5.10: Stoichiometry by the Mole Ratio Method

The calculation of quantities of materials involved in chemical reactions is called **stoichiometry.** To illustrate stoichiometric calculations consider a typical chemical reaction, in this case the heat-producing combustion of ethane, a hydrocarbon fuel with a chemical formula of C_2H_6:

$$2\,C_2H_6 + 7\,O_2 \rightarrow 4\,CO_2 + 6\,H_2O \tag{5.10.1}$$

Rather than viewing this reaction in terms of individual molecules, it is possible to scale up to moles. Recall from Section 4.8 that the mole is a fundamental unit for quantity of material and that each mole contains Avogadro's number (6.022×10^{23}) of formula units (molecules of covalently bound compounds). This equation simply says that 2 moles of C_2H_6 react with 7 moles of O_2 to yield 4 moles of CO_2 and 6 moles of H_2O. Now we can examine the equation in more detail to do some quantitative calculations. Before doing that, however, review the following two terms

Formula mass: The sum of the atomic masses of all the atoms in a formula unit of a compound. Although the average masses of atoms and molecules may be expressed in atomic mass units (amu or u), formula mass is generally viewed as being relative and without units.

Molar mass: Where X is the formula mass, the molar mass is X grams of an element or compound, that is, the mass in grams of 1 mole of the element or compound

Given the atomic masses H 1.0, C 12.0, and O 16.0 the molar mass of C_2H_6 is 2×12.0 + 6×1.0 = 30.0 g/mol, that of O_2 is 2×16.0 = 32.0 g/mol, that of CO_2 is 12.0 + 2×16.0 = 44.0 g/mol, and that of H_2O is 2×1.0 + 16.0 = 18.0 g/mol. Now consider the chemical equation

$$2\,C_2H_6 + 7\,O_2 \rightarrow 4\,CO_2 + 6\,H_2O \tag{5.10.2}$$

in terms of the minimum whole number of moles reacting and produced and the masses in grams of these quantities. The equation states that 2 moles of C_2H_6 with a mass of 2×30.0 g = 60.0 g of C_2H_6 react with 7 moles of O_2 with a mass of 7×32.0 g = 224 g of O_2 to produce 4 moles of CO_2 with a mass of 4×44.0 g = 176 g of CO_2 and 6 moles of H_2O with a mass of 6×18.0 g = 108 g of H_2O. The total mass of reactants is

$$60.0 \text{ g of } C_2H_6 + \text{ 224 g of } O_2 = 284.0\text{g of reactants} \tag{5.10.3}$$

and the total mass of products is

$$176 \text{ g of } CO_2 + 108\text{g of } H_2O = 284 \text{ g of products} \tag{5.10.4}$$

Note that, as in all chemical reactions, the total mass of products equals the total mass of reactants. Stoichiometry, the calculation of quantities of materials involved in chemical reactions, is based upon the *law of conservation of mass* which states that *the total mass of reactants in a chemical reaction equals the total mass of products*, because matter is neither created nor destroyed in chemical reactions. The basic premise of the **mole ratio method** of stoichiometric calculations is that the relative numbers of moles of reactants and products remain the same regardless of the total quantity of reaction. To illustrate stoichiometric calculations, consider again the following reaction:

$$2\,C_2H_6 + 7\,O_2 \rightarrow 4\,CO_2 + 6\,H_2O \tag{5.10.5}$$

As noted above, this equation states that 2 moles C_2H_6 react with 7 moles of O_2 to produce 4 moles of CO_2 and 6 moles of H_2O. The same ratios hold true regardless of how much material reacts. So for 10 times as much material, 20 moles C_2H_6 react with 70 moles of O_2 to produce 40 moles of CO_2 and 60 moles of H_2O

Suppose that it is given that 18.0 g of C_2H_6 react. What is the mass of O_2 that will react with this amount of C_2H_6? What mass of CO_2 is produced? What mass of H_2O is produced? This problem can be solved by the **mole ratio method**. Mole ratios are, as the name implies, simply the ratios of various moles of reactants and products to each other as shown by a chemical equation. Mole ratios are obtained by simply examining the chemical equation in question; the three that will be used in solving the problem posed are the following:

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$\frac{7\text{mol } O_2}{2 \text{ mol } C_2H_6}$ $\frac{4 \text{ mol } CO_2}{2 \text{ mol } C_2H_6}$ $\frac{6 \text{ mol } H_2O}{2 \text{ mol } C_2H_6}$

To solve for the mass of O_2 reacting the following steps are involved:

