20.16
5	0.00	2.55	5.10	7.65	10.20	12.75	15.30	17.85
10	0.00	2.27	4.53	6.80	9.07	11.33	13.60	15.87
15	0.00	2.05	4.10	6.15	8.20	10.25	12.30	14.35
20	0.00	1.87	3.75	5.62	7.50	9.37	11.24	13.12
25	0.00	1.73	3.46	5.18	6.91	8.64	10.37	12.10
30	0.00	1.61	3.23	4.84	6.46	8.07	9.68	11.30
40	0.00	1.43	2.86	4.29	5.72	7.15	8.58	10.01
50	0.00	1.32	2.63	3.95	5.26	6.58	7.89	9.21
60	0.00	1.23	2.46	3.70	4.93	6.16	7.39	8.62
80	0.00	1.16	2.33	3.49	4.65	5.81	6.98	8.14
100	0.00	1.16	2.33	3.49	4.65	5.81	6.98	8.14

Fig. 2.6. Pressure inside
a gas bubble.



4.4. Gas Bubble Formation and Size Distribution

The internal force of the air on the water is countered by the force holding the air in place that is caused by the surface tension, as shown by Fig. 2.6 (22).

Table 2.10
Bubble diameter vs. internal pressure (22)

Diameter (micrometers)	1,000	100	10	1
Net internal pressure (atm)	0.0029	0.029	0.29	2.9

1 atm = 101.325 kPa = 1.013 bar

Let r be the surface tension of the solution, D be the diameter of the gas bubble, P be the pressure of the bubble, and A be the area of a cross section (Fig. 2.6), then the internal force (F_{internal}) and surface force (F_{surface}) can be calculated by Eqs. (13) and (14).

$$F_{\text{internal}} = \text{internal force},$$

$$F_{\text{internal}} = (\text{pressure})(\text{area}),$$

$$F_{\text{internal}} = P(3.14D^2)/4, \quad (13)$$

$$F_{\text{surface}} = \text{surface force},$$

$$F_{\text{surface}} = (\text{surface tension})(\text{perimeter}),$$

$$F_{\text{surface}} = (r)(3.14 D), \quad (14)$$

where F_{internal} is the internal force, dyne; F_{surface} is the surface force, dyne; r is the surface tension, dyne/cm (or lb/in); D is the bubble diameter, cm (or in); and P is the internal bubble pressure, dyne/cm² (or psi).

When the internal force is equal to the surface force during a bubble formation process, Eq. (15) is derived.

$$P(3.14 D^2)/4 = (r)(3.14 D), \quad (15)$$

$$P = 4 r/D, \quad (16)$$

Table 2.10 indicates the relationship between the net internal pressure P (atm) and the gas bubble diameter D (micrometer) in pure water. The pressure required inside the bubble is strongly influenced by the surface tension of the solution. The addition of substances that reduce the surface tension leads to smaller bubbles, according to Eq. (16). The addition of milligram per liter amounts of surface-active agents can significantly alter the flotation process – sometimes by altering the attachment mechanism, sometimes by altering the gas bubble formation process, sometimes both; KSV Instruments Ltd, Finland has developed a modern gas bubble pressure tensiometer for such an investigation (28).

4.5. Bubble Attachment, Rising, and Flotation

Many researchers (29–35) have investigated the theories, principles of gas bubble formation, size distribution, absorption/adsorption, solids attachment, detachment, decompression, surface chemistry, rising velocities, and instrumentation (17–38).

