Educational Module: Incorporating Sustainable Design Principles into the Process Separations Course

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Abstract

This module is intended to provide guidance to incorporating sustainable design principles into the Process Separations Course. Process Separations is typically a core course in the Chemical Engineering curriculum. The concepts developed in this module are geared toward junior level students in Chemical Engineering. Typical engineering prerequisites for this module will include Mass and Energy Balances and Chemical Engineering Thermodynamics. Separation unit operations such as Liquid-Liquid Extraction, Absorption, Binary Distillation, Multicomponent Distillation, Membrane separation and Vapor-Liquid Equilibrium concepts are covered in this module. A set of practice problems with solutions follows this module. These problems will reinforce the sustainable design principles presented in the module.

Sustainability and Chemical Engineering Education

The effects that chemical processes have on the environment and the economy are of increasing concern to the general public, the chemical and allied industries and regulatory agencies. Ensuring that the natural resources required to manufacture the products and services needed by society are utilized in a way that ensures their availability for future generations is the core of the field of sustainability. In its 1987 report titled *Our Common Future*, the U.N. World Commission on Environment and Development, also commonly called the Bruntland Commission, defined sustainable development as follows:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Bruntland, 1987)

Although there is no single accepted definition of the term sustainability, the Bruntland Commission definition of sustainable development forms the basis of what sustainability means to the field of engineering. For chemical engineers in particular, sustainability has come to refer to the goal of designing, operating and maintaining chemical processes in a manner that is economically viable, environmentally benign, and beneficial to society. In other words, a sustainable process is one that is designed, operated and maintained to meet the triple bottom line of economics, environment and society, both now and in the future. Chemical engineering graduates entering careers in the chemical and allied industries will increasingly be tasked with job functions that require both an understanding of sustainable chemical engineering principles and competency in set of sustainable chemical engineering skills. Therefore, the AIChE Sustainable Engineering Forum has developed a set of modules that will address the growing need for incorporating sustainability into the chemical engineering curriculum.

The National Academy of Engineers has expressed this need for sustainability in engineering education in its report titled *The Engineer of 2020: Visions of Engineering in the New Century* as follows:

> "It is our aspiration that engineers will continue to be leaders in the movement toward the use of wise, informed, and economical sustainable development. This should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions." (NAE, 2004)

How to incorporate sustainability in engineering education is a challenge to the academic community (Davidson, *et al.*, 2010),(Allen, *et al.*, 2006). However, by utilizing modules that integrate sustainability into core courses and concepts, we can begin to address this challenge.

Sustainable Separation

Separation is one of the fundamental processes in chemical engineering. Most chemical processes involve separation, whether it is multiphase, multicomponent or both. Reactions that generate unwanted side products, or occur in a solvent phase all require separation. Naturally occurring raw materials often require filtration or refining to be suitable for industrial use. So, because of their prevalence in the chemical process industries, looking at the design of separation systems from the perspective of sustainability is important. Unfortunately, many traditional separation processes are highly energy intensive, or utilize mass separating agents with adverse environmental impacts. However, when considered in the design phase, many common separation problems can be addressed using techniques and technology that is sustainable with optimized energy usage and consequently, minimal environmental impacts. This module will introduce various types of separation processes and present an overview of how they can be an integral part of sustainable process design. Specific example problems illustrating these techniques are included with this module.

Overview of Sustainability Principles in Separation Process Design

Distillation

Distillation is the traditional workhorse of chemical process separations. The technology is well established and understood. This makes, and will continue to make, distillation the primary choice for many classes of separation processes. However, distillation is a highly energy intensive process which can make operating cost a concern amid rising energy prices. Furthermore, the environmental impact of a highly energy intensive process can be great. However, distillation systems can often be easily optimized from the standpoint of energy utilization.

Because of the relationship between reflux ratio and the number of theoretical stages required for a given separation, it is easy to calculate the influence of additional theoretical stages and the energy required for reflux and boil-up. For the standpoint of sustainability, this becomes a trade-off between additional capital cost due to additional trays or packing and additional operating costs due to increased energy usage. Understanding trade-offs between different types of costs is an important concept in the sustainable design of distillation systems. Two sample distillation design examples are included in the problems following this module.

