CHAPTER 12

Mixed-Gas Diving Theory

12-1 INTRODUCTION

12-1.1 Purpose. The fundamental laws and concepts of underwater physics presented in Chapter 2 (Volume 1) are basic to a proper understanding of mixed-gas diving techniques. In mixed-gas diving, calculations requiring the use of the various gas laws are vital to safe diving. A thorough working knowledge of the application of the gas laws is mandatory for the mixed-gas diver. This chapter reviews the gas laws.

12-1.2 Scope. This chapter discusses the theory and techniques used in mixed-gas diving.

12-2 BOYLE'S LAW

Boyle's law states that at constant temperature, the absolute pressure and the volume of gas are inversely proportional. As pressure increases, the gas volume is reduced; as the pressure is reduced, the gas volume increases.

The formula for expressing Boyle's law is:

$$C = P \times V$$

Where:
C *is* constant
P *is* absolute pressure
V *is* volume

Boyle's law can also be expressed as:

$$P_1V_1 = P_2V_2$$

Where:

P_1 = initial pressure
V_1 = initial volume
P_2 = final pressure
V_2 = final volume

When working with Boyle's law, absolute pressure may be measured in atmospheres absolute. To calculate absolute pressure using atmospheres absolute:

$$P_{ata} = \frac{\text{Depth fsw} + 33 \text{ fsw}}{33 \text{ fsw}} \quad \text{or} \quad P_{ata} = \frac{\text{psig} + 14.7 \text{ psi}}{14.7 \text{ psi}}$$

Sample Problem 1. The average gas flow requirements of a diver using a MK 21 MOD 1 UBA doing moderate work is 1.4 acfm when measured at the depth of the diver. Determine the gas requirement, expressed in volume per minute at surface conditions, for a diver working at 132 fsw.

1. Rearrange the formula for Boyle's law to find the initial volume (V_1):

$$V_1 = \frac{P_2 V_2}{P_1}$$

2. Calculate the final pressure (P_2):

$$P_2 = \frac{132\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$
$$= 5\ \text{ata}$$

3. Substitute known values to find the initial volume (V_1):

$$V_1 = \frac{5\ \text{ata} \times 1.4\ \text{acfm}}{1\ \text{ata}}$$
$$= 7.0\ \text{acfm}$$

4. The gas requirement for a diver working at 132 fsw is 7.0 acfm.

Sample Problem 2. Determine the gas requirement, expressed in volume per minute at surface conditions, for a diver working at 231 fsw.

1. Rearrange the formula for Boyle's law to find the initial volume (V_1):

$$V_1 = \frac{P_2 V_2}{P_1}$$

2. Calculate the final pressure (P_2):

$$P_2 = \frac{231\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$
$$= 8\ \text{ata}$$

3. Substitute the known values to find the initial volume (V_1):

$$V_1 = \frac{8\ \text{ata} \times 1.4\ \text{acfm}}{1\ \text{ata}}$$
$$= 11.2\ \text{acfm}$$

The gas requirement for a diver working at 231 fsw is 11.2 surface acfm.

Sample Problem 3. Determine the gas requirement, expressed in volume per minute at surface conditions, for a diver working at 297 fsw.

1. Rearrange the formula for Boyle's law to find the initial volume (V_1):

$$V_1 = \frac{P_2 V_2}{P_1}$$

2. Calculate the final pressure (P_2):

$$P_2 = \frac{297\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$
$$= 10\ \text{ata}$$

3. Substitute the known values to find the initial volume (V_1):

$$V_1 = \frac{10\ \text{ata} \times 1.4\ \text{acfm}}{1\ \text{ata}}$$
$$= 14.0\ \text{acfm}$$

The gas requirement for a diver working at 297 fsw is 14.0 surface acfm.

Sample Problem 4. An open diving bell of 100-cubic-foot internal volume is to be used to support a diver at 198 fsw. Determine the pressure and total surface equivalent volume of the helium-oxygen gas that must be in the bell to balance the ambient water pressure at depth.