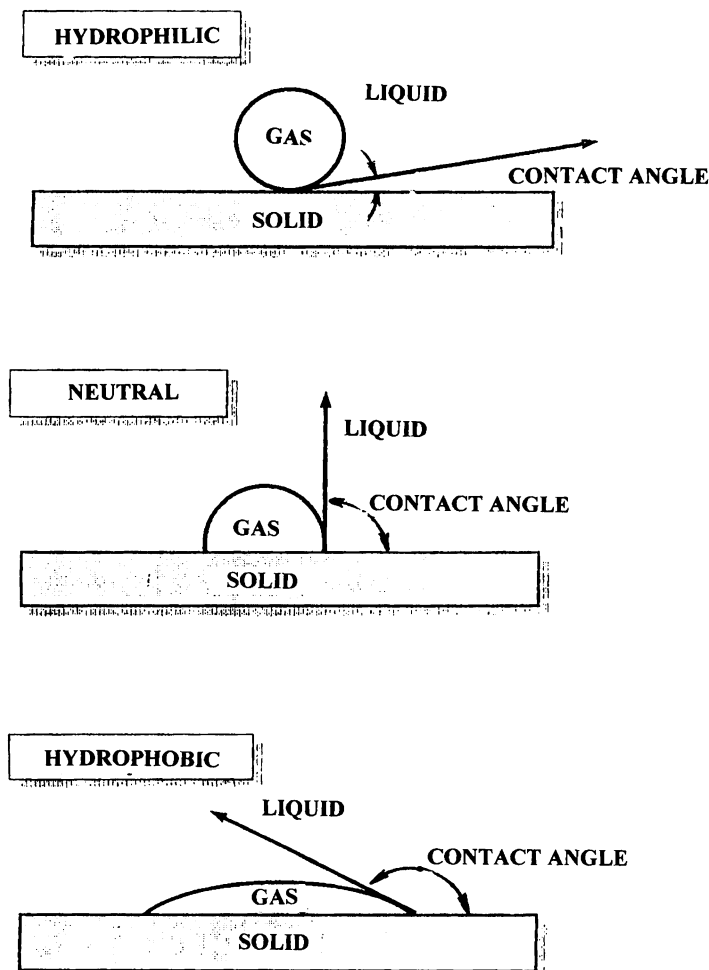


Fig. 2.7. Attachment of solids onto gas bubbles.

Figure 2.7 shows how the solids in a flotation system can be attached onto gas bubbles. Adsorptive bubble separation processes (including flotation) are surface-chemistry processes, mainly for separating fine solids that take advantage of the differences of wettability at solids particle-surfaces. Solid surfaces are often naturally wettable by water and termed hydrophilic. A surface that is nonwetable is water repelling and termed hydrophobic.

If a surface is hydrophobic, it is typically air attracting termed aerophilic, and is strongly attracted to an air interface, which readily displaces water at the solid's surface, as shown in Fig. 2.7. In a flotation system, separation of a binary solids mixture may be accomplished by the selective attachment of hydrophobic solid particles to gas bubbles (typically air bubbles). The other hydrophobic solid particles remain in the liquid (typically water). The difference in

the density between the air bubbles and water provides buoyancy that preferentially lifts the hydrophobic solids particles to the surface where they remain entrained in a froth or scum that can be drained off or mechanically skimmed away, thus, effecting the separation.

A flotation system may be used to separate solids of similar densities and sizes, which cannot be achieved by other types of separations based on gravity alone. It is especially useful for particles below 100 μm , which are typically too small for gravity separation by sedimentation clarification. The lower size limit for flotation separation is approximately 35 μm ; although particles as small as 1 μm can be separated. At these small particles sizes, it may be difficult to take advantage of surface properties differences to induce selective hydrophobicity. On the other hand, particles greater than 200 μm tend to be readily sheared from the bubble surfaces by collision with other particles or the vessel walls. However, relatively low density materials, such as coal, may be successfully separated at sizes up to 1,600 μm in some systems.

Lenox Institute of Water Technology (22) has developed engineering design data for use in various adsorptive bubble separation processes (including flotation process). Tables 2.11–2.15 introduce the design data relative to bubble attachment and bubble rising in the flotation systems.

4.5.1. Example

What is the rise rate of a bubble with a diameter of 50 μm at a water temperature of 20°C.

Solution

Stoke's law shown in Eqs. (1a) and (1b) can be used to calculate the rise rate, or falling rate of a spherical object in a fluid. The following is an example showing how Table 2.11 can be used and verified, and how Eq. (1b) can be applied to the determination of bubble rise rate in a flotation system.

$$V_T = g(d_W - d_B)D^2/(18\nu), \quad (1b)$$

where D is the diameter of a spherical gas bubble, m; V_T is the terminal velocity of a spherical bubble diameter D , m/s; d_W is the density of water, kg/m^3 ; d_B is the density of gas bubble, kg/m^3 ; ν is the water viscosity, Pa-s; and g is the gravitational acceleration = 9.8 m/s^2 .

