Paper ID #22085

Incorporation of Process Sustainability Concepts in a Senior Design Course at a Minority Serving University

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Work In Progress: Incorporation of Process Sustainability Concepts in a Senior Design Course at a Minority Serving University

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Introduction

Sustainability is an important topic for chemical engineers to understand and apply in our energy- and resource-constrained world. The petroleum energy crises that occurred in the US in the 1970s heightened the awareness of the need to conserve energy in a multitude of personal and industrial areas. The implementation of the Clean Water Act in 1972 and the Resource Conservation and Recovery Act in 1976 additionally provided regulatory impetus for more extensive implementation of sustainability-related improvements in refinery and chemical process operations. More recently, the recognition that potentially detrimental climate change trends are related to mankind's continued consumption of fossil fuels adds an additional layer of complexity to sustainability considerations. For these reasons, it is important for graduate chemical engineers to have experience with implementing process improvements representing sustainability concepts.

Approach to Sustainability Instruction in Senior Design Course

Chemical engineering students of senior standing are enrolled in the Chemical Process Design II and Design III course sequence at our minority-serving institution (MSI), Texas A&M University-Kingsville (TAMUK). In this two-semester course sequence, students are introduced to sustainability concepts during instruction in chemical process formulation and process simulation (Design II). Subsequently, students are further instructed on this topic during their semester-long senior design project (Design III) course. For the senior design experience, students are required to form into groups of four and complete a senior design project that involves process simulation, using Aspen Plus software, and cost estimation of a chosen chemical process. The author has been the primary course instructor for this two-course sequence for only the last three years, and thus has been steadily increasing the extent of sustainability concepts included in the courses. Recently, instruction in sustainability concepts was expanded from the Design III course to the Design II course, as a result of the instructor receiving internal grant funding for a course-redesign on a Title V I-CARE (Integrating a Culture of Academic and Research Engagement) federal grant. For the course re-design, a new instructional module was created on heat integration in chemical processes, and then a short term student project was assigned to students.

The sustainability concepts that are discussed in the Design II and Design III courses are (1) recycling of unreacted feed or other chemical; (2) heat integration; (3) water use minimization or recycling; and (4) harsh or hazardous chemical or catalyst substitution. Once students are introduced to these concepts, they are expected to incorporate them to the extent applicable in their chemical process selected for the capstone design experience in Design III. The fourth concept of hazardous chemical substitution has rarely been implemented based on the instructor's experience in the senior design courses, since this tends to be more in the purview of chemical product development rather than chemical process formulation and simulation. The list of chemical processes offered to students for their senior design project topic are commonly bulk organic chemical production processes that typically include reactor conditions well above ambient temperature (and sometimes also pressure) and flash separators, absorbers, or distillation towers for excess reactant separation and product recovery. Therefore, the instructor's choice of chemical processes offered to the student groups are, to some extent, pre-selected for being amenable to optimization by one or more of the sustainability applications listed above.

Student Incorporation of Sustainability Concepts in Design Projects

The instructional results and observations presented below are from Design II and Design III course experiences in the academic years 2015-2016 and 2016-2017. Figure 1 summarizes the number of sustainability concepts incorporated per senior design project, as compared to the total of 21 groups that conducted chemical-process related design projects in the years cited above. Nine of the 21 groups incorporated two sustainability concepts, namely mass recycle and heat integration, while one group incorporated those two, as well as water use minimization. Amongst all three course offerings, there were only two senior design groups that selected not to incorporate any sustainability concept; both of these were biochemical conversion processes (corn or other biomass to bioethanol). A minor portion of the students' grade on their senior design project deliverables is based on their incorporation of a sustainability improvement into the project in Design III.

