

A **process** is any operation or series of operations by which a particular objective is accomplished. In this chapter, we address those operations that cause a physical or chemical change in a substance or mixture of substances. The material that enters a process is referred to as the **input or feed** and that which leaves is the **output or product**. It is common for processes to consist of multiple steps, each of which is carried out in a process unit, and each process unit has associated with it a set of input and output **process streams**.

PROCESS CLASSIFICATION

Chemical processes may be classified as **batch, continuous, or semibatch** and as either **steady state or transient**. Before writing material balances for a process system, you must know into which of these categories the process falls.

1. **Batch process.** The feed is charged (fed) into a vessel at the beginning of the process and the vessel contents are removed sometime later. No mass crosses the system boundaries between the time the feed is charged and the time the product is removed. Example: Rapidly add reactants to a tank and remove the products and unconsumed reactants sometime later when the system has come to equilibrium.
2. **Continuous process.** The inputs and outputs flow continuously throughout the duration of the process. Example: Pump a mixture of liquids into a distillation column at a constant rate and steadily withdraw product streams from the top and bottom of the column.
3. **Semibatch process.** Any process that is neither batch nor continuous. Examples: Allow the contents of a pressurized gas container to escape to the atmosphere; slowly blend several liquids in a tank from which nothing is being withdrawn. If the values of all the variables in a process (i.e., all temperatures, pressures, volumes, flow rates) do not change with time, except possibly for minor fluctuations about constant mean values, the process is said to be operating at steady state. If any of the process variables change with time, transient or unsteady-state operation is said to exist. By their nature, batch and semibatch processes are unsteady-state operations (why?), whereas continuous processes may be either steady state or transient. Batch processing is commonly used when relatively small quantities of a product are to be produced on any single occasion, while continuous processing is better suited to large production rates. Continuous processes are usually run as close to steady state as possible; unsteady-state (transient) conditions exist

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Classify the following processes as batch, continuous, or semibatch, and transient or steady state.

1. A balloon is filled with air at a steady rate of 2 g/min.
2. A bottle of milk is taken from the refrigerator and left on the kitchen table.
3. Water is boiled in an open flask.
4. Carbon monoxide and steam are fed into a tubular reactor at a steady rate and react to form carbon dioxide and hydrogen. Products and unused reactants are withdrawn at the other end. The reactor contains air when the process is started up. The temperature of the reactor is constant, and the composition and flow rate of the entering reactant stream are also independent of time. Classify the process (a) initially and (b) after a long period of time has elapsed.

Solution

1. Semibatch, transient
2. Batch, transient
3. Semibatch, transient
4. (a) Continuous, transient;
(b) Continuous, steady state.

THE GENERAL BALANCE EQUATION

A balance on a conserved quantity (total mass, mass of a particular species, energy, momentum) in a system (a single process unit, a collection of units, or an entire process) may be written in the following general way:

$$\begin{array}{ccccccccc}
 \textit{input} & + & \textit{generation} & - & \textit{output} & - & \textit{consumption} & = & \textit{accumulation} \\
 \text{(enters} & & \text{(produce} & & \text{(leaves} & & \text{(consumed} & & \text{(build up} \\
 \text{through} & & \text{within the system} & & \text{through} & & \text{within system)} & & \text{within} \\
 \text{the system} & & \text{system)} & & \text{the system} & & & & \text{system)} \\
 \text{boundaries)} & & & & \text{boundaries)} & & & &
 \end{array}$$

The meaning of each term of the equation is illustrated in the following example

1. Each year 50,000 people move into a city, 75,000 people move out, 22,000 are born, and 19,000 die. Write a balance on the population of the city.

Solution

Let P denote people:

$$\text{input} + \text{generation} - \text{output} - \text{consumption} = \text{accumulation}$$

$$50,000 \frac{P}{Yr} + 22,000 \frac{P}{Yr} - 75,000 \frac{P}{Yr} - 19,000 \frac{P}{Yr} = A \frac{P}{Yr}$$

$$A = -22,000 \frac{P}{Yr}$$

Each year the city's population decreases by 22,000 people.

We will generally use the symbol m to denote a mass, \dot{m} mass flow rate, n a number of moles, and \dot{n} a molar flow rate.