From Table 2.11, the following data are obtained for water temperature at 20°C:

$$d_W = \text{density of water} = 998.2 \text{ kg/m}^3,$$

$$d_B = \text{density of gas bubble} = 1.2 \text{ kg/m}^3,$$

$$\nu = \text{water viscosity} = 1,002 \times 10^{-6} \text{ Pa-s}.$$

The following data are given:

$$D = \text{diameter of a spherical gas bubble} = 50 \times 10^{-6} \text{ m},$$

$$g = \text{gravitational acceleration} = 9.8 \text{ m/s}^2.$$

Table 2.11
Rise velocity of air bubbles in water by Stoke’s law (22)

Temp °C	Visc. μPa-s	VP torr	Density (kg/m ³)		Effective diameter of air bubbles in micrometers (μm)										
			Water	Air	10	25	50	75	100	125	150	175	200	225	250
			Rise velocity in centimeters/second												
0	1,770	4.58	999.9	1.3	0.0031	0.019	0.077	0.173	0.307	0.480	0.691	0.941	1.229	1.555	1.920
10	1,304	9.21	999.7	1.2	0.0042	0.026	0.104	0.234	0.417	0.651	0.938	1.277	1.668	2.110	2.605
20	1,002	17.5	998.2	1.2	0.0054	0.034	0.135	0.305	0.542	0.846	1.219	1.659	2.167	2.743	3.386
25	890.3	23.8	997.1	1.2	0.0061	0.038	0.152	0.343	0.609	0.952	1.370	1.865	2.436	3.083	3.807
30	797.3	31.8	995.7	1.1	0.0068	0.042	0.170	0.382	0.679	1.061	1.528	2.080	2.717	3.438	4.245
50	546.9	92.5	988.1	1.0	0.0098	0.061	0.246	0.553	0.983	1.535	2.211	3.009	3.931	4.975	6.141
75	379.2	289	974.9	0.9	0.0140	0.087	0.350	0.787	1.399	2.185	3.147	4.283	5.594	7.080	8.741
100	284.0	760	958.4	0.6	0.0184	0.115	0.459	1.033	1.836	2.869	4.132	5.623	7.345	9.296	11.47

All rise velocities are in cm/s.

Table 2.12
Number of bubbles needed to lift a particle of density 1.1 (22)

Particle (density = 1.10)		Number of bubbles needed to lift a particle of density 1.10									
		Effective diameter of air bubbles in micrometers μm									
		10	25	50	75	100	125	150	175	200	225
		Multiplication factor for number of bubbles									
<i>D</i> μm	<i>V</i> μm ³	524	8,180	65,444	2.21E +05	5.24E +05	1.02E +06	1.77E +06	2.81E +06	4.19E +06	5.96E +06
10	524	1	1	1	1	1	1	1	1	1	1
25	8,180	2	1	1	1	1	1	1	1	1	1
50	65,444	13	1	1	1	1	1	1	1	1	1
75	2.21E+05	43	3	1	1	1	1	1	1	1	1
100	5.24E+05	101	7	1	1	1	1	1	1	1	1
125	1.02E+06	196	13	2	1	1	1	1	1	1	1
150	1.77E+06	338	22	3	1	1	1	1	1	1	1
175	2.81E+06	536	35	5	2	1	1	1	1	1	1
200	4.19E+06	801	52	7	2	1	1	1	1	1	1
225	5.96E+06	1,140	73	10	3	2	1	1	1	1	1
250	8.18E+06	1,563	101	13	4	2	1	1	1	1	1
300	1.41E+07	2,701	173	22	7	3	2	1	1	1	1
400	3.35E+07	6,401	410	52	16	7	4	2	2	1	1
500	6.54E+07	12,501	801	101	30	13	7	4	3	2	2
1,000	5.24E+08	1,00,001	6,401	801	238	101	52	30	19	13	9

The gas bubble rise velocity can then be calculated using Eq. (1b):

$$\begin{aligned} V_T &= g(d_W - d_B)D^2/(18\nu) \\ &= (9.8 \text{ m/s}^2)(998.2 \text{ kg/m}^3 - 1.2 \text{ kg/m}^3)(50 \times 10^{-6} \text{ m})^2/(18 \times 1,002 \times 10^{-6} \text{ Pa-s}) \\ &= 0.00135 \text{ m/s} \\ &= 0.135 \text{ cm/s.} \end{aligned}$$

One can then review the data in Table 2.11. When water temperature is 20°C, and the bubble diameter is 50 μm, Table 2.11 indicates that the bubble rise velocity should be 0.135 cm/s, which is identical to the calculated value of 0.135 cm/s.