1. Calculate final pressure (P_2):

$$P_2 = \frac{198\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$
$$= 7\ \text{ata}$$

2. Rearrange the formula to solve for the initial volume (V_1):

$$V_1 = \frac{P_2\ V_2}{P_1}$$

3. Substitute the known values to find the initial volume (V_1):

$$V_1 = \frac{7\ \text{ata} \times 100\ \text{ft}^3}{1\ \text{ata}}$$
$$= 700\ \text{ft}^3$$

There must be 700 ft^3 of helium-oxygen gas in the bell to balance the water pressure at depth.

Sample Problem 5. The open bell described in Sample Problem 4 is lowered to 297 fsw after pressurization to 198 fsw and no more gas is added. Determine the gas volume in the bell at 297 fsw.

1. Calculate the final pressure (P_2):

$$P_2 = \frac{297\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$
$$= 10\ \text{ata}$$

2. Rearrange the formula to solve for the final volume (V_2):

$$V_2 = \frac{P_1 V_1}{P_2}$$

3. Substitute the known values to find the final volume (V_2):

$$V_2 = \frac{7\ \text{ata} \times 100\ \text{ft}^3}{10\ \text{ata}}$$
$$= 70\ \text{ft}^3$$

The gas volume in the bell at 297 fsw is 70 ft^3.

12-3 CHARLES'/GAY-LUSSAC'S LAW

Charles' and Gay-Lussac's laws state that at a constant pressure, the volume of a gas is directly proportional to the change in the absolute temperature. If the pressure is kept constant and the absolute temperature is doubled, the volume will double. If temperature decreases, volume decreases. If volume instead of pressure is kept constant (i.e., heating gas in a rigid container), then the absolute pressure will change in proportion to the absolute temperature.

The formula for expressing Charles'/Gay-Lussac's law when the pressure is constant is:

$$V_2 = \frac{V_1 T_2}{T_1}$$

Where:
V_1 = initial volume
V_2 = final volume
T_1 = initial absolute temperature
T_2 = final absolute temperature

The formula for expressing Charles'/Gay-Lussac's law when the volume is constant is:

$$P_2 = \frac{P_1 T_2}{T_1}$$

Where:
P_1 = initial absolute pressure
P_2 = final absolute pressure
T_1 = initial absolute temperature
T_2 = final absolute temperature

Sample Problem 1. The on-board gas supply of a PTC is charged on deck to 3,000 psig at an ambient temperature of 32°C. The capsule is deployed to a depth of 850 fsw where the water temperature is 7°C. Determine the pressure in the gas supply at the new temperature. Note that in this example the volume is constant; only pressure and temperature change.

1. Transpose the formula for Charles'/Gay-Lussac's law to solve for the final pressure:

$$P_2 = \frac{P_1 T_2}{T_1}$$

2. Convert Celsius temperatures to absolute temperature values (Kelvin):

$$°K = °C + 273$$

$$T_1 = 32°C + 273 = 305°K$$

$$T_2 = 7°C + 273 = 280°K$$

3. Convert initial pressure to absolute pressure:

$$P_1 = \frac{3,000 \text{ psig} + 14.7 \text{ psi}}{14.7 \text{ psi}}$$
$$= 205 \text{ ata}$$

4. Substitute known values to find the final pressure:

$$P_2 = \frac{205 \text{ ata} \times 280°K}{305°K}$$
$$= 188.19 \text{ ata}$$

5. Convert the final pressure to gauge pressure:

$$P_2 = (188.19\ \text{ata} - 1\ \text{ata}) \times (14.7\ \text{psi})$$
$$= 2,751.79\ \text{psig}$$

The pressure in the gas supply at the new temperature is 2749 psig.

Sample Problem 2. A habitat is deployed to a depth of 627 fsw at which the water temperature is 40°F. It is pressurized from the surface to bottom pressure, and because of the heat of compression, the internal temperature rises to 110°F. The entrance hatch is opened at depth and the divers begin their work routine. During the next few hours, the habitat atmosphere cools down to the surrounding sea water temperature because of a malfunction in the internal heating system. Determine the percentage of the internal volume that would be flooded by sea water assuming no additional gas was added to the habitat. Note that in this example pressure is constant; only volume and temperature change.

