Performing Non - Reactive Mass and Energy Balances

Now that we know *how* to write the equations that will get us started for balances, we need to worry about *when* they are useful.How do we know when to write these equations, or how many we need ?

- Perform single - unit mass balances
  - # Perform a degree - of - freedom analysis for a single - unit mass balance process
  - # Do the calculations suggested in the degree - of - freedom analysis

Real processes often include more than one process unit.How do we handle arbitrary numbers of units ? arbitrarily complex arrangements of those units ?

- Identify relevant sub - systems within a multi - unit process on which to perform a degree - of - freedom analysis(and subsequently do the required calculations)
- Perform mass balances(degree - of - freedom plus calculations) for systems with recycle, bypass, and purge streams

Energy balances can be used as an additional equation in mass balances.

- Simplify and solve the General Energy Balance for non - reactive systems

Degrees of Freedom Analysis

When attempting to solve a material balance problem, two questions that one may ask are:

- How many equations do I need?
- Where do they come from?

DEFINITION

> *A **Degrees of Freedom Analysis** is used to answer these two questions. (For now we will only consider non-reactive systems.)*

Counting unknowns is simple! Just look at your (carefully drawn) flowchart. As you (should) remember from algebra, the number of equations necessary is equal to the number of unknowns.

There are multiple places that the necessary equations might come from.

- **Material Balance Equations = Number of independent species
- Energy Balance Equations - These provide additional relationships, but will be covered later in the course
- **Process Specifications or Constraints - These are provided in the problem statement.
- Physical Properties/Laws - These include relations about the properties of the materials in the process. They may include relationships between volumetric flowrates and mass flowrates (density!), or equilibrium constraints (for example, dissolving sugar in water).
- **Physical Constraints - These include simple physical requirements, like the total mass in a stream is equal to the sum of the masses of components in the stream or (equivalently) the sum of mole (or mass) fractions must be equal to 1.
- Stoichiometric relations - If a chemical reaction occurs, the stoichiometry of the reaction describes a relationship between the amounts of reactants and the amounts of the products. (For example A + 2B -> C would tell us that you must react two (somethings) of B for every C that you make!)

OUTCOME:

> Perform a degree-of-freedom analysis for a single-unit mass balance process

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NRB: Do the calculations suggested in the degree-of-freedom analysis

Material Balance Calculations

As suggested in the previous lesson, once the degrees of freedom analysis yields a value of zero, you have a roadmap for solving the material balance equation.

IMPORTANT

The equations suggested by the Degrees of Freedom analysis (# of species = # of balance equations; # of process specifications; # of physical constraints) MUST be the equations used to solve the material balance!

General Procedure for (single unit) Material Balances

STEP 1

Choose a basis of calculation from among the given data.

STEP 2

Choose one of the given stream amounts (batch) or flowrates (continuous or semi-batch) OR (if no stream amounts or flowrates are given) choose something convenient (like 100 mol(/s) or 100 g(/s)).

IMPORTANT

Its called conservation of MASS not VOLUME, do NOT choose a volume as your basis!

STEP 3

Draw the flowchart. (Follow the procedure previously outlined.)

IMPORTANT

Remember, to fully specify a stream, you must know BOTH the total amount of the flow within the stream and the composition of the stream (label what you DON'T know with variables). (Alternatively, you can know the flow of each component separately.)

STEP 4

Do the degrees of freedom analysis. (Follow the procedure previously outlined.) Can you match the number of unknowns with the number of equations? (i.e., is the DofF = 0?)

IMPORTANT

Remember, if they DO NOT match, you may have a problem! If there are too few equations, you CAN'T solve it. If there are too many, you MAY solve the problem, but then you must CHECK THE ANSWER against your additional equations (the problem may be overspecified).

STEP 5

If DofF is zero then simply do the algebra for each of the equations suggested by the DofF!

OUTCOME:

Do the calculations suggested in the degree-of-freedom analysis

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Single Unit Material Balance Example

Once you have completed the Degrees of Freedom analysis, you literally have a roadmap for solving the system.