4.6. Gas Dissolution in Water Containing High Dissolved Solids or High Salinity

4.6.1. Environmental Engineering Significance

The greater the solubility of a gas in water, the more gas bubbles can be generated, and in turn, the higher the efficiency of a flotation system. It is known that the gas solubility in water

Table 2.13
Number of bubbles needed to lift a particle of density 1.5 (22)

Particle (density = 1.5)		Number of bubbles needed to lift a particle of density 1.50									
		Effective diameter of air bubbles in micrometers μm									
		10	25	50	75	100	125	150	175	200	225
		Multiplication factor for number of bubbles									
$D \mu\text{m}$	$V \mu\text{m}^3$	524	8,180	65,444	2.21E+05	5.24E+05	1.02E+06	1.77E+06	2.81E+06	4.19E+06	5.96E+06
10	524	1	1	1	1	1	1	1	1	1	1
25	8,180	8	1	1	1	1	1	1	1	1	1
50	65,444	63	5	1	1	1	1	1	1	1	1
75	2.21E+05	211	14	2	1	1	1	1	1	1	1
100	5.24E+05	501	33	5	2	1	1	1	1	1	1
125	1.02E+06	977	63	8	3	1	1	1	1	1	1
150	1.77E+06	1,688	109	14	5	2	1	1	1	1	1
175	2.81E+06	2,680	172	22	7	3	2	1	1	1	1
200	4.19E+06	4,001	257	33	10	5	3	2	1	1	1
225	5.96E+06	5,696	365	46	14	6	3	2	2	1	1
250	8.18E+06	7,813	501	63	19	8	5	3	2	1	1
300	1.41E+07	13,501	865	109	33	14	7	5	3	2	2
400	3.35E+07	32,001	2,049	257	76	33	17	10	6	5	3
500	6.54E+07	62,501	4,001	501	149	63	33	19	12	8	6
1,000	5.24E+08	5,00,001	32,001	4,001	1,186	501	257	149	94	63	44

decreases with increasing water temperature, salinity, or dissolved solids concentration. These negative effects should be avoided when operating a flotation system.

On the other hand, the gas solubility in water increases with increasing the total pressure above the water, which is good for the flotation system.

This section demonstrates the negative effects (caused by high water temperature, high dissolved solids, and high salinity) as well as the positive effect (caused by high total pressure over the water) on a flotation system, using dissolved oxygen concentration in water as an example. Engineering approaches for overcoming the negative effects are also introduced.

4.6.2. Engineering Experience and Solutions

Both dissolved solids (or salinity) and water temperature have significant effects on bubble formation and solids attachment in flotation systems. In general gas solubilities decrease with increasing either the dissolved solids concentration or the water temperature. Since sea water contains high concentrations of dissolved solids (as shown in Table 2.16), generally special attention is needed if a flotation system is to be used for treatment of contaminated sea water (or another contaminated water with high dissolved solids concentration) or high temperature

Table 2.14
Number of bubbles needed to lift a particle of density 2.0 (22)

Particle (density = 2.00)		Number of bubbles needed to lift a particle of density 2.00									
		Effective diameter of air bubbles in micrometers μm									
		10	25	50	75	100	125	150	175	200	225
		Multiplication factor for number of bubbles									
$D \mu\text{m}$	$V \mu\text{m}^3$	524	8,180	65,444	2.21E +05	5.24E +05	1.02E +06	1.77E +06	2.81E +06	4.19E +06	5.96E +06
10	524	2	1	1	1	1	1	1	1	1	1
25	8,180	16	2	1	1	1	1	1	1	1	1
50	65,444	126	9	2	1	1	1	1	1	1	1
75	2.21E+05	422	28	4	2	1	1	1	1	1	1
100	5.24E+05	1,001	65	9	3	2	1	1	1	1	1
125	1.02E+06	1,954	126	16	5	2	2	1	1	1	1
150	1.77E+06	3,376	217	28	9	4	2	2	1	1	1
175	2.81E+06	5,360	344	43	13	6	3	2	2	1	1
200	4.19E+06	8,001	513	65	19	9	5	3	2	2	1
225	5.96E+06	11,391	730	92	28	12	6	4	3	2	2
250	8.18E+06	15,626	1,001	126	38	16	9	5	3	2	2
300	1.41E+07	27,001	1,729	217	65	28	14	9	6	4	3
400	3.35E+07	64,001	4,097	513	152	65	33	19	12	9	6
500	6.54E+07	1,25,001	8,001	1,001	297	126	65	38	24	16	11
1,000	5.24E+08	1,000,001	64,001	8,001	2,371	1,001	513	297	187	126	88

wastewater. For instance, much higher pressure may be required to dissolve air in water, in turn, to release pressure for bubble formation. Alternatively, special surface-active collectors may be used to overcome the problems of high dissolved solids and/or high water temperature (39).