The first sustainability concept students are expected to consider is recycling of mass (chemicals), such as unreacted feed material to improve the overall conversion, or chemicals used in a product recovery step that has a sufficient unit value indicating it should be recycled. Students have been introduced to the concept of mass recycle back in the Conservation Principles (mass and energy balances) course. Thus, most student groups readily understand the need to incorporate recycling of unreacted reactant when the single pass conversion is not very high (that is, above approximately 90 or 95%). However, one of the stumbling blocks that students encounter is the increased difficulty in obtaining error-free simulation runs with a recycle loop in the Aspen Plus simulation of their process. Most groups are indeed able to overcome this hurdle, but in some cases it takes a bit of time. In the 2016 offering of Design III, 4 out of 6 groups successfully incorporated chemical recycle in their process (see Figure 1). In the spring 2017 offering of Design III, 8 out of 11 groups successfully incorporated chemical recycle in their process, while in the summer 2017 offering of Design III, 3 out of 4 groups successfully incorporated reactant recycle in their process. Table 1 below presents an overview of the primary material recycled for all of the senior design groups that chose to include mass recycle in their project. Eleven groups chose mass recycle of reactants to improve reaction conversion, but only three of these groups reported sufficient information to document that an improved conversion resulted (last column of Table 1). Some groups that included reactant recycle reported only minimal improvement in conversion associated with the recycle. In the case of a vinyl chloride process (performed by two different groups), hydrochloric acid generated as a by-product of a third reactor was recycled back to the beginning of the process where it was utilized as a reactant in one of the first two parallel reactions. Besides reactant recycle, three design groups included recycling of non-reactant chemicals added for the express purpose of product recovery (triethylene glycol for water recovery, paraffin oil for isobutylene recovery, and dibutyl phthalate for maleic anhydride recovery). In the future, the instructor plans to request that the students include a value of dollar benefit related to their decision choice to include mass (reactant) recycle, as compared to a system with no recycle.

Slightly fewer student groups followed through with incorporating heat integration or recycling of heat between different heat exchangers in a process. The instructor believes that the seniors have not been exposed to heat integration prior to the second semester senior year, other than a one-day introduction to heat exchanger network design initiated in Design II in fall 2017. The lower incidence of application of heat integration concepts into design group projects is attributable to one of two reasons: (1) students may have a process where temperatures do not get significantly above ambient, and thus heat integration is not suitable for processes that do not require high temperatures for a reaction step, or (2) students encounter a lack of available time near project completion because too much time is spent early in the project on correct implementation of reaction kinetics. In the 2016 offering of Design III, 4 out of 6 groups successfully incorporated heat integration in their process (see Figure 1). In the spring 2017 offering of Design III, 7 out of 11 groups successfully incorporated heat integration in their process, while in the summer 2017 offering of Design III, only 1 out of 4 groups successfully incorporated heat integration in their process. Table 2 below presents an overview of the utility cost benefit for the 12 senior design groups that chose to include heat integration in their project. The incorporation of heat integration resulted in minimal savings (amount saved only several thousand dollars or less, representing less than 1% of the total utility costs) for two of these groups. For five of the groups, the annual utility savings were over $1 million dollars, which represented 50 to 75% of the annual utility costs in three of these cases. Overall, the percentage of utility costs saved by incorporating heat integration ranged from approximately 1% at the low end to 90% at the high end. Comparison of the quantitative information presented in Tables 1 and 2, which was culled from final senior design reports and final group presentations, indicates students more readily develop the cost benefit associated with heat integration (reduction in utility costs) as compared to mass recycle (savings realized by mitigating unreacted reactant loss). In the future, additional data will be available as a result of a survey administered to the spring 2018 Design III project students who were recipients of a new heat integration instructional unit and project assignment that was incorporated into the curriculum in fall 2017 Design II.

The third sustainability concept the students are expected to consider is minimization or recycling of any water used in the process, either for heating or cooling applications, or as water involved directly in the process chemistry. The water use minimization or recycling concept is typically included by student groups only in the instance when water is a reactant, product, or a component used for product extraction or absorption after a reaction step. In the spring 2016 offering of Design III, no groups incorporated water recycling in their process (see Figure 1). In the spring 2017 offering of Design III, 3 out of 11 groups successfully incorporated water recycling in their process. In two instances, the water available towards the end of the chemical process was reused for cooling purposes, while in the third instance, the water was used to generate steam by heat integration with a hot process stream that required cooling, and was subsequently used to generate power in a turbine, which was then reintegrated as compressor work elsewhere in the process. These results suggest that more instruction on opportunities for process and utility water recycling should be incorporated into the Design II curriculum.

Summary

Less than a quarter of our students avail themselves of any industrial internship opportunity during their undergraduate career at TAMUK; an industrial internship is not a requirement in our undergraduate degree program. Additionally, roughly one half of the students in our chemical engineering curriculum come from parts of our state where there are numerous refineries and chemical process plants, while the remainder come from nearby areas of our state where there is no refinery or chemical process industry whatsoever. Based on this information, only a small fraction of our students may have been exposed to recycling and sustainability concepts applicable to the chemical industry via direct experience or contact and discussion with industry personnel. Therefore, we should not expect any significant number of our undergraduate seniors to have any previous background in this area. For this reason, more extensive instruction in Design II and Design III on sustainability concepts, as they relate to the chemical industry, is warranted. The data presented here indicates that progress has been made in getting the students to understand the importance of sustainability, but further efforts are necessary for our majors to fully appreciate this topic that is of increasing importance in our resource-constrained world.