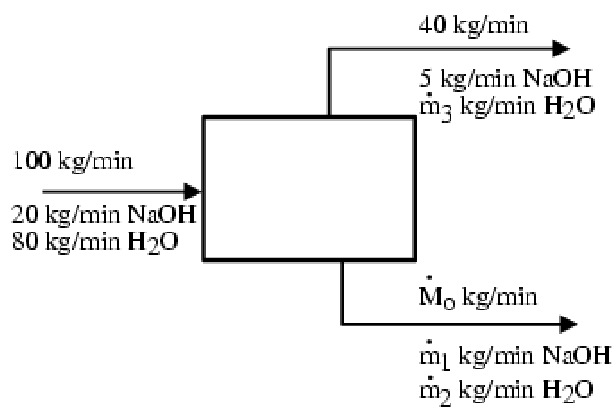
As in any simple algebraic problem (OK, it is a **system** of algebraic equations so maybe its not THAT simple!) you have matched the number of unknowns with the number of equations. You now simply *use those equations to find those unknowns*!

OUTCOME:

Do the calculations suggested in the degree-of-freedom analysis

TEST YOURSELF

Let's actually solve the example that we have already looked at...



How many Unknowns are there?
How many different Species
(material balances) are there?
How many Process Specifications are we given?
How many Physical Constraints are there?
The total number of Degrees of Freedom is

Let's start with material balances....

Using a differential balance equation (since it is a continuous process), let's write down our material balance equations....

If we can solve them, let's do so now....

Next, let's write down our process specifications....

If we can solve them, do it now...

Finally, let's write down our physical constraints....

If we can solve them, do it now...

IMPORTANT

> We may need to solve several (all) of these simultaneously or there may be a "preferred" order in which we should solve them!

TEST YOURSELF

> *Try one yourself...*

Another Single Unit Material Balance Example

One thousand kilograms per hour of a mixture containing equal parts by mass of methanol and water is distilled. Product streams leave the top and bottom of the distillation column. The flow rate of the bottom stream is measured and found to be 673 kg/h, and the overhead stream is analyzed and found to contain 96.0 wt% methanol.

Determine the flow and composition of all of the streams.

The first step is to draw the flowchart. Let's start there...

How many Unknowns are there?
How many different Species
(material balances) are there?
How many Process Specifications are we given?
How many Physical Constraints are there?
The total number of Degrees of Freedom is

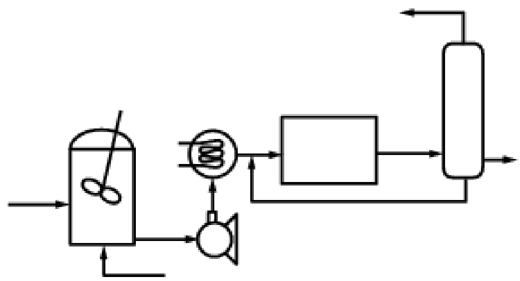
Multi-Unit Balance Calculations

So far we have only looked at single-unit processes. Here we might consider the system to be solely the process unit itself (we had no other choice).

DEFINITION

> *A **system** is the region of a process on which we are currently performing a balance. You will typically think of a box surrounding this "system" and will perform the balance on the box.*

In most real process, we have more than one process unit. In these cases, it will often be convenient (or even necessary) to define our system as something other than one single process unit. Look at the following diagram as an example:



Once we have chosen a sub-system, however, the problem becomes *identical* to a single-unit process (where our sub-system plays the role of the single unit!).

> (New?) Method for solving multi-process units:
>
> - Choose a Basis
> - Draw Flowchart
> - Choose a Sub-system!
> - Degrees of Freedom
> - Do Algebra

IMPORTANT

> A multi-process system requires: that you be clever in choosing your system, that you solve equations in the "right" order, that you remember how to solve a system of algebraic equations.