Equations (17) and (18) illustrate the effects of dissolved solids and water temperature on the dissolved oxygen concentration (mg/L) in water (37, 40–42).

$$C_{\text{DO}} = (475 - 2.65 S)/(33.5 + T), \tag{17}$$

$$C_{\text{DO}} = (0.68 - 6 \times 10^{-4}T)(P' - p)(1 - 9 \times 10^{-6}S_a)/(T + 35), \tag{18}$$

where C_{DO} is the dissolved oxygen concentration in water at equilibrium with air above the water, mg/L; T is the water temperature, °C; S is the dissolved solids concentration, g/L; P' is the total pressure above the water, mm Hg; p is the water vapor pressure, mm Hg; and S_a is the salinity, mg/L.

Equation (17) was reported by Gameson and Robertson (40) for water at atmospheric pressure at equilibrium with air. The negative effects of high dissolved solids concentration and high water temperature on the solubility of dissolved oxygen in water are clearly illustrated by the equation.

Table 2.15
Bubble diameter, number, total surface area, silhouette area and total volume (22)

Volume of air	$D \mu\text{m} \rightarrow$	Effective average diameter of air bubbles in micrometers										
		10	25	50	75	100	125	150	175	200	225	250
mL/L % v/v	$V \mu\text{m}^3 \rightarrow$	524	8,180	65,400	2.21E+05	5.24E+05	1.02E+06	1.77E+06	2.81E+06	4.19E+06	5.96E+06	8.18E+06
	$A \mu\text{m}^2 \rightarrow$	314	1,963	7,853	17,670	31,410	49,080	70,680	96,200	125,700	159,000	196,000
	$S \mu\text{m}^2 \rightarrow$	79	491	1,963	4,417	7,853	12,270	17,700	24,100	31,400	39,800	49,100
2.5 0.25%	No./Liter	4.78E+09	3.06E+08	3.82E+07	1.13E+07	4.78E+06	2.44E+06	1.41E+06	8.91E+05	5.97E+05	4.19E+05	3.06E+05
	Tot A cm^2	15,000	6,000	3,000	2,000	1,500	1,200	1,000	857	750	667	600
	% a/a/ cm^*	375	150	75	50	38	30	25	21	19	17	15
5.0 0.50%	No./Liter	9.55E+09	6.11E+08	7.64E+07	2.26E+07	9.55E+06	4.89E+06	2.83E+06	1.78E+06	1.19E+06	8.38E+05	6.11E+05
	Tot A cm^2	30,000	12,000	6,000	4,000	3,000	2,400	2,000	1,714	1,500	1,333	1,200
	% a/a/cm	750	300	150	100	75	60	50	43	38	33	30
7.5 0.75%	No./Liter	1.43E+10	9.17E+08	1.15E+08	3.40E+07	1.43E+07	7.33E+06	4.24E+06	2.67E+06	1.79E+06	1.26E+06	9.17E+05
	Tot A cm^2	45,000	18,000	9,000	6,000	4,500	3,600	3,000	2,571	2,250	2,000	1,800
	% a/a/cm	1,125	450	225	150	113	90	75	64	56	50	45
10.0 1.0%	No./Liter	1.91E+10	1.22E+09	1.53E+08	4.53E+07	1.91E+07	9.78E+06	5.66E+06	3.56E+06	2.39E+06	1.68E+06	1.22E+06
	Tot A cm^2	60,000	24,000	12,000	8,000	6,000	4,800	4,000	3,429	3,000	2,667	2,400
	% a/a/cm	1,500	600	300	200	150	120	100	86	75	67	60
12.5 1.25%	No./Liter	2.39E+10	1.53E+09	1.91E+08	5.66E+07	2.39E+07	1.22E+07	7.07E+06	4.45E+06	2.98E+06	2.10E+06	1.53E+06
	Tot A cm^2	75,000	30,000	15,000	10,000	7,500	6,000	5,000	4,286	3,750	3,333	3,000
	% a/a/cm	1,875	750	375	250	188	150	125	107	94	83	75
15.0 1.5%	No./Liter	2.87E+10	1.83E+09	2.29E+08	6.79E+07	2.87E+07	1.47E+07	8.49E+06	5.35E+06	3.58E+06	2.52E+06	1.83E+06
	Tot A cm^2	90,000	36,000	18,000	12,000	9,000	7,200	6,000	5,143	4,500	4,000	3,600
	% a/a/cm	2,250	900	450	300	225	180	150	129	113	100	90
17.5 1.75%	No./Liter	3.34E+10	2.14E+09	2.67E+08	7.92E+07	3.34E+07	1.71E+07	9.90E+06	6.24E+06	4.18E+06	2.93E+06	2.14E+06
	Tot A cm^2	105,000	42,000	21,000	14,000	10,500	8,400	7,000	6,000	5,250	4,667	4,200
	% a/a/cm	2,625	1,050	525	350	263	210	175	150	131	117	105
20.0 2.0%	No./Liter	3.82E+10	2.44E+09	3.06E+08	9.05E+07	3.82E+07	1.96E+07	1.13E+07	7.13E+06	4.78E+06	3.35E+06	2.44E+06
	Tot A cm^2	120,000	48,000	24,000	16,000	12,000	9,600	8,000	6,857	6,000	5,333	4,800
	% a/a/cm	3,000	1,200	600	400	300	240	200	171	150	133	120

