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Expanding the Frontiers for Chemical Engineers in Green Engineering Education

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'Greening' the engineering curriculum is an important consideration for sustainable engineering education from fundamentals to design in the 21st century. This paper describes the latest advances in an educational project sponsored by the United States Environmental Protection Agency (EPA) to integrate green engineering principles into the chemical engineering curriculum. This project has engaged faculty from engineering schools across the country to develop Web-based instructional modules to allow for the seamless integration for green engineering principles such as risk concepts, green chemistry, mass and energy integration, life-cycle assessment into chemical engineering courses. Faculty have contributed to chemical engineering core courses from material and energy balances to plant design. In addition, faculty have developed modules for multidisciplinary offerings such as freshman-level introduction to engineering and upper-level system dynamics and control. This paper will review some of the innovative modules developed and show how they can be used in the chemical engineering curriculum. This educational project's goal is to integrate green engineering concepts horizontally and vertically into the curriculum by taking existing courses and integrating topics as appropriate through examples, problems and case studies. Using green engineering principles at the start of the design process can lead to processes and products of a sustainable future.

Keywords: curriculum development; green engineering; pollution prevention; sustainability; web-based course modules

INTRODUCTION

THE EPA ORIGINALLY defined green engineering as the design, commercialization and use of processes and products that are feasible and economical, while minimizing the generation of pollution at the source and also minimizing risk to human health and the environment [1]. The definition of green engineering was more broadly defined in a recent conference (Sandestin, Florida, 2003) to transforming existing engineering disciplines and practices to those that lead to sustainability. Green engineering incorporates development and implementation of products, processes and systems that meet technical and cost objectives, while protecting human health and welfare and elevating the protection of the biosphere as a criterion in engineering solutions [2]. Nine green engineering principles were developed as a result of this conference. Engineers should follow these principles to fully implement green engineering solutions:

- Engineer processes and products holistically, use systems analysis and integrate environmental impact assessment tools.
- Conserve and improve natural ecosystems while protecting human health and well-being.
- Use life cycle thinking in all engineering activities.
- Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
- Minimize depletion of natural resources.
- Strive to prevent waste.
- Develop and apply engineering solutions, while being cognizant of local geography, aspirations and cultures.
- Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability.
- Actively engage communities and stakeholders in development of engineering solutions.

Chemical companies have adopted a green engineering approach to achieve a sustainable future. This is a more significant driver for teaching green engineering to students. Many of their future employers in the chemical industry have moved toward a sustainable future. Many of these companies are members of the Dow Jones Sustainability Index (DJSI) World & DJSI STOXX, which totals 300 companies from 22 countries and was launched in 1999 [3]. For example, the leaders in chemicals, energy and food & beverages, industrial goods & services, non-cyclical goods & services sectors in 2004 were DuPont, BP, Unilever, 3M, Procter & Gamble, respectively [4].

The need to introduce green engineering concepts to undergraduate students has become recognized as increasingly important [5]. Engineering programs that are accredited in the United

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States by the Engineering Accreditation Commission (2006) of the Accreditation Board for Engineering and Technology (ABET) state that students must have:

- An ability to design a system, component or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability, (Criteria 3c).
- An understanding of professional and ethical responsibility, (Criteria 3f).
- The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental and societal context, (Criteria 3h).
- A knowledge of contemporary issues, (Criteria 3j).
- Discipline specific criteria, such as in chemical engineering, further specify that engineers must have safety and environmental aspects (Criteria 8) included in the curriculum.

Engineering faculty role in informing society about green engineering is through teaching their students this subject in the classroom. Engineering students who are taught how to incorporate green engineering into their work, will help its implementation in industry and this will lead us to a sustainable future for all.

CURRICULUM DEVELOPMENT

The traditional, and probably most common, method of introducing aspects of green engineering has been through a senior and graduate level elective course on environmental engineering, with an emphasis on process treatment. Courses were developed that focus on methods to minimize or prevent waste streams from existing chemical plants in the 1990s. The educational progression mirrors the progression in industry. In industry initial efforts were applied to waste treatment whereas current efforts are aimed at reducing the total volume of effluent treated as well as the nature of the chemicals treated. Currently, many of the environmental and pollution prevention courses have been replaced by courses in green engineering, environmentally conscious chemical process engineering and engineering for sustainable development and a discussion of some of these efforts has been previously presented [6].