Liquid-Liquid Extraction

Liquid-liquid extraction is another well established and well understood process. Although liquid-liquid extraction is often less energy intensive than distillation, choosing an effective, yet environmentally benign solvent can be challenging. From the perspective of sustainability, students must be able to incorporate potential environmental impacts as well as overall energy utilization into their analysis to ensure that potential energy saving from switching to an extraction process are not negated by the use of an environmentally harmful mass separating agent. In addition, the selected solvent must be available at a reasonable cost today and for the foreseeable future. An example of a sustainable process utilizing liquid-liquid extraction is included in the sample problems following this module.

Gas-Liquid Absorption

Gas-Liquid absorption can also be used as a sustainable unit operation in separation process design, especially in pollution abatement applications. Gas-Liquid absorption can be an efficient and cost effective means of removing vapor or gas phase pollutants or recovering/recycling valuable products from a gas stream. However, for pollution abatement, this is an "end-of-pipe" solution rather than the preferred method of pollution prevention at the source. This means that, much like liquid-liquid extraction, a gas-liquid process is only sustainable if the chosen mass separating agent has a minimal environmental impact or can be easily regenerated and recycled. An example of gas-liquid absorption using sustainable design principles is the use of sea water to absorb pollutants from flue gas. This example is included in the sample problem following this module.

Membrane Separation

In terms of sustainability the key concepts to be considered with membrane separation systems involve reduced energy consumption when compared with distillation. The principle challenge is finding membrane materials that are suitable for a particular application. The permeance and selectivity of membrane materials vary widely, so it is important to have appropriate data in order to compare a membrane system to traditional distillation. Natural and synthetic materials are available for use as membrane material. In addition to energy considerations, when comparing membrane processes to traditional distillation, it is important to consider the source of the membrane, especially from a life-cycle assessment perspective. An example of the use of a natural membrane material is included in the sample problems following this module.

A subset of membrane separation processes is pervaporation. Pervaporation combines permeation with evaporation in a membrane process. This technology has application as either a standalone technology or in conjunction with distillation in the recovery of ultrapure solvents from waste streams. One example of this concept is azeotropic distillation where a pervaporation process can be used to replace a traditional process based on using extractive distillation. A specific application of pervaporation is in the drying of alcohols that form azeotropes with water.

A second subset of membrane separation is reverse osmosis. This technology is especially common in water purification. Reverse osmosis differs from traditional osmosis in that the solvent phase is forced through the membrane by pressure, rather than by concentration gradient. Because of this, reverse osmosis results in an ultra pure solvent phase. An example of the use of reverse osmosis for the desalination of sea water is included in the sample problems following this module.

Educational Objectives

The objective of this module is to provide a framework for incorporating sustainability into the Process Separations Course. After completing this module, students should have achieved the following objectives:

- Demonstrate an understanding of the trade-offs between the number of theoretical stages and total energy consumption in distillation systems.
- Be able to perform sensitivity analyses of energy utilization to reflux ratio for distillation systems.
- Demonstrate an understanding of the importance of substitution of solvents in extractive separations systems.
- Explain how a variety of separations processes can be used to reduce the environmental impact of common processes such as the usage of coal for energy and the production of drinking water from sea water.
- Demonstrate an understanding of the heuristics of sustainable separation process design.
- Demonstrate an understanding of the role the principles of process separations plays in design for sustainability.

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Sample Problems

***Note to Instructors**: A complete set of solutions to the sample problems is available to credentialed instructors by contacting the corresponding author at jseay@engr.uky.edu.*

1. Liquid-Liquid Extraction:

Adipic acid is used in industry as a monomer in the production of nylon. Traditionally, the synthesis begins with benzene, a non-renewable carcinogen (Allen and Shonnard: 2002). An alternative synthesis begins with non-volatile, sustainable D-glucose. Consider a plant using D-glucose for the synthesis of adipic acid. The final product of this plant is 35 mass % adipic acid in solvent. Distillation is not an economically viable option for purifying this solution so a countercurrent liquid-liquid extraction process is using liquid CO_2 has been proposed.

(a) If the solution flow out of the plant and into the extraction column at 1000 lb/hr and the pure liquid CO_2 stream is fed at 2000 lbs/hr, how many equilibrium stages are needed in order to achieve 98% removal of adipic acid? Assume that the original solvent is immiscible with liquid CO_2 and the distribution coefficient K'_D is 1.3.

(b) Explain why liquid-liquid extraction is often a more sustainable option than distillation.