(Continued)

Table 2.15
(Continued)

Volume of air	$D \mu\text{m} \rightarrow$	Effective average diameter of air bubbles in micrometers											
		10	25	50	75	100	125	150	175	200	225	250	
25.0	No./Liter	4.78E+10	3.06E+09	3.82E+08	1.13E+08	4.78E+07	2.44E+07	1.41E+07	8.91E+06	5.97E+06	4.19E+06	3.06E+06	
	Tot A cm ²	150,000	60,000	30,000	20,000	15,000	12,000	10,000	8,571	7,500	6,667	6,000	
	% a/a/cm	3,750	1,500	750	500	375	300	250	214	188	167	150	
50.0	No./Liter	9.55E+10	6.11E+09	7.64E+08	2.26E+08	9.55E+07	4.89E+07	2.83E+07	1.78E+07	1.19E+07	8.38E+06	6.11E+06	
	Tot A cm ²	300,000	120,000	60,000	40,000	30,000	24,000	20,000	17,143	15,000	13,333	12,000	
	% a/a/cm	7,500	3,000	1,500	1,000	750	600	500	429	375	333	300	

*Looking down through one cm depth of the water, what % of the surface area is silhouetted by the projected area (S) of the bubbles in the water (% a/a/cm).

Table 2.16
Composition of sea water (22)

Component	g mol/L	g/kg	Equivalents/kg
Na ⁺	0.47015	10.5561	0.4590
Mg ²⁺	0.05357	1.2720	0.1046
Ca ²⁺	0.01024	0.4001	0.0200
K ⁺	0.00996	0.3800	0.0097
Sr ²⁺	0.00015	0.0133	0.0003
<i>Total</i>			0.5936
Cl ⁻	0.54830	18.9799	0.5353
SO ₄ ²⁻	0.03824	2.6486	0.0551
HCO ₃ ⁻	0.00234	0.1397	0.0023
Br ⁻	0.00083	0.0646	0.0008
F ⁻	0.00007	0.0013	0.0001
H ₃ BO ₃	0.00043	0.0260	—
<i>Total</i>	1.13194	34.4816	0.5936
H ₂ O	54.89457	965.5184	
<i>Total</i>	56.02651	1,000.0000	

Density at 20°C = 1.0243 g/mL.

Dissolved solids = 35,320 mg/L.

Chloride concentration = 19,440 mg/L.

Equation (18) was reported by Fair, Geyer, and Okun (41), who considered the pressure above the water, and the water vapor partial pressure (Table 2.17). While the negative effects of high dissolved solids (in terms of high salinity) and high water temperature on dissolved oxygen concentration are similar, Eq. (18) further shows that the higher the total pressure above the water, the higher the dissolved oxygen concentration.

Wang (26) and Wang and Elmore (27) have developed more accurate dissolved oxygen concentration equations that are suitable for mathematical modeling and computer calculations. Wang and Elmore's equations (26, 27), shown in Table 2.18, can be applied to either fresh water or saline water, and cover all related parameters, such as water temperature, chloride concentration, barometric pressure, saturated water vapor pressure, etc.

4.6.3. Example 1

Predict the dissolved oxygen concentration in fresh water and sea water (Table 2.16) at 20°C.