1. Convert Fahrenheit temperatures to absolute temperature values (Rankine):

$$°R = °F + 460$$
$$T_1 = 110°F + 460$$
$$= 570°R$$
$$T_2 = 40°F + 460$$
$$= 500°R$$

2. Substitute known values to solve for the final volume:

$$V_2 = \frac{V_1 T_2}{T_1}$$
$$= V_1 \times \frac{500°R}{570°R}$$
$$= 0.88 V_1$$

3. Change the value to a percentage:

$$V_2 = (0.88 \times 100\%)\ V_1$$
$$= 88\%\ V_1$$

4. Calculate the flooded volume:

$$\text{Flooded volume} = 100\% - 88\%$$
$$= 12\%$$

Sample Problem 3. A 6-cubic-foot flask is charged to 3000 psig and the temperature in the flask room is 72°F. A fire in an adjoining space causes the temperature in the flask room to reach 170°F. What will happen to the pressure in the flask?

1. Convert gauge pressure unit to absolute pressure unit:

$$P_1 = 3,000 \text{ psig} + 14.7$$
$$= 3,014.7 \text{ psia}$$

2. Convert Fahrenheit temperatures to absolute temperatures (Rankine):

$$°R = °F + 460$$
$$T_1 = 72°F + 460$$
$$= 532°R$$
$$T_2 = 170°F + 460$$
$$= 630°R$$

3. Transpose the formula for Charles's/Gay-Lussac's law to solve for the final pressure (P_2):

$$P_2 = \frac{P_1 T_2}{T_1}$$

4. Substitute known values and solve for the final pressure (P_2):

$$P_2 = \frac{3,014.7 \text{ psia} \times 630°R}{532°R}$$
$$= \frac{1,899,261}{532°R}$$
$$= 3,570.03 \text{ psia}$$

The pressure in the flask increased from 3,000 psig to 3,570.03 psia. Note that the pressure increased even though the flask's volume and the volume of the gas remained the same.

12-4 THE GENERAL GAS LAW

The general gas law is a combination of Boyle's law, Charles' law, and Gay-Lussac's law, and is used to predict the behavior of a given quantity of gas when pressure, volume, or temperature changes.

The formula for expressing the general gas law is:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Where:

P_1	=	initial absolute pressure
V_1	=	initial volume
T_1	=	initial absolute temperature
P_2	=	final absolute pressure
V_2	=	final volume
T_2	=	final absolute temperature

The following points should be noted when using the general gas law:

- There can be only one unknown value.
- If it is known that a value remains unchanged (such as the volume of a tank) or that the change in one of the variables will be of little consequence, cancel the value out of both sides of the equation to simplify the computations.

Sample Problem 1. A bank of cylinders having an internal volume of 20 cubic feet is to be charged with helium and oxygen to a final pressure of 2,200 psig to provide mixed gas for a dive. The cylinders are rapidly charged from a large premixed supply, and the gas temperature in the cylinders rises to 160°F by the time final pressure is reached. The temperature in the cylinder bank compartment is 75°F. Determine the final cylinder pressure when the gas has cooled.

1. Simplify the equation by eliminating the variables that will not change. The volume of the tank will not change, so V_1 and V_2 can be eliminated from the formula in this problem:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

2. Multiply each side of the equation by T_2, then rearrange the equation to solve for the final pressure (P_2):

$$P_2 = \frac{P_1T_2}{T_1}$$

3. Calculate the initial pressure by converting the gauge pressure unit to the atmospheric pressure unit:

$$\begin{aligned} P_1 &= 2,200 \text{ psig} + 14.7 \text{ psi} \\ &= 2,214.7 \text{ psia} \end{aligned}$$

4. Convert Fahrenheit temperatures to absolute temperature values (Rankine):

$$°R = °F + 460$$
$$T_1 = 160°F + 460$$
$$= 620°R$$
$$T_2 = 75°F + 460$$
$$= 535°R$$

5. Fill in known values to find the final pressure (P_2):

$$P_2 = \frac{2,214.7\ \text{psia} \times 535°R}{620°R}$$
$$= 1,911.07\ \text{psia}$$

6. Convert final pressure (P_2) to gauge pressure:

$$P_2 = 1,191.07\ \text{psig}$$
$$= 1,896.3\ \text{psig}$$

The pressure when the cylinder cools will be 1896.3 psig.

