Processes

Chemical processes fall under one of the categories:

Continuous processes: Input and output streams flow continuously in the processes. Many chemical processes which produce high volumes (up to few millions tons per annum) of products are continuous.

Batch processes: A feed vessel is charged with reactants or chemicals to be mixed for a certain time during which no products flow out of the vessel. At the end of the process, the products and unreacted reactants are withdrawn.

Semibatch/semicontinuous processes: Those which can be neither called continuous nor batch come under this category.

Chemical processes operate in either steady state or transient modes. Generally, continuous processes operate in steady state and batch and semibatch in transient mode.

General balance equation

In – Out + generation – consumption = accumulation

This is the most general balance equation that can be written to balance quantities like mass, energy, momentum etc. Each term in the balance equation has the following meaning

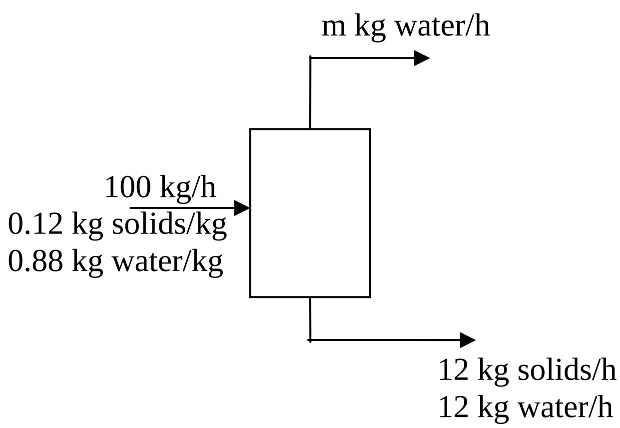
In: entering the system boundary
Out: leaving the system boundary
Generation: produced in the system
Consumption: destroyed in the system
Accumulation: buildup in the system

Remember: balances are always written on a system boundary where a system could be a single unit or multiple units.

For a continuous process, balances are written at any instant of time and the balanced quantity has units of quantity/time (mass/time, energy/time etc). For a batch process, balances are made between two instants of time and the balanced quantity has units of quantity itself (mass, energy).

For a steady state process, nothing changes with time; therefore, accumulation is zero.
For a nonreactive process, generation and consumption terms can be knocked off.

Example of balances on a steady state process: An orange juice flowing continuously into an evaporator at a rate of 100 kg/h containing 12 wt% solids and the balance water is to be concentrated such that 24 kg/h of solution leaves the evaporator continuously. Calculate the flow rate at which water is leaving the evaporator.



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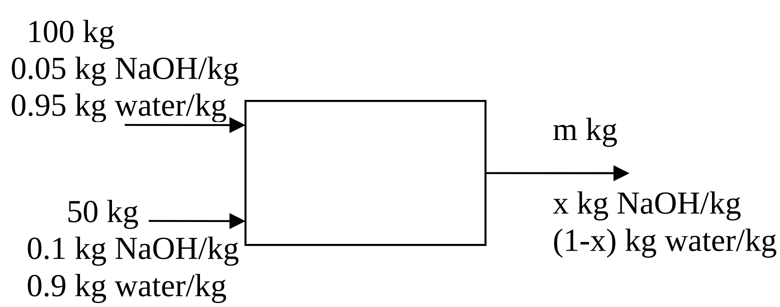
Balance on water: In – out + generation – consumption = accumulation

Generation = consumption = 0 because the system is nonreactive; accumulation = 0 because the process is steady state.

Therefore, in = out or 100 kg/h x 0.88 kg water/kg = 12 kg water/h + m kg water/h

Solving, m = 76 kg/h.

Example of balances on a batch process: 100 kg of a solution containing 5% sodium hydroxide is mixed with 50 kg of a solution containing 10% sodium hydroxide. Make balances for this system.



Here the balances are written after mixing is completed. The arrows do not indicate flow rates but just input and output streams to the mixing process.

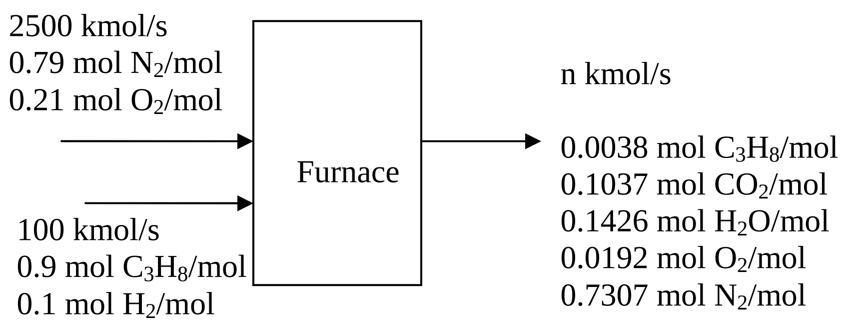
For this process, the overall balance yields: 100 kg + 50 kg = m kg or m = 150 kg
Balance on NaOH gives, 100 kg x 0.05 kg NaOH/kg + 50 kg x 0.1 kg NaOH/kg = m kg x x kg NaOH/kg
Solving, x = 0.067 kg NaOH/kg