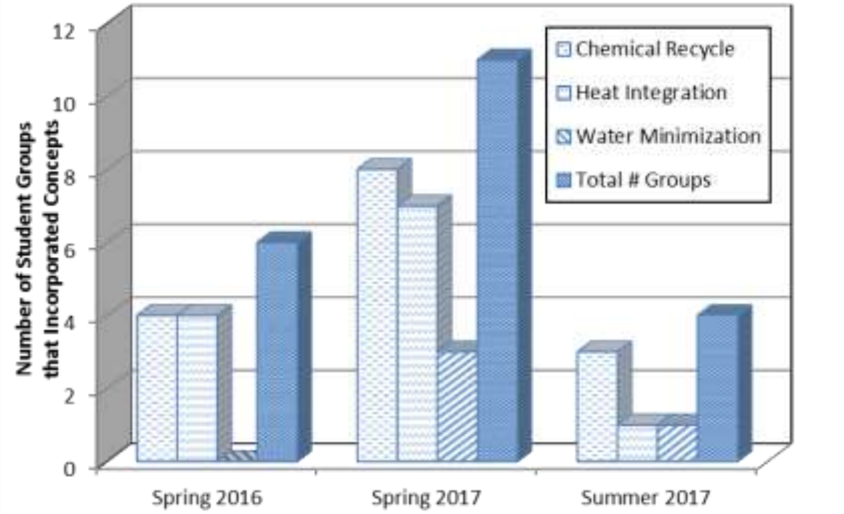

Figure 1. Student Incorporation of Sustainability Concepts

Table 1. Summary of Chemical Recycle Concepts Incorporated

Semester	Project Name	Material Recycled	Improved Conv. (SPC to OC)
Spring 2016	Production of Ethyl Acetate from Ethanol and Acetic Acid	Reactants and products to assist with product purification	None
	Natural Gas Dehydration	Absorbent (triethylene glycol) for water removal	NA
	Production of Olefins from Natural Gas	Synthesis gas (reactant)	98% to 99.8%
	Production of Vinyl Chloride Monomer	Hydrochloric acid (reactant in 1st reaction) is produced in 3rd reaction	NA
Spring 2017	Production of L-Phenylalanine	Biochemical reaction nutrients	INSF
	Production of Cumene from Benzene	Benzene (excess reactant)	75% to 99%
	Production of Phenol from Cumene	Hydrogen (reactant) and α-methylstyrene (intermediate)	22% to 98%
	Production of Terephthalic Acid	Oxygen and p-xylene	INSF
	Isobutylene Production from Catalytic Dehydrogenation of Isobutane	Absorbent (paraffin oil) for product recovery	NA
	Production of Ethylene Glycol from the Hydrolysis of Ethylene Oxide	Water (reactant)	INSF
	Production of Maleic Anhydride from n-Butane	Absorbent (Dibutyl phthalate) for product recovery	NA
	Production of Acetaldehyde from Ethylene	Ethylene (reactant)	INSF
Summer 2017	Production of Methyl Formate	Synthesis gas and methanol	Minimal
	Production of Vinyl Chloride	Hydrochloric acid (reactant in 1st reaction) is produced in 3rd reaction	NA
	Production of Methyl Tert Butyl Ether	Isobutylene (reactant)	minimal
NA – not applicable; SPC – single pass conversion; OC – overall conversion; INSF – reported information insufficient to complete calculation			

Table 2. Summary of Heat Integration Concepts Incorporated

Semester	Project Name	Number of Integrated Heat Exchangers	Utility Cost Savings per Annum	Savings as Percent of Total Utility Cost
Spring 2016	Production of Ethyl Acetate from Ethanol and Acetic Acid	3	$75 K	3%
	Natural Gas Dehydration	2	$91 K	90%
	Production of Olefins from Natural Gas	3	$2.3 MM	6%
	Production of Ammonia	1	$600 K	2%
Spring 2017	Production of L-Phenylalanine	1	$400	<1%
	Production of Cumene from Benzene	1	$1.3 MM	75%
	Production of Phenol from Cumene	3	$2.6 MM	5%
	Production of Synthetic Fuels from Natural Gas	1	$1.9 MM	50%
	Isobutylene Production from Catalytic Dehydrogenation of Isobutane	2	$15 K	1.5%
	Production of Olefins from Methanol	2	$150 K	3%
	Production of Ethylene Glycol from the Hydrolysis of Ethylene Oxide	4	$2.3 MM	67%
Summer 2017	Production of Triethanol Amine	1	$4 K	< 1%