DEGREE-OF-FREEDOM ANALYSIS

Everyone who has done material balance calculations has had the frustrating experience of spending a long time deriving and attempting to solve equations for unknown process variables, only to discover that not enough information is available. Before you do any lengthy calculations, you can use a properly drawn and labeled flowchart to determine whether you have enough information to solve a given problem. The procedure for doing so is referred to as **degree-of-freedom analysis**.

To perform a degree-of-freedom analysis, draw and completely label a flowchart, count the unknown variables on the chart, then count the independent equations relating them, and subtract the second number from the first. The result is the number of degrees-of-freedom of the

process. In general, degree-of-freedom DoF analysis for steady state non-reactive process (without chemical reaction) is written as

Degree-of-Freedom = number of unknowns – numbers of independent ant equations

Degree-of-Freedom analysis for reactive process (with chemical reaction) is given as follows

DoF = number of unknowns + number of independent reactions – number of independent material balance equations – auxillary relation (density relationship relating mass flow rate and volumetric flow rate, specified split – bottom and top product). There are three possibilities:

If $\text{DoF} = 0$, the system is completely defined and you get a unique solution

If $\text{DoF} > 0$, the system is under defined and there are infinite number of solutions

If $\text{DoF} < 0$, the system is over defined and there are too many restrictions. Over defined problems cannot be solved to be consistent with all equations.

INDEPENDENT EQUATION

Equations are independent if you cannot derive one by adding and subtracting combinations of the others. For example, only two of the three equations $x = 3$, $y = 2$ and $x + y = 5$ are independent; anyone of them can be obtained from the other two by addition or subtraction.

In other words, a set of equations is independent if you cannot derive one by adding and subtracting combination of others.

(a) Is the following set of equation independent?

$$x + 2y + z = 1 \quad (1)$$

$$2x + y - z = 2 \quad (2)$$

$$y + 2z = 5 \quad (3)$$

Solution

Yes, the above equations are independent because we cannot derive one by adding and subtracting the combination of others.

(b) Is the following set of equations independent?

$$x + 2y + z = 1 \quad (1)$$

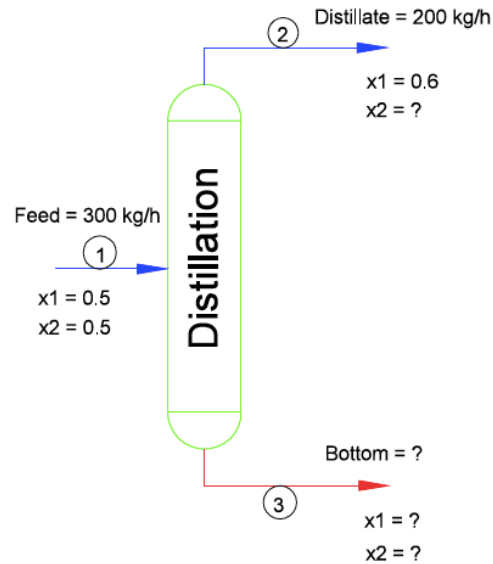
$$2x + y - z = 2 \quad (2)$$

$$3x - 3y = 5 \quad (3)$$

the above set of equations are not independent because we can derive (3) by adding equations (1) and (2)

Now we introduce the degree-of-freedom analysis for single unit operation where the steady state conditions prevail.