Flowcharts

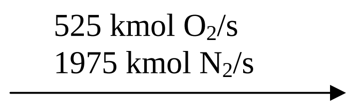
Usually, chemical engineering problems/processes are described in a text as below

100 kmol/h of a mixture of 90 mole% propane and the balance hydrogen is burned in a furnace with 2500 kmol/h of air. The product stream has the following composition: 0.38 mole% propane, 10.37% carbon dioxide, 14.26% water, 1.92% oxygen and the balance nitrogen. You could be asked to calculate several variables such as the flow rate of product stream and so on.

If the information is provided in the above format, it is always useful to draw a flowchart and label the streams to organize the given information better. For the above simple description of a single unit (chemical processes are a lot complicated), which is just for an illustration, the flowchart could like



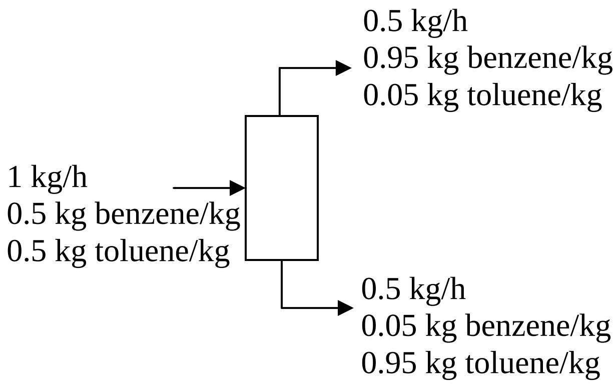
The two inlet streams and one outlet stream are labeled in the above figure. By labeling we mean the flow rate and the composition of the stream are specified. The inlet air stream could also be labeled as follows:



Here, the flow rates of components are specified. The flow rate of outlet is not known and a symbol n is used for the flow rate. Usually, n is used for molar flows and m for mass flows. In labeling, also indicate temperature and pressure if they are important in the calculations.

A multiunit flowchart is complicated. Recall the problem solved in the class on crystallization of potassium chromate solution. For a given problem description, draw the flowchart indicating all units by boxes and connections among them by lines and arrows. Then, label all streams. This kind of organization helps us solve for the unknowns in the flowchart.

Consider the following separation process



Now, the inlet and outlet stream flow rates could be multiplied with any number (say 100, 1000) and the balance will be still hold. Note compositions of the streams remain same. This process of multiplication is called scale up. This brings us to choosing a basis for any material balance calculation. For the above separation, the basis could be 1 kg/h or 100 kg/h or 1000 kg/h of inlet stream. A convenient basis is the flow rate of a given stream or flow rate of a component of a given stream.

Choosing a basis is the first step in solving any material balance problem. Next step is to perform a degree of freedom analysis on a single or multiple units or on entire process.

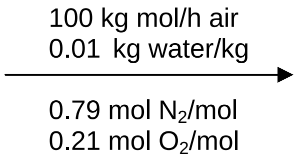
Degrees of freedom = number of variables – number of equations.

If degrees of freedom = 0, the variables can be solved for. If it's > 0, some more specifications (= degrees of freedom) are needed. If it's < 0, the problem is overspecified.

On a single unit or multiple units, find degrees of freedom; if it's = 0, write down the equations and solve them. Else, analyze next unit or combination of units for degrees of freedom, till you can solve for all variables. Remember the way we solved crystallization problem starting from filter?

Test Your Understanding

1. Air is leaking out of balloon at a constant rate? Is this process batch or continuous or semibatch?
2. Hot nitrogen is supplied to a dryer at a constant rate of 1 kg/min to dry a powder containing 5% water. The powder is also input at constant rate. Powder with about 750 ppm of water and nitrogen with some moisture leave the dryer. What kind of a process is this?
3. Is the above process transient or steady state?
4. If hot nitrogen is passed through 10 kg of powder to dry it, what kind of a process is it?
5. Mention a couple of reasons for recycle in chemical processes.
6. Can the below stream be labeled better? If so, how?



7. 2000 mol of air is mixed with 100 mol/h of ethane to yield a product 2100 mol/h containing 0.0476 mol ethane/mol, 0.2 mol O_2/mol and 0.752 mol N_2/mol. Scale up to a feed rate of 1000 kmol ethane /h and a feed rate of 100 lbm/h of ethane.
8. What is basis of calculation?
9. Under what conditions, can you write input = output in a balance equation?
10. Can balance equation be written for volume flow rate? In other words, can volume be balanced? If so, under what condition?