These courses are typically offered during the senior year and are optional engineering courses. These stand-alone courses are excellent in providing detailed coverage of the subject and are needed in the engineering curriculum. Students may get the impression that green engineering is either optional or something done at the end of the design process, since this course is usually both optional and at the end of their undergraduate education. Students may also get the impression that only one professor, the one currently teaching the course, knows about this subject matter which reduces the importance of this subject in the students mind.

A better method is to introduce these concepts throughout the curriculum [6], which helps to better emphasize that engineers should be using green engineering and sustainability throughout the design process. Implementing this integrated approach, in which students see green engineering throughout their 4 years of engineering shows the importance of this subject to the students and reinforces the need to employ this subject in industry. Both of these methods of education should be encouraged and further development is needed.

In 1998, a program was initiated with support from the EPA to develop a textbook on green engineering; disseminate these materials and assist university faculty in using these materials through national and regional workshops coordinated with the American Society for Engineering Education (ASEE), Chemical Engineering Division. The textbook entitled, *Green Engineering: Environmentally Conscious Design of Chemical Processes* [7] by Allen and Shonnard was designed for a senior/graduate chemical engineering course and has a series of accompanying materials that can be employed throughout the curriculum. The current efforts described in this paper are to develop curriculum modules that can be used to easily integrate green engineering concepts throughout the curriculum. These efforts include the development of instructor guides, case studies, homework problems and in-class examples. These green engineering course modules can be found on the green engineering Web site (www.rowan.edu/greenengineering) [8].

Our initial efforts started with developing some pilot modules and incorporating them into our own chemical engineering curriculum at Rowan University [9], where we start integrating green engineering in the freshman year and continuing through the senior year. Through these initial efforts we saw that green engineering concepts can be readily coupled with what is currently being taught in a chemical engineering curriculum. In the freshmen year at Rowan University we start with multidisciplinary projects [10] and case studies utilizing aspects of green engineering. In Rowan University's multidisciplinary sophomore engineering clinic all engineering students participate in projects related to green engineering [6]. Chemical engineering students use the Allen and Shonnard text [7] in conjunction with all of their chemical engineering courses and with their projects. Based on the success with this pilot effort we have expanded the scope and variety of the green engineering concepts and courses impacted and involved faculty from across the country in module development and implementation. We have also further disseminated our work through regional and national workshops [11].

GREEN ENGINEERING MODULES

Overview

The goal of our project is to develop easy-to-use problems/solutions that incorporate green engineering principles and that can be integrated into various chemical engineering courses. These problems are grouped together into a module based on the course in which they are used. These unique educational materials, which can be used for chemical engineering courses, have been developed by the faculties from various engineering schools (Table 1). These modules are available on-line (www.rowan.edu/greenengineering) as part of the EPA grant [6, 8]. The initiative is to provide materials that can be readily adapted to currently existing courses. The materials that are provided consist of instructor guides to assist in mapping green engineering topics into various chemical engineering courses and provide homework problems, in-class examples and case studies for faculties to use. Green engineering modules prepared for core courses are available on-line. The site is password protected with four levels of privileges: administrator, professor, student and guest. Students do not have access to the homework problem solutions, but have access to the problem statements, unless the module author provides professor access. When a faculty member first logs on to the Web site they use the username guest and password guest. This then prompts an e-mail to the Rowan Webmaster, where we verify that the person requesting professor privileges is actually a faculty member. A separate username and password are then sent to the faculty member, who is now able to view all instructor guides, problems, solutions and even post material of their own.

The goal of each module is to map some topics from the Allen and Shonnard *Green Engineering* text and the nine green engineering principles to those taught in the specific course. The ultimate goal is to make it easy for a teacher, so problems are developed that link to a popularly used text. For example in the Material and Energy Balance module, Felder and Rousseau text, *Elementary Principles of Chemical Processes*, 3rd edition was used. The curriculum modules developed [8] have a wide assortment of problems (with solutions) that can be used by an instructor for in-class examples, cooperative learning, homework problems, etc. Each problem can be downloaded from the Web site and faculty that develop new problems for the courses they teach can upload problems as well.

