Chemistry 20

Lesson 31 – Combined Gas Law

I. Molar volume of gases

As we saw in Lesson 30, according to Avogadro's theory, equal volumes of any gas at the same temperature and pressure contain an equal number of particles. A mole is a specific number of particles. Therefore, for all gases at each specific pressure and temperature, there must be a certain volume that contains exactly one mole of particles. The volume that one mole of a gas occupies at a specified temperature and pressure is called its **molar volume**. The molar volume is the same for all gases at the same temperature and pressure. For scientific work, the most useful specific pressure and temperature conditions are either SATP or STP. It has been determined empirically that the molar volume of a gas at SATP and at STP are:

$V_{SATP} = 24.8$ L/mol

$V_{STP} = 22.4$ L/mol

Knowing the molar volume of gases allows scientists to work with easily measured volumes of gases when specific masses of gases are needed. Measuring the volume of a gas is much more convenient than measuring its mass. Imagine trapping a gas in a container and trying to measure its mass on a balance – and then making corrections for the buoyant force of the surrounding air. Also, working with gas volumes is more precise, as the process involves measuring relatively large volumes rather than relatively small masses. Molar volume can be used as a conversion factor to convert moles to volume, and vice versa, as shown in the following examples. Note that you should feel free to use either unit analysis or the molar volume equation

$$n = \frac{v}{V}$$

to solve problems.

Example 1

What is the volume of 9.0 mol of $CO_{2\,(g)}$ at STP?

$$n = \frac{v}{V}$$

$$v = n\,V = 9.0\text{mol}(22.4\,{}^{L}\!/\!_{mol})$$

$$v = \mathbf{2.0 \times 10^2\,L}$$

Example 2

If 8.86 g of $Cl_{2\,(g)}$ is required for an experiment at SATP, what should the container volume be?

$$n = \frac{m}{M} = \frac{8.86\text{g}}{70.90\,{}^{g}\!/\!_{mol}} = 0.125\,\text{mol}$$

$$v = n\,V = 0.125\text{mol}(24.8\,{}^{L}\!/\!_{mol})$$

$$v = \mathbf{3.10\ L}$$

II. Combined gas law problems

In this section we learn how to use the combined gas law through a set of examples.

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

Example 3

A balloon is filled with 30 L of helium gas at 1.0 atm. What is the volume if the balloon rises to an altitude where the pressure is 0.25 atm?

$V_1 = 30\,L$

$V_2 = ?$

$P_1 = 1.0\,atm$

$P_2 = 0.25\,atm$

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

$$P_1V_1 = P_2V_2$$

$$V_2 = \frac{P_1V_1}{P_2} = \frac{1.0\,atm(30\,L)}{0.25\,atm}$$

$$V_2 = \mathbf{1.2\times10^2\,L}$$

Since we are not given any information about the temperature of the gas, we must assume that it remains unchanged (i.e. $T_1 = T_2$). Therefore, temperature can be eliminated from the equation.

Example 4

A balloon is inflated at STP to a volume of 4.0 L. What is its final volume if it is heated to 57°C?

$V_1 = 4.0\,L$

$V_2 = ?$

$T_1 = 0^\circ C = 273K$

$T_2 = 57^\circ C = 330K$

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

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

$$V_2 = \frac{V_1T_2}{T_1} = \frac{(4.0\,L)(330K)}{273K}$$

$$V_2 = \mathbf{4.8\,L}$$

Since we are not given any information about the pressure of the gas, we must assume that it remains unchanged (i.e. $P_1 = P_2$). Therefore, pressure can be eliminated.

