Separation Processes, ChE 4M3, 2012

Assignment 1

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There are several viewpoints we can use to understand separation processes. One is to consider them based on the mechanism being exploited; another is to consider them based on separations of solids, liquids and gases from various combinations of each other.

Solutions: prepared by Daryl and Kevin.

Question 1

Fill in the grid of 9 squares with as many unit operations as possible

		MINOR COMPONENT		
		SOLID	LIQUID	GAS/VAPOUR
MAJOR COMPONENT	SOLID			
	LIQUID			
	GAS/VAPOUR			

For each of the nine entries, give an actual unit and state what the streams in and out of the unit are. For example, cryogenic distillation columns are used during gas from gas separation for nitrogen (major) vs oxygen (minor) separations.

Solution

Some possibilities are listed in the matrix below. Entries in brackets involve dissolved components.

		MINOR COMPONENT		
		SOLID	LIQUID	GAS/VAPOUR
MAJOR COMPONENT	SOLID	Sorting Screening Hydrocyclones Classifiers Jigs Tables Centrifuges Dense media Flotation Magnetic Electrostatic	Pressing Drying	Crushing Heating
	LIQUID	Thickeners Clarifiers Hydrocyclones Filtration Centrifuges (Crystallisers) (Evaporators)	Decanters Coalescers (Solvent extraction) (Distillation) (Adsorption) (Ion exchange)	(Stripping)
	GAS/VAPOUR	Gravity settlers Impingement settlers Cyclones Filters Wet scrubbers Electrostatic precipitators	Separating vessels Demisting pads Cyclones Wet scrubbers Electrostatic precipitators	(Adsorption) (Absorption)

Regarding the units and the streams in and out:

- Solid and solid: Gel electrophoresis and separation of a protein mixture into individual proteins based on size and charge.
- Solid (major) and liquid (minor): Drying and freeze-drying removes water from fruit to produce dried fruit.
- Solid (major) and gas (minor): heating and removal of volatile components (carbon monoxide, hydrogen) from coal in the production of coke.
- Liquid (major) and solid (minor): wastewater treatment plants use centrifuges, settlers and/or filters to remove water from sludge to create fertilizer and clean water.

- Liquid and liquid: fractional distillation will separate crude oil into different components (gasoline, kerosene, *etc*).
- Liquid (major) and gas (minor): stripping towers can remove ammonia from water solutions.
- Gas (major) and solid (minor): Filters and HEPA filters will remove airborne particulate from contamination drug production facilities.
- Gas (major) and liquid (minor): Impingement separators are used to remove oil droplets from gas mixtures.
- Gas and gas: adsorption can occur in packed beds to remove of carbon dioxide in the production of hydrogen.

Question 2

1. Identify the mechanism by which the components are being separated in the following instances. For example, when concentrating orange juice in an evaporator, we are exploiting the difference in *volatility* between water, and the complex aqueous compounds that make up the juice.
2. Also identify the separating agent and state whether it is an MSA or ESA.

Unit operations to consider:

- Waste water treatment: secondary clarifier
- Distillation column separating methanol and water
- A chromatography column
- Drying laundry
- Protein purification using a membrane
- Liquid-liquid (solvent) extraction

Solution

- A secondary clarifier in a waste water treatment plant exploits differences in density between the solid and fluid phase. The energy separating agent (ESA) is the gravitational field.
- Distillation column separating methanol and water uses the difference in volatility. Heat is the ESA.
- A chromatography column can use a variety of mechanisms, such as size or affinity of particles for the solid column packing (mass separating agent).
- Drying laundry: the difference in volatility of the liquid and solid phase is used. The heat added is the ESA.
- Protein purification using a membrane exploits size differences through the membrane pores. Pressure gradients (ESA) and the membrane itself (MSA).
- Liquid-liquid (solvent) extraction uses the different solubilities of the materials. The solvent is the MSA.

Question 3

Give actual example(s) of where the following mechanism could be used to split components from a given feed stream. State what is in the feed stream and the output separated streams. Also state the name of a unit operation that exploits this mechanism to cause the separation.

- Density
- Particle size
- Solubility
- Mobility
- Charge
- Phase change
- Magnetism

Solution

- Density differences are used during centrifugation. For example a wastewater stream with solids and liquids could be separated into an outlet stream of water and another of solids/cake in a centrifuge.
- Particle size differences are used during size exclusion chromatography. A mixture of proteins and excipients can be separated into a purified protein stream and a mostly excipient stream.
- Solubility differences could be used in a supercritical fluid extractor, using liquid carbon dioxide. The coffee bean feed is separated into a stream containing decaffinated beans, and the supercritical stream contains the dissolved caffeine, which is then recovered and separated further.
- Mobility differences are exploited in gel electrophoresis. A feed of mixed proteins is separated into purer protein outlet streams.
- Charge differences are used in electrostatic precipitation. For example an air-dust feed stream can be cleaned to an air stream and a concentrated dust stream.
- Phase changes are used in many separating units, e.g. freeze-drying (lyophilisation). e.g. foods can be separated into dried food and a water stream.
- Magnetism is used in a magnetic separator to isolate iron-bearing material from the gangue.

