Material Balances

Introduction

What do a person, an engine and a chemical plant all have in common? Each is a type of chemical reactor! A chemical reactor is a vessel designed to contain chemical reactions. Materials and energy go in, useful products are created, and wastes go out. This is the fundamental concept for chemical engineering.

Engineers use this process to model medicine in a person, gas in an engine, and hydrocarbons in a chemical factory. What goes into a system must either stay there or come out. The same applies to energy. In a hot water heater, water enters at a certain temperature; heat energy is supplied to the water, and exits at a higher temperature. For this activity, we will focus on material balances.

Background

What is a **material balance**? The idea that "what goes in must come out" (unless it has stayed in the system) seems pretty straight forward, but it can get complicated quickly. Is it how much volume goes in and out that must be conserved? Or is it mass? Could it be moles of a substance? What about when a chemical reaction occurs, or when one of the components undergoes a phase change by boiling or freezing? In the most general sense, a material balance refers to **mass**. In phase changes and in some chemical reactions, the volume changes substantially, and can vary depending on temperature and pressure. In some systems, we can balance **moles** of a compound, but in chemical reactions the number of moles changes as well. However, mass is always conserved in chemical and physical systems. This means that mass can be neither created nor destroyed. It can only be rearranged. Based on this principle, called the **conservation of mass**, engineers use the following equation on which to base their material balance calculations (write this on the board).

$$In - Out + Generation - Consumption = Accumulation$$

In this equation, *In* refers to anything that is in or flows into the system. *Out* refers to anything taken out or flowing out. *Generation* accounts for anything that is generated in the system from a chemical reaction, while *Consumption* refers to what is used as fuel or changes form. Finally, *Accumulation* is whatever stays in the system. It is important to recognize that this refers to a specific species or part of a system. Imagine a campfire. Wood logs are burning to create smoke and ashes. Now let's imagine that we are also adding logs to the fire once per hour. A material balance around the wood would look like:

$$Wood\ In - Wood\ Burned = Wood\ Accumulated$$

The *input* is the quantity of wood being put on the fire every hour, and the *consumption* is the amount of wood burned away or consumed in the fire. The *accumulation* is whatever is left over as charred wood pieces in the morning. The balance on the smoke looks different:

$$-Smoke\ Out + Smoke\ Generated = 0$$

Because all of the smoke floats away, none accumulates. No smoke is being added to the fire, and the fire is not fueled by smoke, so there are no input or consumption terms. There is only the smoke *generated* by burning, and the smoke floating *out* of the system. The balances on the wood and smoke are called species mass balances, because they are a balance of a specific part of the system.

By measuring the mass of wood we put into the system, how much is left, and how much is turned to ash, we can calculate the mass of smoke produced by the fire. This is called an overall mass balance. Remember, mass cannot be generated or destroyed, so there is only an input and an output term in an overall mass balance.

For this activity, we will be doing a **species mass balance** and an **overall mass balance** for a reaction of baking soda and vinegar to predict how much carbon dioxide is produced. We will then react the two chemicals and capture the carbon dioxide in a balloon. Finally, we will weigh the balloon and compare the mass of the carbon dioxide to the predicted mass.