Solution

For fresh pure water using Eq. (17):

$$\begin{aligned}
 C_{DO} &= (475 - 2.65S)/(33.5 + T) \\
 &= (475 - 2.65 \times 0)/(33.5 + 20) \\
 &= 8.88 \text{ mg/L.}
 \end{aligned}
 \tag{17}$$

Table 2.17
Vapor pressure of pure water* (22, 43)

Temp., °C	<i>P</i> , mm Hg	Temp., °C	<i>P</i> , mm Hg
0	4.579	55	118.0
5	6.543	60	149.4
10	9.209	65	187.5
15	12.79	70	233.7
20	17.54	75	289.1
25	23.76	80	355.1
30	31.82	85	433.6
35	42.18	90	525.8
40	55.32	95	633.9
45	71.88	100	760.0
50	92.51		

*From “Handbook of Chemistry and Physics,” 36th Edition, C. D. Hodgeman, Editor in Chief, Chemical Rubber Publishing Co. 1954–1955 (43).

Table 2.18 shows that the expected dissolved oxygen saturation concentration in fresh water at 1 atm and 20°C is 9 mg/L.

For sea water also using Eq. (17):

$$\begin{aligned}
 C_{\text{DO}} &= (475 - 2.65 S)/(33.5 + T) \\
 &= (475 - 2.65 \times 35.32)/(33.5 + 20) \\
 &= 7.13 \text{ mg/L.}
 \end{aligned} \tag{17}$$

Table 2.18 indicates that the expected dissolved oxygen saturation concentration in sea water (chloride concentration = 19,440 mg/L) at 1 atm and 20°C is about 7.3 mg/L.

4.6.4. Example 2

Calculate the dissolved oxygen concentration in sea water (Table 2.16) at 740 mm Hg pressure and 30°C.

Solution

From Table 2.17, the water vapor partial pressure is found to be 31.8 mm Hg.

The salinity is calculated using the data from Table 2.16 for the sea water.

$$S_a = (0.5483 \text{ g mole/L})(35,450 \text{ mg/g mole}) = 19,440 \text{ mg/L of chloride,}$$

$$\begin{aligned}
 C_{\text{DO}} &= (0.68 - 6 \times 10^{-4} T)(P' - p)(1 - 9 \times 10^{-6} S_a)/(T + 35) \\
 &= (0.68 - 6 \times 10^{-4} \times 30)(740 - 31.8)(1 - 9 \times 10^{-6} \times 19,440)/(30 + 35) \\
 &= 5.95 \text{ mg/L.}
 \end{aligned} \tag{18}$$

Table 2.18
Wang and Elmore's Equations* for Saturation Values of Dissolved Oxygen in Fresh and Sea Water Exposed to an Atmosphere Containing 20.9% Oxygen under a Pressure of 760 mm of Mercury (26, 27)

Water Temperature (T, °C)	Dissolved Oxygen (C _{DO} , mg/L) for Stated Concentrations of Chloride (CL, mg/L)					Difference per 1000 mg/L Chloride
	0	5000	10000	15000	20000	
0	14.7	13.8	13.0	12.1	11.3	0.165
1	14.3	13.5	12.7	11.9	11.1	0.160
2	13.9	13.1	12.3	11.6	10.8	0.154
3	13.5	12.8	12.0	11.3	10.5	0.149
4	13.1	12.4	11.7	11.0	10.3	0.144
5	12.8	12.1	11.4	10.7	10.0	0.140
6	12.5	11.8	11.0	10.4	9.8	0.135
7	12.1	11.5	10.8	10.2	9.6	0.130
8	11.8	11.2	10.6	10.0	9.4	0.125
9	11.6	11.0	10.4	9.7	9.1	0.121
10	11.3	10.7	10.1	9.5	8.9	0.118
11	11.0	10.4	9.9	9.3	8.7	0.114
12	10.8	10.2	9.7	9.1	8.6	0.110
13	10.5	10.0	9.4	8.9	8.4	0.107
14	10.3	9.7	9.2	8.7	8.2	0.104
15	10.0	9.5	9.0	8.5	8.0	0.100
16	9.8	9.3	8.8	8.4	7.9	0.098
17	9.6	9.1	8.7	8.2	7.7	0.095
18	9.4	9.0	8.5	8.0	7.6	0.092
19	9.2	8.8	8.3	7.9	7.4	0.089
20	9.0	8.6	8.1	7.7	7.3	0.088
21	8.8	8.4	8.0	7.6	7.1	0.086
22	8.7	8.3	7.8	7.4	7.0	0.084
23	8.5	8.1	7.7	7.3	6.8	0.083
24	8.3	7.9	7.5	7.1	6.7	0.083
25	8.2	7.8	7.4	7.0	6.5	0.082
26	8.0	7.6	7.2	6.8	6.4	0.080
27	7.9	7.5	7.1	6.7	6.3	0.079
28	7.7	7.3	6.9	6.6	6.2	0.078
29	7.6	7.2	6.8	6.5	6.1	0.076
30	7.4	7.1	6.7	6.3	6.0	0.075