Question 4

Separation processes cannot operate without bounds (energy input into the process is expensive). But in some instances we are constrained also by the nature of the products being separated. Give examples of a separation process where we have to meet additional constraints on the design and operation of the unit in terms of:

- temperature
- contamination from other sources (human, airborne, limited choices of solvents to separate the components)

For example, in protein separation, we have to ensure the proteins remain in an aqueous phase, else they will denature, in other words, they are sensitive to the chemical environment.

Solution

- Temperature: The production of natural aromatic organic compounds is temperature sensitive. These compounds tend to decompose at elevated temperatures. Therefore, when separating them from their natural source, one should be careful with the temperature of the process. An alternative to regular distillation that helps depress temperature sensitivity is steam distillation.
- Contamination: When completing filtration of protein solutions for drug delivery, the appropriate type of membrane should be utilized. This can be through size exclusion or charge as long as the producer is mindful that potential viruses or pyrogens may be the same size and charge of the proteins to be separated. Therefore, producers should select separation processes that will remove these harmful contaminants.

Question 5

For each of the following general industries, please identify two separation systems (unit operations):

- petrochemical
- bioprocessing
- food and beverage
- pharmaceutical
- minerals/mining
- metals
- air products
- wastewater treatment

Solution

- Petrochemical: stripping; fractionation distillation
- Bioprocessing: membrane filtration; centrifugation
- Food and beverage: freeze-drying; mechanical deboner; centrifuges
- Pharmaceutical: membrane filtration; crystallization
- Minerals/mining: cyclones; flotation columns
- Metals: magnetic separator (feed ore); and ion exchange (e.g. Ni/Co separation)
- Air products: cryogenic distillation, pressure swing adsorption
- Wastewater treatment: clarifier, filtration

Question 6

A particle 1mm in diameter, with density of 5000 $kg.m^{-3}$ is settling in an unhindered environment of water. Calculate an estimate of its terminal velocity.

Solution

Assuming ambient conditions for water, we have approximately that $\rho_f = 1000$ kg.m^{-3} and $\mu_f = 0.001$ N.s.m^{-2} (more accurate figures may be used).

A reasonable starting guess in most situations is to assume Stokes' law applies, i.e. Re < 1.

Terminal settling velocity, in SI units, $v = \dfrac{(\rho_p - \rho_f)\, g D_p^2}{18\mu_f} = \dfrac{(5000 - 1000)\,(9.81)(0.001)^2}{18(0.001)} = 2.18$ m.s^{-1}.

Verify the Reynolds number = Re = $\dfrac{D_p v \rho_f}{\mu_f} = \dfrac{(0.001)(2.18)(1000)}{(0.001)} = 2180$, which is above the Re = 1 threshold. So our initial assumption was incorrect.

But use this newer Reynolds number estimate to calculate $C_D = 0.44$, which holds in the $1000 <$ Re $< 2 \times 10^5$ range.

Now $v = \sqrt{\dfrac{4\,(\rho_p - \rho_f)\, g D_p}{3 C_D \rho_f}} = \sqrt{\dfrac{4(4000)(9.81)(0.001)}{3(0.44)(1000)}} = 0.345$ m.s^{-1}.

A revised estimate of the Reynolds number is Re = $\dfrac{(0.001)(0.345)(1000)}{(0.001)} = 345$, which is outside the assumed Reynolds number range.

A revised estimate is $C_D = \frac{24}{\text{Re}}\left(1 + 0.15\text{Re}^{0.687}\right) = \frac{24}{345}\left(1 + 0.15 \cdot 345^{0.687}\right) = 0.65$, which holds in the $1 <$ Re < 1000 range.

Now $v = \sqrt{\dfrac{4(4000)(9.81)(0.001)}{3(0.65)(1000)}} = 0.28$ m.s^{-1}, for which the Reynolds number is 280, which is in the assumed range.

We can iterate again, and calculate drag coefficients and velocities of 0.70 and 0.27 m.s^{-1} respectively, which are little different to the previous drag and velocity.

So the terminal velocity is estimated to be around **0.27** m.s^{-1}.

END