Sample Problem 2. Using the same scenario as in Sample Problem 1, determine the volume of gas at standard temperature and pressure (STP = 70°F @ 14.7 psia) resulting from rapid charging.

1. Rearrange the formula to solve for the final volume (V_2):

$$V_2 = \frac{P_1 V_1 T_2}{P_2 T_1}$$

2. Convert Fahrenheit temperatures to absolute temperature values (Rankine):

$$°R = °F + 460$$
$$T_1 = 160°F + 460$$
$$= 620°R$$
$$T_2 = 70°F + 460$$
$$= 530°R$$

3. Fill in known values to find the final volume (V_2):

$$V_2 = \frac{2,214.7\ \text{psia} \times 20\text{ft}^3 \times 530°\text{R}}{14.7\ \text{psia} \times 620°\text{R}}$$

$$= 2,575.79\ \text{ft}^3\text{STP}$$

Sample Problem 3. Determine the volume of the gas at STP resulting from slow charging (maintaining 70°F temperature to 2,200 psig).

1. Rearrange the formula to solve for the final volume (V_2):

$$V_2 = \frac{P_1V_1T_2}{P_2T_1}$$

2. Convert Fahrenheit temperatures to absolute temperature values (Rankine):

$$T_1 = 75°\text{F} + 460$$

$$= 535°\text{R}$$

$$T_2 = 70°\text{F} + 460$$

$$= 530°\text{R}$$

3. Substitute known values to find the final volume (V_2):

$$V_2 = \frac{2,214.7\ \text{psia} \times 20\text{ft}^3 \times 530°\text{R}}{14.7\ \text{psia} \times 535°\text{R}}$$

$$= 2,985.03\ \text{ft}^3\text{STP}$$

Sample Problem 4. A 100-cubic-foot salvage bag is to be used to lift a 3,200-pound torpedo from the sea floor at a depth of 231 fsw. An air compressor with a suction of 120 cfm at 60°F and a discharge temperature of 140°F is to be used to inflate the bag. Water temperature at depth is 55°F. To calculate the amount of time required before the torpedo starts to rise (neglecting torpedo displacement, breakout forces, compressor efficiency and the weight of the salvage bag), the displacement of the bag required to lift the torpedo is computed as follows:

1. Calculate the final volume (V_2):

$$V_2 = \frac{3200\ \text{lbs}}{64\ \text{lb} / \text{ft}^3}$$

$$= 50\text{ft}^3$$

2. Calculate the final pressure (P_2):

$$P_2 = \frac{231\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$
$$= 8\ \text{ata}$$

3. Convert Fahrenheit temperatures to absolute temperature values (Rankine):

$$°R = °F + 460$$
$$T_1 = 60°F + 460$$
$$= 520°R$$
$$T_2 = 55°F + 460$$
$$= 515°R$$

4. Rearrange the formula to solve for the initial volume (V_1):

$$V_1 = \frac{P_2 \times V_2 \times T_1}{P_1 \times T_2}$$

5. Substitute known values to find the initial volume (V_1):

$$V_1 = \frac{8\ \text{ata} \times 50\ \text{ft}^3 \times 520°R}{1\ \text{ata} \times 515°R}$$
$$= 403.8\ \text{ft}^3$$

6. Compute the time:

$$\text{Time} = \frac{\text{Volume Required}}{\text{Compressor Displacement}}$$
$$= \frac{403.8\ \text{ft}^3}{120\ \text{ft}^3 / \text{min}}$$
$$= :03::22$$

(Note that the 140°F compressor discharge temperature is an intermediate temperature and does not enter into the problem.)