$$\begin{aligned}
 {}^*C_{DO} = & (14.53475 - 0.4024407T + 0.834117 \times 10^{-2}T^2 - 0.1096844 \times 10^{-3}T^3 \\
 & + 0.6373492 \times 10^{-6}T^4) + CL \times 10^{-3} (-0.1591768 + 0.5374137 \times 10^{-2}T \\
 & - 0.1152163 \times 10^{-3}T^2 + 0.1516847 \times 10^{-5}T^3 - 0.8862202 \times 10^{-8}T^4).
 \end{aligned}$$

Example 1: C_{DO} = 7.6 mg/L when T = 29 °C and CL = 0 mg/L.
 Example 2: C_{DO} = 7.2 mg/L when T = 29 °C and CL = 5000 mg/L.

$$\begin{aligned}
 {}^*C'_{DO} &= C_{DO} (P' - p)/(760 - p) \\
 {}^*p &= 4.571512 + 0.352142T + 0.007386T^2 + 0.000371T^3
 \end{aligned}$$

NOMENCLATURE

C_1 = Solubility of a gas in water (% v/v) under pressure P_1 (atm)

C_2 = Solubility of a gas in water (% v/v) under pressure P_2 (atm)

C_{air} = Concentration of air in water, % v/v (% air volume/water volume)

$C_{\text{carbondioxide}}$ = Concentration of pure carbon dioxide in water, % v/v (% carbon dioxide volume/water volume)

$C_{\text{carbondioxide-a}}$ = Actual concentration of carbon dioxide component in water, % v/v (% carbon dioxide volume/water volume)

C_{DO} = Dissolved oxygen concentration in water at equilibrium with air above the water, mg/L

C'_{DO} = Dissolved oxygen concentration in water at any barometric pressure, water temperature or chloride concentration, mg/L

C_{gas} = Concentration of a pure gas in water, % v/v (% gas volume/water volume = mL gas/100 mL water)

$C_{\text{gas-a}}$ = Actual concentration of a gas component in water, % v/v (% gas volume/water volume)

C_i = Concentration of dissolved gas, mole/L

C_{nitrogen} = Concentration of pure nitrogen in water, % v/v (% nitrogen volume/water volume)

$C_{\text{nitrogen-a}}$ = Concentration of nitrogen component in water, % v/v (% nitrogen volume/water volume)

C_{oxygen} = Concentration of pure oxygen in water, % v/v (% oxygen volume/water volume)

$C_{\text{oxygen-a}}$ = Actual concentration of oxygen component in water, % v/v (% oxygen volume/water volume)

C_{water} = Molar concentration of water

CL = Chloride concentration, mg/L

D = Bubble diameter, cm (or in) (or m)

d_B = Density of gas bubble, kg/m³

D_e = Effective depth of air dispersion cylinder, cm

d_W = Density of water, kg/m³

f = A constant

F_{internal} = Internal force, dyne

F_{surface} = Surface force, dyne

g = Gravitational acceleration = 9.8 m/s² = 32.174 ft/s²

h = The elevation above sea level in thousands of meters ($h = 1.0$ when elevation = 1000 m)

H_i = Henry's law constant for the particular gas, i

i = A gas

p = Water vapor pressure, mm Hg

P = Internal bubble pressure, dyne/cm² (or psi)

P' = Total pressure above the water, mm Hg

P_1 = Normal atmospheric pressure = 1 atm (which may be corrected by elevation)

P_2 = Pressure of a gas above the water, atm

PCT_{gas} = Actual percentage of a gas component, %

PCT_{nitrogen} = Actual percentage of nitrogen component, %

PCT_{oxygen} = Actual percentage of oxygen component, %

$P_{i,0}$ = The partial pressure of the gas, i, at sea level where h is 0 m

$P_{i,h}$ = The partial pressure of the gas, i, at an elevation h

r = Surface tension, dyne/cm (or lb/in)

S = Dissolved solids concentration, g/L

S_a = Salinity, mg/L

T = Water temperature, °C

t = Bubbles traveling time to water surface, s or min

ν = Water viscosity, Pa-s

V_{br} = Percent volume of gas bubble released from a previously pressurized water, %

V_T = Bubbles vertical rising velocity = terminal velocity of a spherical gas bubble, cm/s, or cm/min, or m/s

X_i = Dissolved gas mole fraction of any gas

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