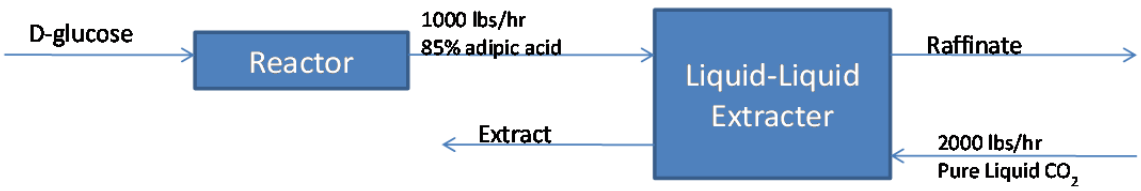

Figure 1: A sustainable liquid-liquid extraction process in the manufacture of adipic acid.

2. Gas-Liquid Absorption:

Recent research into clean coal technology has been proposed to make coal fired power generation more efficient and more environmentally friendly in producing electricity. One way of doing this is to use an absorption process to capture the carbon dioxide emissions from the flue gas and use it to help power the plant. The process shown below should be designed to recover 97 mole % of the CO_2:

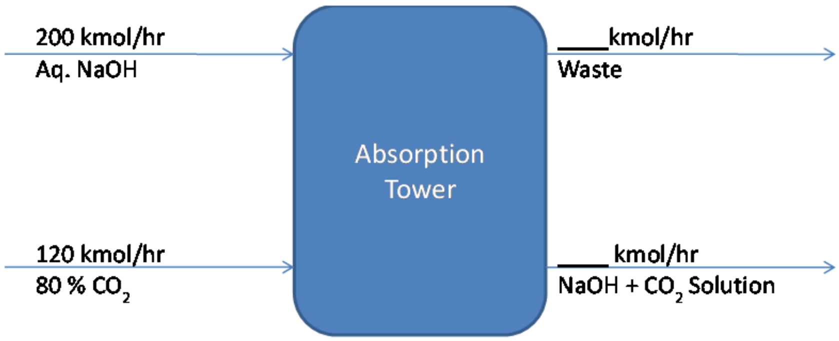

Figure 2: Recovery of carbon dioxide from flue gas by gas-liquid absorption

For this process find:

(a) Absorption Factors
(b) N Number of stages.
(c) Thinking about sustainability, what are the important advantages and disadvantages to adding additional theoretical stages to the absorber.

Given Data for Problem 2:

Equilibrium relationships y = 1.65X
The system is at 25°C and 1 atm
Pure NaOH aq is fed at 200 kmol/hr
The flue gas stream flow at 120 kmol/hr contains 80% CO_2

3. Vapor-Liquid Equilibrium (VLE):

Carbon dioxide is used in many processes as an environmentally preferable solvent because it is non-volatile. At STP (273 K and 1 atm) find the following:

a) K-values using Raoult's Law
b) Heat of Vaporization
c) Thinking about life cycle assessment (LCA) what are the important advantages and disadvantages to using carbon dioxide as a reaction solvent.

4. Distillation:

Glycerol is the principal by-product of biodiesel production. Glycerol currently has limited commercial value and is disposed of for its waste heat value. Research is being done to make this sustainable process more efficient by converting waste crude glycerol into economically viable specialty chemical compounds (Jernigan, *et al.*: 2009). Glycerol leaves the biodiesel process dissolved in water. In order to react the glycerol, it needs to be separated into a more concentrated solution. Glycerol leaves the process as an equimolar solution in water and needs to be separated by distillation to a 90 mol % glycerol solution. Find the minimum number of stages, minimum reflux ratio, and actual number of stages if $R=1.5R_{min}$, and the q-line has a slope of -0.45 using the equilibrium data below.

X	Y	X	Y
0	0	0.6	0.001611
0.1	1.61E-05	0.7	0.004802
0.2	4.87E-05	0.8	0.018742
0.3	0.000117	0.9	0.117994
0.4	0.000268	1	1
0.5	0.00063		

5. Membrane Separation:

Sustainable separation membranes can be made out of a number of different biobased materials including waste shrimp shells (You, *et al.*: 2003). Shrimp shells are a renewable resource and available in huge abundance, thus making them a sustainable and effective membrane. Suppose that a solution needs to be separated but the boiling points of the components are too close for distillation to be an economically viable option. Membrane separation has been determined to be the best option to achieve this separation. Calculate the selectivity and the transmembrane flux of the two solvents listed in the data below.