Example 5

The gas left in an aerosol can is at SATP. If the can is thrown into a fire and the temperature rises to 900°C, what is the internal pressure?

$$P_1 = 100\,kPa$$
$$P_2 = ?$$
$$T_1 = 25^\circ C = 298K$$
$$T_2 = 900^\circ C = 1173K$$

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

Since we are not given any information about the volume of the gas, we must assume that it remains unchanged and therefore it can be eliminated.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$
$$P_1T_2 = P_2T_1$$
$$P_2 = \frac{P_1T_2}{T_1} = \frac{(100\,kPa)(1173K)}{298K}$$
$$P_2 = \mathbf{394\,kPa}$$

Example 6

A cylinder of compressed oxygen has a volume of 30 L and 100 atm pressure at 27°C. The cylinder is cooled until the pressure is 20 atm, while the volume is decreased to 10 L. What is the new temperature?

$$V_1 = 30\,L$$
$$V_2 = 10\,L$$
$$P_1 = 100\,atm$$
$$P_2 = 20\,atm$$
$$T_1 = 27^\circ C = 300K$$
$$T_2 = ?$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$
$$T_2 = \frac{P_2V_2T_1}{P_1V_1} = \frac{(20\,atm)(10L)(300K)}{(100\,atm)(30L)}$$
$$T_2 = \mathbf{20K}$$

III. Assignment

1. Carbon dioxide produced by yeast in bread dough causes the dough to rise, even before baking. During baking, the carbon dioxide expands. Predict the final volume of 0.10 L of carbon dioxide in bread dough that is heated from 25°C to 98°C.

2. An automobile tire has a volume of 27 L at 225 kPa and 18°C.
   a. What is the air pressure in the tire if the temperature increases to 45°C? Assume constant volume.
   b. What volume would this air occupy at SATP?

3. A bicycle pump cylinder contains a volume of 600 mL of air at 100 kPa. What is the volume of the air when the pressure increases to 250 kPa?

4. A balloon has a volume of 5.00 L at 20°C and 100 kPa. What is its volume at 35°C and 90 kPa?

5. A storage tank is designed to hold a fixed volume of butane gas at 150 kPa and 35°C. To prevent dangerous pressure build-up, the tank has a relief valve that opens at 250 kPa. At what (Celsius) temperature does the valve open?

6. In a cylinder of a diesel engine, 500 mL of air at 40°C and 1.00 atm is powerfully compressed just before the diesel fuel is injected. The resulting pressure is 35.0 atm. If the final volume is 23.0 mL, what is the final temperature in the cylinder?

7. A cylinder of helium gas has a volume of 1.0 L. The gas in the cylinder exerts a pressure of 800 kPa at 30°C. Assuming no temperature change occurs when the valve is opened, what volume of gas at SATP can be obtained from the cylinder?

8. A non-rigid balloon is filled with 10,000 L of helium at 7°C and 101 kPa. What will be the volume if the balloon rises to a point where the temperature is -33°C and the pressure drops to 26.6 kPa?

9. A rigid balloon is filled with 10,000 L of helium at 7 °C and 101 kPa. What will be the pressure if the balloon rises to an altitude where the temperature is -33 °C?

10. 10 L of a gas at STP has a mass of 60 g. What is the mass of the gas at 57°C and 2.0 atm?

11. 20 L of a gas at STP has a mass of 40 g. What is the density of the gas at 27°C and 202 kPa? Remember, density = mass/volume.

12. Weather balloons filled with hydrogen gas are occasionally reported as UFOs. They can reach altitudes of about 40 km. What volume does 7.50 mol of hydrogen gas in a weather balloon occupy at SATP?

13. Sulfur dioxide gas is emitted from marshes, volcanos, and refineries that process crude oil and natural gas. What amount of sulfur dioxide is contained in 50 mL of the gas at SATP?

14. Neon gas under low pressure emits the red light that glows in advertising signs. What volume does 2.25 mol of neon gas occupy at STP before being added to neon tubes in a sign?

15. Oxygen is released by plants during photosynthesis and is used by plants and animals during respiration. What amount in moles of oxygen is present in 20.0 L of air at STP? Assume that air is 20% oxygen (by volume).