OUTCOME:

> Identify relevant sub-systems within a multi-unit process on which to perform a degree-of-freedom analysis (and subsequently do the required calculations)

TEST YOURSELF

> *Let's try one...*

Multi-Unit Process Example

From the following process description draw a flowchart that concisely summarizes each stage of the process (properly labeling all streams and species within those streams)

> *A mixture of two components, A and B, are fed at 100 kg/hr to a process unit (Unit 1) in equal parts by mass. One stream, which contains 90 mass % A exits this unit at a rate of 40 kg/hr. A second stream leaves Unit 1 and is mixed with a 30 kg/hr stream which is 70 mass % B. This combined stream serves as the inlet for Unit 2. One of the two outlets (flowing at 30 kg/hr) from Unit 2 is analyzed and found to contain 60 mass % A.*

When you are finished, let's try to analyze this system!

Multi-Unit Process Example (cont.)

If you had correctly drawn the flowchart, you would have obtained the image below. If not, why not try again?

> *The next step in doing the material balance is to choose a subsystem to analyze. Let's try that together below.*

To define your subsystem simply click in the area below to signify the vertices of your subsystem "box" (a closed shape containing all the process units you would like to include in your subsystem) and then click "Analyze the Subsytem".

Now that a subsystem is defined, you need to determine whether it (by itself) is solvable! simple fill in the blanks to answer the questions below in order to determine this.

DEGREES OF FREEDOM ANALYSIS

How many Unknowns are there?

How many different Species (material balances) are there?

How many Process Specifications are we given?

How many Physical Constraints are there?

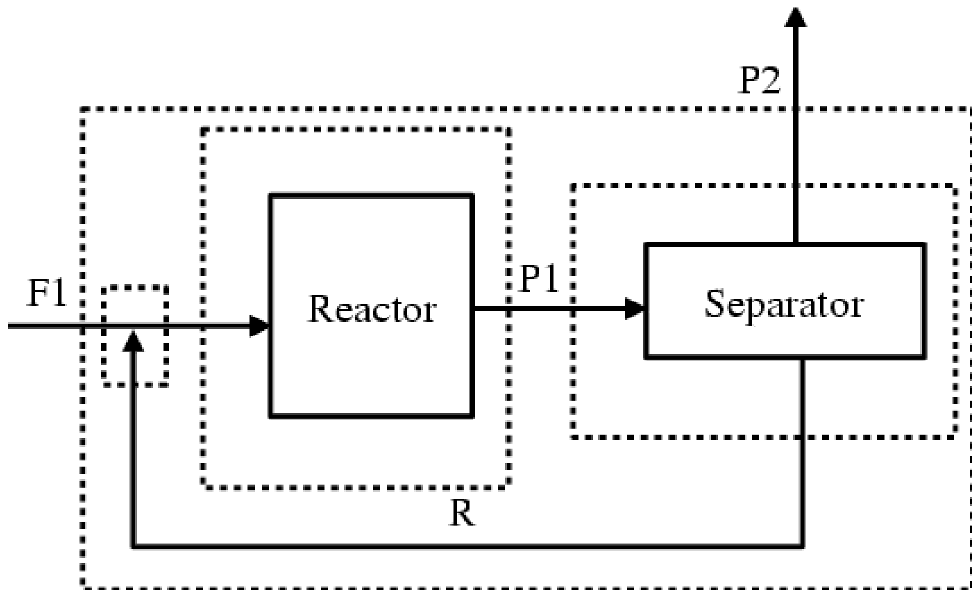
The total number of Degrees of Freedom is

Recycle, Bypass, and Purge

For a variety of reasons it is not typical that a process runs so smoothly that material enters the system, goes through each process unit once, and your product is on the first try. For this reason there are a few "special" types of streams that should be mentioned:

DEFINITION

*A **recycle stream** is one where a portion of the outlet of a process unit is combined with fresh feed and sent into the same unit again.*