Shrimp Shell Membrane:		
Thickness	5.32	µm
Pore Diameter	643	nm
Tortuosity	1.15	τ
Porosity	0.0198	Є

Solutes	Diffusion Coeffient $*10^6$ cm^2/s	Molecular Diameter nm	c_{iO} g/cm^3	c_{iL} g/cm^3
SLT 1	15.6	68.2	0.0007	0.0002
SLT2	5.2	123.7	0.0004	0.00009

6. Gas-Liquid Absorption:

Flue gases emitted from the burning of fossil based fuels such as pulverized coal fuel (PF) and natural gas (NG) contain high amounts of sulfur dioxide and carbon dioxide (Pepitone and Bolland: 2003). Studies have shown that seawater can be used in a gas-liquid absorber to reduce the emissions of these volatile compounds. Consider a process where the sulfur dioxide in the flue gas emissions needs to be lowered to at least 30 ppm. The tray diameter can be determined by the equation below:

$$d = \Psi\left[Q(\rho_g)^{0.5}\right]^{0.5}$$

where Ψ is the empirical correlation [$m^{0.25}(h)^{0.25}/(kg)^{0.25}$], Q is the volumetric gas flow (m^3/h), and ρ_g is the gas density (kg/m^3). Determine the height and diameter of the scrubber for both NG and PF processes using the following data:

DATA:			
Ψ	0.0125		
Spacing between each plate (m)	0.61		
h (plates)	0.65		
Number of theoretical plates	4		
Actual number of plates	7		
NG- flue gas		PF-flue gas	
P (atm)	20	P (atm)	20

q (kg/m^3)	38.5	q (kg/m^3)	35.6
Q (m^3/h)	5327	Q (m^3/h)	16707

7. Membrane Separation Reverse Osmosis:

Sustainable water usage is a challenge in arid regions of the planet. Although 70% of the earth is covered with water, only a small percentage of that water is clean enough to be used for human consumption. Converting salt water or contaminated water into clean water by reverse osmosis through a membrane a means of generating a sustainable source of clean water (Subrata, *et al.*: 2008).

(a) Assume that the State of California has been estimated to run out of clean water in a relatively short amount of time. Therefore, engineers need to start producing fresh water from alternative sources. If sea water is pumped from the ocean into the water treatment plant at 25^{o}C and 850 psia, then it has to pass through a membrane 3 cm thick with a presence for water and salt respectively 3.5 x 10 $^{-5}$ g/cm s atm and 15.2 x 10 -6 cm^2/s. The permeate side contains 5000 ppm NaCl and is released at 25^{o}C and 1 atm. Calculate the flux of salt and water in g/ m^2 h, the salt passage and salt rejection.

(b) Think about and discuss the role membrane technology might play in the future regarding sustainable water usage.

8. Multi-component Distillation:

In the production of biodiesel there are two major components produced in the reaction step: biodiesel and glycerin (MDNR: 2009). However, water and methanol are also present in the reaction product. The reactor product is first separated using a centrifuge. After the separation there is a second separation step to remove the residual methanol from the recovered glycerin and water. Assume that 95 mol% of this methanol must be removed from the glycerin. After the glycerin is separated from the biodiesel it flows at a rate of 150 kmol/hr and contains 15 mol % methanol and 20 mole % water at 25 ^{o}C and 1atm.

(a) For this system, determine the following:
Distribution of the components using the Fenske equation
Minimum number of stages
Minimum Reflux Ratio
Actual Reflux Ration if R=1.35R
Actual Number of stages
The feed stage

(b) From the perspective of sustainability, discuss the trade-offs between reflux ratio and number of theoretical stages.

9. Separation Economics:

For the system described in problem 8 Graph the reboiler duty versus number of stages and find the optimum number of stages to minimize energy usage and utility cost. Also, graph number of stages verse annual utility cost to show the impact the number of stages can make on the system. The cost of electricity is about 7 cent per kwh or 2.05E-5 cents per Btu. Comment on the use of optimization in sustainable process design.

10. Eco-friendly Separation:

A plant in Austin, TX produces paint thinner which contains a large fraction of volatile component A. In order to reduce the cost of production and help remove this VOC from the environment, the plant has decided to design a process to recover 99.9% of volatile component A from the waste stream. The waste contains 15 mol% volatile A. The waste water is released at a rate 200 kmol/hr at 25 ^{o}C and 1 atm. Given the graph below solve graphically for the number of stages needed to achieve this kind of separation if the R=1.4 R_{min} and only 0.1 mol% of the water is lost to the volatile A in the distillation process.