Chapter 8
GASES

Chapter Check-In

- ❑ Learning how the volume of any gas is affected by temperature
- ❑ Using the Ideal Gas Equation
- ❑ Learning to use Avogadro's number

Of the three common states of matter, the gaseous state was most easily described by early scientists. As early as 1662, Robert Boyle showed how the volume of a gas, any gas, changed as the pressure applied to it was changed. Soon thereafter, the effects of temperature and the quantity of gas on volume were discovered. The result of all these studies was a set of fundamental mathematical equations known as the gas laws that applied equally well to any gas, whether pure oxygen, nitrogen, or a mixture of the two. Through careful studies of gases reacting with one another, Amedeo Avogadro later concluded that equal volumes of different gases must contain the same number of molecules. For example, 10.0 L of oxygen contained the same number of oxygen molecules as there were nitrogen molecules in 10.0 L of nitrogen.

As time passed, it became clear that one mole of any gas contained the same number of molecules, 6.02×10^{23} molecules to be exact, a number known today as **Avogadro's number.** One mole of anything is Avogadro's number of that thing—atoms, molecules, people, or dollars—and that would be a lot of dollars!

Boyle's Law

Pressure is the amount of force exerted on one unit of area. The example of an ocean diver should make the concept clearer: The greater the depth the diver reaches, the greater the pressure due to the weight of the overlying water. Pressure is not unique to liquids but can be transmitted by gases and solids, too. At the surface of the Earth, the weight of the overlying air exerts a pressure equal to that generated by a column of mercury 760 mm high. The two most common units of pressure in chemical studies are atmosphere and millimeters of mercury

$$1 \text{ atm} = 760 \text{ mm Hg}$$

The English scientist Robert Boyle performed a series of experiments involving pressure and, in 1662, arrived at a general law—that the volume of a gas varied inversely with pressure.

$$PV = \text{constant}$$

This formulation has become established as **Boyle's law.** Of course, the relationship is valid *only if the temperature remains constant.*

As an example of the use of this law, consider an elastic balloon holding 5 L of air at the normal atmospheric pressure of 760 mm Hg. If an approaching storm causes the pressure to fall to 735 mm Hg, the balloon expands. The product of the initial pressure and volume is equal to the product of the final pressure and volume temperature is constant.

$$P_1 V_1 = P_2 V_2$$

$$(760 \text{ mm})(5 \text{ liters}) = (735 \text{ mm})(x \text{ liters})$$

$$x = \frac{(760)(5)}{735} = 5.17 \text{ liters}$$

It is important that you realize that pressure and volume vary inversely; therefore, an increase in either one necessitates a proportional decrease in the other.

Problem 18: Convert a pressure of 611 mm Hg to atmospheres.

Problem 19: If a gas at 1.13 atm pressure occupies 732 milliliters, what pressure is needed to reduce the volume to 500 milliliters?

Charles' Law

In 1787, the French inventor Jacques Charles, while investigating the inflation of his man-carrying hydrogen balloon, discovered that the volume of a gas varied directly with temperature. This relation can be written as

$$\frac{V}{T} = \text{constant}$$

and is called **Charles' law** (or Gay-Lussac's law, after the French physicist who first published it). For this law to be valid, *the pressure must be held constant and the temperature must be expressed on the absolute temperature scale.*

Because the volume of a gas decreases with falling temperature, scientists realized that a natural zero-point for temperature could be defined as the temperature at which the volume of a gas theoretically becomes zero. At a temperature of absolute zero, the volume of an ideal gas would be zero. The absolute temperature scale was devised by the English physicist Kelvin, so temperatures on this scale are called *Kelvin* (*K*) temperatures. The relationship of the Kelvin scale to the common Celsius scale must be memorized by every chemistry student:

$$K = °\ C + 273.15$$

Therefore, at normal pressure, water freezes at 273.15 *K* (0° C) and boils at 373.15 *K* (100° C). Room temperature is approximately 293 *K* (20° C). Both temperature scales are used in tables of chemical values, and many simple errors arise from not noticing which scale is presented.

Use Charles' law to calculate the final volume of a gas, which occupies 400 ml at 20° C and is subsequently heated to 300° C. Begin by converting both temperatures to the absolute scale:

$$T_1 = 20°\ C = 293.15\ K$$

$$T_2 = 300°\ C = 573.15\ K$$

Then substitute them into the constant ratio of Charles' law:

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

$$\frac{400\text{ mL}}{293.15K} = \frac{x\text{ mL}}{573.15\ K}$$

$$x = \frac{(400)(573.15)}{(293.15)} = 782\text{ mL}$$

When using Charles' law, remember that volume and Kelvin temperature vary directly; therefore, an increase in either requires a proportional increase in the other.

> **Problem 20:** A gas occupying 660 ml at a laboratory temperature of 20° C was refrigerated until it shrank to 125 ml. What is the temperature in degrees Celsius of the chilled gas?