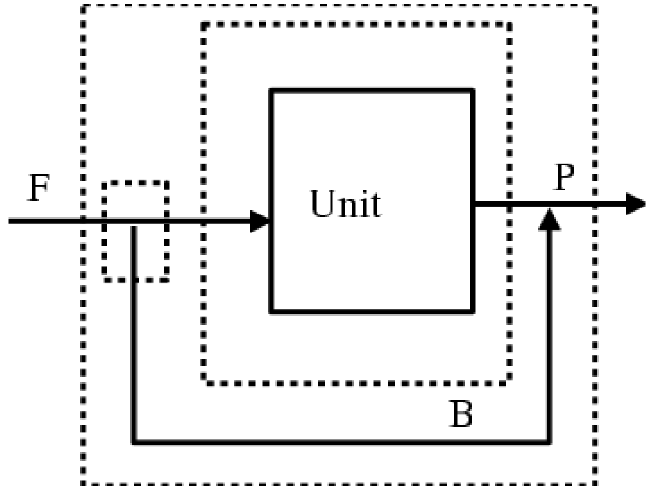


There are several reasons one might employ a recycle stream:

- increase conversion of a reactant to product
- recovery of catalyst
- dilution of a process stream (either to improve flow of the stream or control the rate of a reaction)
- re-use of a "working fluid" (like a lubricant or refrigerant)

DEFINITION

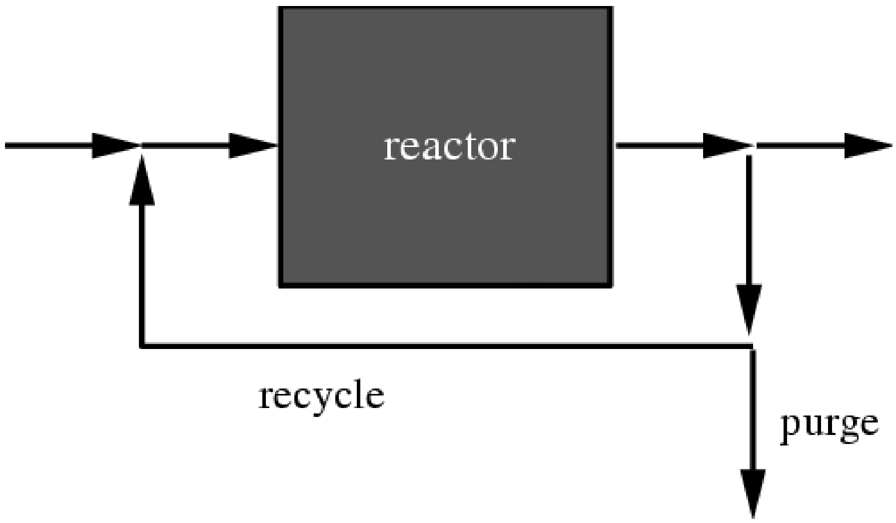
*A **bypass stream** is one where a portion of the inlet to a process unit is split from the feed and instead of entering the process is combined with the outlet from that process.*



This practice is far less common than recycle, but may be used if your ultimate goal is a material with properties "in-between" the untreated reactant and the process outlet product.

DEFINITION

*A **purge stream** is one where a portion of a recycle stream is removed from the system in order to avoid accumulation of undesired material in a recycled system.*



This is common with multi-phase systems where only 1 phase is either removed or recycled (i.e., if one recycles catalyst pellets, but adds "make-up" fresh catalyst a purge will be needed to discard some "spent" catalyst).

OUTCOME

Perform mass balances (degree-of-freedom plus calculations) for systems with recycle, bypass, and purge streams

Recycle Example

Benzene and Toluene are to be separated in a distillation column. The feed is composed of a mixture of the two with 50 wt% benzene and a total flow of 160kg/hr. The material taken off from the "bottoms" is found to flow at a total rate of 60kg/hr and contains 50kg/hr benzene and 10kg/hr toluene. The "tops" has a total flow of 100kg/hr and a composition of 0.3 mass fraction of benzene.