Problem 1: Perform a degree-of-freedom analysis for flow chart given below



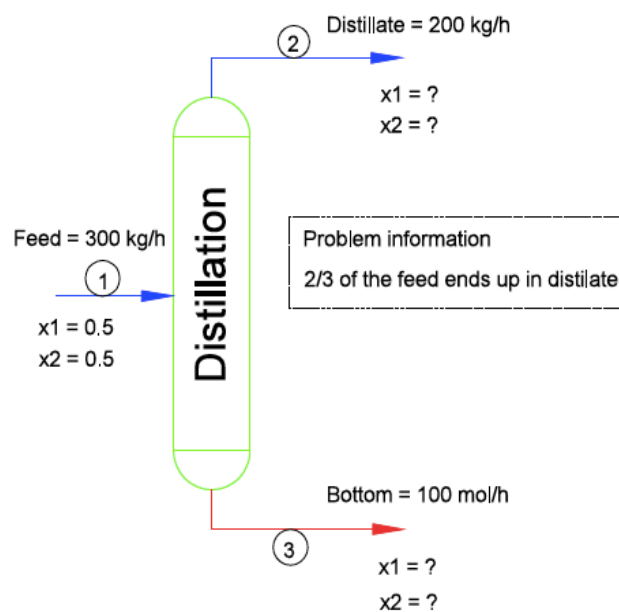
Number of unknowns ($B, x_1,$) = 2

Number of independent equations (two components 1,2) = 2

Number of auxillary relations = 0

Therefore, $\text{DoF} = 2 - 2 = 0$

Problem 2: Perform a degree-of-freedom analysis for flow chart given below



Number of unknowns (x_1 in Bottom and x_1 in Distillate) = 2

Number of independent equations (two components 1,2) = 2

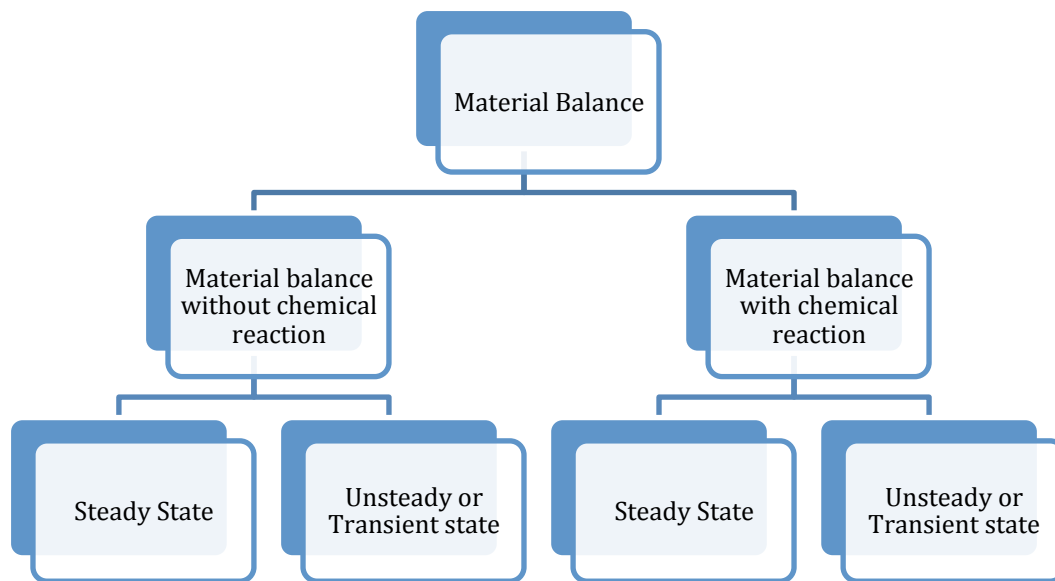
Number of auxiliary relations (2/3 of the feed = 200 kg/s ends up in distillate which is already given in the flowchart may not be a useful relation.

Hence auxiliary relation for this problem = 0

Therefore, $\text{DoF} = 2 - 2 = 0$

MATERIAL BALANCE CALCULATIONS

Material balance calculations are grouped as follows:



Material balance without chemical reactions for single unit operation

Calculation procedure for material balance without chemical reaction for single and multiple unit operations is as follows:

- Choose an appropriate basis.
- Draw and label (known and unknown quantities) the flowchart.
- Write expressions for the quantities requested in the problem statement.
- If you are given mixed mass and mole units for a stream (**such as a total mass flow rate and component mole fractions or vice versa**), convert all quantities to one basis
- Perform degree-of-freedom analysis.
- Write system equations and outline a solution procedure.
- Solve the equations, get the unknowns and label the identified unknown values in the flow sheet and check for the balance

Reference:

1. Richard M. Felder, Ronald W. Rousseau, *Elementary Principles of Chemical Processes*, 3rd Ed., 2005, pp. 102 – 112.
2. Nayef Ghasen, Redhounae Henda, *Principles of Chemical Engineering Processes*, CRC Press, pp. 51-52.