Avogadro's Law

The volume of a gas is determined not only by the pressure and volume but also by the quantity of gas. When the quantity is given in moles, the mathematical relation is

$$\frac{V}{n} = \text{constant}$$

where *n* represents the number of moles of the gas. This relationship is known as **Avogadro's law** because, in 1811, Amedeo Avogadro of Italy proposed that equal volumes of all gases contain the same number of molecules. His theory explained why the volumes of gases in reactions are in ratios of small integers, as in the combustion of hydrogen:

$2H_2\,(g)$	+	$O_2\,(g)$	→	$2H_2O\,(g)$
hydrogen		oxygen		water vapor
(2 volumes)		(1 volume)		(2 volumes)

You should recall from the review of the mole unit that the reaction coefficients (2, 1, and 2 in the preceding example) can be interpreted as molecules, or as moles, or as volumes. This is because Avogadro's law holds for all gases. The number of molecules in 1 mole of a gas is known to be

6.02×10^{23}, a value called **Avogadro's number.** As an example of the use of this important number, calculate the mass in grams of a single oxygen atom:

$$1 \text{ mole } O_2 = 2(16.00) = 32.00 \text{ grams}$$

$$1 \text{ molecule of } O_2 = \frac{32.00 \text{ gram}}{6.02 \times 10^{23}} = 5.32 \times 10^{-23} \text{ gram}$$

$$1 \text{ atom of O} = \frac{5.32 \times 10^{-23} \text{ gram}}{2} = 2.66 \times 10^{-23} \text{ grams}$$

Problem 21: How many hydrogen atoms are there in 10 grams of methane, CH_4?

Ideal Gas Equation

The relations known as Boyle's law, Charles' law, and Avogadro's law can be combined into an exceedingly useful formula called the **Ideal Gas Equation,**

$$PV = nRT$$

where R denotes the gas constant:

$$R = 0.082 \frac{\text{liter} - \text{atm}}{\text{deg} - \text{mole}}$$

The temperature is, as always in gas equations, measured in Kelvin.

This formula is strictly valid only for ideal gases—those in which the molecules are far enough apart so intermolecular forces can be neglected. At high pressures, such forces cause significant departure from the Ideal Gas Equation, and more complicated equations have been devised to treat such cases. The Ideal Gas Equation, however, gives useful results for most gases at pressures less than 100 atmospheres.

The conditions of 0° C temperature and 1 atm pressure may easily be produced in the laboratory; such conditions are called **standard temperature and pressure** (**STP**). Because the properties of gases vary with both temperature and pressure, many published values are for gases at STP. Note that room temperature differs from standard temperature.

Use the Ideal Gas Equation to calculate the volume of 1 mole of gas at STP:

$$V = \frac{nRT}{P}$$

$$V = \frac{(1\,\text{mole})\left(\frac{0.082\,\text{L}-\text{atm}}{K-\text{mole}}\right)(273.15\,K)}{(1\,\text{atm})}$$

$$V = 22.40\,\text{liters}$$

This is the value stated in the carbon dioxide reaction; you were asked to memorize that 1 mole of any gas occupies 22.40 liters at STP.

You should be able to use the Ideal Gas Equation to determine any one of the four quantities—pressure, volume, moles, or temperature—if you are given values for the other three.

One important application is to deduce the molecular weight and formula for a gas. Assume you know that the hydrocarbon propylene is, by weight, 85.6% carbon and 14.4% hydrogen. Then the atomic ratios of the compound are

$$C = \frac{85.6}{12.01} = \frac{7.13}{7.13} = 1$$

$$H = \frac{14.4}{1.01} = \frac{14.26}{7.13} = 2$$

Therefore, the propylene molecule is some integral multiple of CH_2: it can be CH_2 or C_2H_4 or C_3H_6 or a yet larger molecule. Measuring the volume of 10 grams of propylene at STP yields 5.322 liters, which you can use to calculate its molecular weight.

$$\frac{5.322\,\text{liters}}{22.40\,\text{liters/mole}} = 0.2376\,\text{mole}$$

$$\frac{10\,\text{grams}}{0.2376\,\text{mole}} = 42.09\,\text{grams/mole (the molecular weight)}$$

Because the atomic weights of 1 CH_2 unit add to 14.03, the molecule contains 3 such units. Consequently, the molecular formula for propylene is C_3H_6.

Problem 22: What is the volume occupied by 1 kilogram of carbon monoxide at 700° C and 0.1 atm?

Problem 23: The ozone molecule contains only oxygen atoms. Determine the molecular formula of ozone given that 2.3 grams occupies 1,073 milliliters at standard temperature and pressure.

Chapter Checkout

Q&A

1. If temperature remains constant and the pressure on 1.0 L of air doubles, the volume of the gas ______.
   - **a.** increases to 2.0 L
   - **b.** stays the same
   - **c.** decreases to 0.5 L
2. The number of atoms in one mole of iron is ______.
   - **a.** Avogadro's number
   - **b.** Ideal Gas Equation constant
   - **c.** one
3. The values referred to as standard temperature and pressure (STP) are ______.
   - **a.** 1 atmosphere of pressure and 25° C
   - **b.** 1 atmosphere of pressure and 0° C
   - **c.** 1 atmosphere of pressure and 100° C
4. Charles' law relates how the volume of a gas varies with ______.
   - **a.** absolute temperature
   - **b.** the number of moles of gas
   - **c.** the pressure applied to the gas
5. At standard temperature and pressure, 2.0 moles of nitrogen gas (N_2) has a volume of ______.
   - **a.** 22.40 L
   - **b.** 11.20 L
   - **c.** 44.80 L

Answers: 1. c 2. a 3. b 4. a 5. c