The "new guy" on the job has gotten the analysis this far (she wrote-up the flow chart), but for scale up purposes you need to know the reflux ratio in the column (the ratio of the mass recycled from the condenser (R) to the mass collected in the "tops"). Unfortunately the only measurement that you can easily make is that the flow rate into the condenser is 150kg/hr. You tell the young ChE not to fear because you can take it from there. So.... take it from there!

If the condensation is complete (in other words, the condensed liquid has the same composition as the incoming gas), can you determine the composition in the recycle (reflux) stream?

DEGREES OF FREEDOM ANALYSIS

How many Unknowns are there?
How many different Species
(material balances) are there?
How many Process Specifications are we given?
How many Physical Constraints are there?
The total number of Degrees of Freedom is

Energy Balance Procedure

Typically, solving energy balance problems is only marginally more involved than mass balances alone. In addition to whatever else we might be solving in the mass balance, we will now be asked to calculate the amount of heat or work going to/from the system or possibly determine something about the state of one of the streams (by finding an unknown enthalpy or energy).

The procedure to solve mass/energy balances...

- (TRY TO) Perform all material balances (doing degrees of freedom and all the rest of that procedure)...it's possible that you will have to count the energy balance as an additional equation in your degrees of freedom analysis (of course, you must then also count any unknowns that arise in the energy equation in this analysis)
- Write down the appropriate energy balance equation (closed or open)
- Choose a reference state for all the species in the process (T, P, phase)
- Simplify the energy balance equation (see previous lectures for hints here)
- Obtain values for all the specific energies (U) or enthalpies (H) and calculate the changes in these values (remember that you are adding all the ins (initials) for each species and all the outs (finals) for each species, you are NOT doing a separate energy balance for each material).
- Calculate any (other) terms that didn't drop out (kinetic or potential)
- Solve the problem!

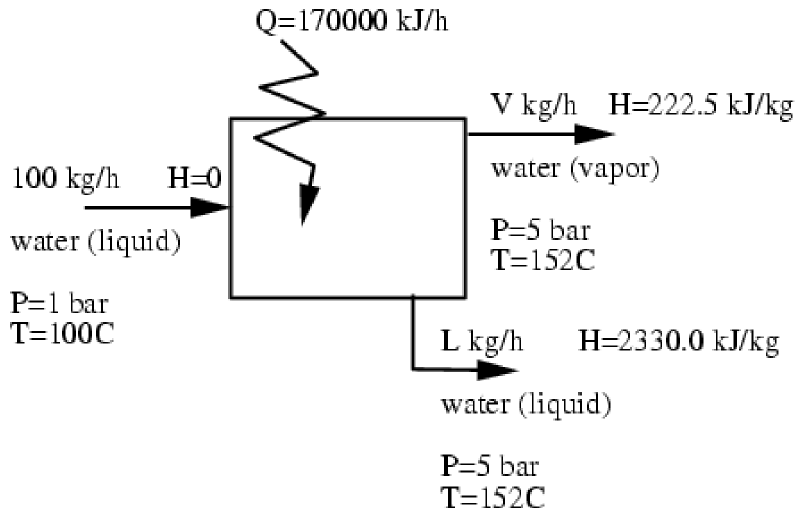
OUTCOME:

Simplify and solve the General Energy Balance for non-reactive systems

TEST YOURSELF

Try this simple example!

You want to make do a mass balance on the following evaporator system, yet you do not have enough material data. Instead you need to rely on an energy balance to help you along. Determine the split of liquid and vapor coming out of the evaporator. (NOTE: check the units, the H's listed here are actually specific enthalpies!)


Q=170000 kJ/h
V kg/h H=222.5 kJ/kg
water (vapor)
P=5 bar
T=152C
100 kg/h H=0
water (liquid)
P=1 bar
T=100C
L kg/h H=2330.0 kJ/kg
water (liquid)
P=5 bar
T=152C