A. Mass of C_2H_6 reacting B. Convert to moles of C_2H_6 C. Convert to moles of O_2 D. Convert to mass of O_2

In order to perform the calculation, it will be necessary to have the molar mass of C_2H_6, stated earlier as 30.0 g/mol, the molar mass of O_2(18.0 g/mol) and the mole ratio relating moles of O_2 reactant to moles of C_2H_6, 7 mol O_2/2 mol C_2H_6. The calculation becomes the following

$$\text{Mass of } O_2 = 18.0 \text{ g } C_2H_6 \times \frac{1 \text{ mol } C_2H_6}{30.0 \text{ g } C_2H_6} \times \frac{7 \text{ mol } O_2}{2 \text{ mol } C_2H_6} \times \frac{32.0 \text{ g } O_2}{1 \text{ mol } O_2} = 67.2 \text{ g } O_2$$

Note that in this calculation units cancel above and below the line, starting with units of g C_2H_6. Now that the mass of O_2 reacting has been calculated, it is possible using the appropriate mole ratios and molar masses to calculate the masses of CO_2 and of H_2O produced as follows:

$$\text{Mass of } CO_2 = 18.0 \text{ g } C_2H_6 \times \frac{1 \text{ mol } C_2H_6}{30.0 \text{ g } C_2H_6} \times \frac{6 \text{ mol } H_2O}{2 \text{ mol } C_2H_6} \times \frac{18.0 \text{ g } H_2O}{1 \text{ mol } H_2O} = 32.4 \text{ g } H_2O$$

$$\text{Mass of } H_2O = 18.0 \text{ g } C_2H_6 \times \frac{1 \text{ mol } C_2H_6}{30.0 \text{g} C_2H_6} \times \frac{6 \text{ mol } H_2O}{2 \text{ mol } C_2H_6} \times \frac{18.0 \text{ g } H_2O}{1 \text{ mol } H_2O} = 32.4 \text{ g } H_2O$$

Are the masses calculated above correct? A good check is to compare the total mass of reactants, 18.0 g C_2H_6 + 67.2 g O_2= 85.2 g of reactants, with the total mass of products, 52.8 g CO_2 + 32.4 g H_2O = 85.2 g of products. The fact that the total mass of reactants is equal to the total mass of products gives confidence that the calculations are correct.

As one more example consider the reaction of 15.0 g of Al with Cl_2 to give $AlCl_3$:

$$2\,Al + 3\,Cl_2 \rightarrow 2\,AlCl_3 \tag{5.10.6}$$

What mass of Cl_2 reacts and what is the mass of $AlCl_3$ produced? The atomic mass of Al is 27.0 and that of Cl is 35.5. Therefore, the molar mass of Cl_2 is 71.0 g/mol and the molar mass of $AlCl_3$ is 133.5 g/mole. The mass of Cl_2 reacting is

$$\text{Mass of } Cl_2 = 15.0 \text{ g Al} \times \frac{1 \text{ mol Al}}{27.0 \text{ g Al}} \times \frac{3 \text{ mol } Cl_2}{2 \text{ mol Al}} \times \frac{71.0 \text{ g } Cl_2}{1 \text{ mol } Cl_2} = 59.2 \text{ g } Cl_2$$

$$\text{Mass of } AlCl_3 = 15.0 \text{ g Al} \times \frac{1 \text{ mol Al}}{27.0 \text{ g Al}} \times \frac{2 \text{ mol } AlCl_3}{2 \text{ mol Al}} \times \frac{133.5 \text{ g } AlCl_3}{1 \text{ mol } AlCl_3} = 74.2 \text{ g } AlCl_3$$

As a check, 15.0 g Al + 59.2 g Cl_2 reactant gives a total of 74.2 g of reactants equal to the mass of the $AlCl_3$ product.

Exercise

Calculate the mass of CH_4 that reacts and the masses of the products when 25.0 g of Fe_2O_3 undergo the reaction below. The atomic masses involved are H 1.0, C12.0, O 16.0, Fe 55.8

$$4\,Fe_2O_3 + 3\,CH_4 \rightarrow 8\,Fe + 3\,CO_2 + 6\,H_2O$$

Answer

Answer: 1.88 g CH4, 17.5 g Fe, 5.2 g CO2, 4.2 g H2O

Exercise

Calculate the mass of O_2 that reacts and the masses of the products when 100 g of benzoic acid, $C_7H_6O_2$ undergo the reaction below. The atomic masses involved are H 1.0, C 12.0, and O 16.0.

$$2\,C_7H_6O_2 + 15\,O_2 \rightarrow 14\,CO_2 + 6\,H_2O$$

Answer

197 g O_2, 252 g CO_2, 44.3 g H_2O

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