12-5 DALTON'S LAW

Dalton's law states that the total pressure exerted by a mixture of gases is equal to the sum of the pressures of the different gases making up the mixture, with each gas acting as if it alone occupied the total volume. The pressure contributed by any gas in the mixture is proportional to the number of molecules of that gas in the total volume. The pressure of that gas is called its partial pressure (pp), meaning its part of the whole.

The formula for expressing Dalton's law is:

$$P_{Total} = pp_A + pp_B + pp_C + \dots$$

Where: A, B, and C are gases and

$$pp_A = \frac{P_{Total} \times \%Vol_A}{100\%}$$

Sample Problem 1. A helium-oxygen mixture is to be prepared which will provide an oxygen partial pressure of 1.2 ata at a depth of 231 fsw. Compute the oxygen percentage in the mix.

1. Convert depth to pressure in atmospheres absolute:

$$P_{Total} = \frac{231\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$

$$= 8\ \text{ata}$$

2. Calculate the oxygen percentage of the mix.

Since:

$$pp_A = P_{Total} \times \frac{\%Vol_A}{100\%}$$

Then:

$$\%Vol_A = \frac{pp_A}{P_{Total}} \times 100\%$$

$$= \frac{1.2\ \text{ata}}{8\ \text{ata}} \times 100\%$$

$$= 15\%\ \text{oxygen}$$

The oxygen percentage of the mix is 15 percent.

Sample Problem 2. A 30-minute bottom time dive is to be conducted at 264 fsw. The maximum safe oxygen partial pressure for a dive under normal operating conditions is 1.3 ata (Table 14-4). Two premixed supplies of HeO_2 are available: 84/16 percent and 86/14 percent. Which of these mixtures is safe for the intended dive?

1. Convert depth to pressure in atmospheres absolute:

$$P_{Total} = \frac{264\ fsw + 33\ fsw}{33\ fsw}$$
$$= 9\ ata$$

2. Calculate the maximum allowable O_2 percentage:

$$\%Vol_A = \frac{pp_A}{P_{Total}} \times 100\%$$
$$= \frac{1.3\ ata}{9\ ata} \times 100\%$$
$$= 14.4\%\ oxygen$$

Result: The 14 percent O_2 mix is safe to use; the 16 percent O_2 mix is unsafe.

$$\text{The pp of the 14\% mix} = 9\ ata \times \frac{14\%}{100\%}$$
$$= 1.26\ ataO_2$$

1.26 ata O_2 is less than the maximum allowable.

$$\text{The pp of the 16\% mix} = 9\ ata \times \frac{16\%}{100\%}$$
$$= 1.44\ ataO_2$$

Use of this mixture will result in a greater risk of oxygen toxicity.

Sample Problem 3. Gas cylinders aboard a PTC are to be charged with an HeO_2 mixture. The mixture should provide a ppO_2 of 0.9 ata to the diver using a MK 21 MOD 0 helmet at a saturation depth of 660 fsw. Determine the oxygen percentage in the charging gas, then compute the oxygen partial pressure of the breathing gas if the diver makes an excursion from saturation depth to 726 fsw.

1. Convert depth to pressure in atmospheres absolute:

$$P_{Total} = \frac{660\ fsw + 33\ fsw}{33\ fsw}$$
$$= 21\ ata$$

2. Calculate the O_2 content of the charging mix:

$$\begin{aligned}\%VolO_2 &= \frac{0.9\ ata}{21\ ata} \times 100\% \\ &= 4.3\%\ O_2\end{aligned}$$

3. Convert excursion depth to pressure in atmospheres absolute:

$$\begin{aligned}P_{Total} &= \frac{726\ fsw + 33\ fsw}{33\ fsw} \\ &= 23\ ata\end{aligned}$$

4. Calculate the O_2 partial pressure at excursion depth:

$$\begin{aligned}ppO_2 &= 23\ ata \times \frac{4.3\%\ O_2}{100\%} \\ &= 0.99\ ata\end{aligned}$$

12-6 HENRY'S LAW

Henry's law states that the amount of gas that will dissolve in a liquid at a given temperature is almost directly proportional to the partial pressure of that gas. If one unit of gas is dissolved at one atmosphere partial pressure, then two units will be dissolved at two atmospheres, and so on.