Two to four problems have been developed for each main topic in each course and the majority of these problems have multiple parts. Most require a quantitative solution, while others combine both a chemical–principle calculation with a subjective or qualitative inquiry. The problems take a topic from a particular subtopic/topic (section/chapter) and then find a green engineering analog. Some cover specific terminology, principles or calculation covered in both texts, such as in the calculation of reaction conversion while others introduce concepts only covered in a green engineering venue. All of the problems have worked-out solutions and are set-up in an easy to follow way with units and calculations shown at all steps of the solution. The instructor can easily change the problems from year to year by changing process parameter values or chemical mentioned.

It is envisioned that the instructor covering a particular chemical engineering topic, like equilibrium-staged separation liquid–liquid extraction calculations, would be presenting some in-class examples or cooperative learning exercise. Instead of a generic type calculation that has no green engineering significance, the instructor could use the problem developed in this module. Not only would the student get the active experience of solving an equilibrium stage type problem, but a new concept from green engineering can be introduced. In this case, the student would learn about the concept of how a separation process is used in the reuse and recovery of materials (process mass integration) in a chemical manufacturing plant. Most of the problems are written in way to introduce this concept to the student taking information from the *Green Engineering* text so that additional lecture activity on the green engineering topic is not needed. Although the instructor may

Table 1. Green engineering courses modules available at www.rowan.edu/greenengineering

Module topic	Faculty developer	Affiliation
Introduction	Robert Hesketh	Rowan University
Freshman engineering	Kathryn Hollar	Harvard University
Material and energy balances	C. Stewart Slater	Rowan University
Thermodynamics	Wallace Whiting	University of Nevada-Reno
Heat transfer	Ann Marie Flynn	Manhattan College
Reaction engineering	Martin Abraham, Neil Schweitzer	University of Toledo
Material science and engineering	James Newell	Rowan University
Separation processes	C. Stewart Slater	Rowan University
Transport phenomena	Luke Achenie	University of Connecticut
Process dynamics and controls	Jim Henry	University of Tennessee-Chattanooga
Product/plant design	David Shonnard	Michigan Tech University
Life cycle analysis	Joseph Shaeiwitz	West Virginia University

wish to review the *Green Engineering* text section beforehand or assign reading of sections to students to accompany the problem.

If the problems are assigned as homework exercises, then the instructor can provide additional green engineering commentary in reviewing the solutions with the students. Alternately, the instructor may require the student to do additional reading from the green engineering text to accompany the homework exercise. It is encouraged that the instructor actively engage students in the learning process for both separation process concepts as well as the green engineering materials. The instructor may decide to use a selection of the problems developed in this module and mix them with other more general problems as listed or use all of the problems in the module.

Presenting a topic found only in the *Green Engineering* text is the most challenging integration of course material. For example, the concept of occupational exposure is introduced by having students perform a unit conversion with a dermal exposure equation. In a similar way, workplace exposure limits are introduced in the context of calculating concentration using mole and mass fractions. This helps optimize time usage and course flow, since as prior papers on various subjects have pointed out: to put in X, you need to take out Y.

By taking basic chemical engineering principles and designing a problem to introduce a green engineering concept, a unique integration of concepts occurs.

Some problems have additional questions that require students to investigate the literature, go to a Web site, or perform a more qualitative analysis of the problem. For example in the dermal exposure problem, the student must go to an EPA or related Web site to determine threshold limiting values and permissible exposure limits for other chemicals. Other such examples include selecting a more benign solvent for an extraction (solv-db.ncms.org), and then use that information in performing the calculation and comparing the alternatives. The level of green engineering material is also matched to the nature of the course. For example in a Freshman Engineering module only basic calculation methods and unit conversions using green engineering principles is appropriate, while in a Process/Plant Design module, life cycle analysis of alternate production paths could be done. The objective in an introductory chemical engineering course is to give students some familiarity with concepts that would form the basis for more substantial green engineering problems in subsequent courses such as transport, thermodynamics, reactor design, separations, plant design, etc.

A summary of where green engineering activities can be incorporated into a chemical engineering curriculum is given in Table 2.

Instructor's guides accompanying each module help a faculty member see where various green

Table 2. Integration of green engineering in the chemical engineering curriculum

Chemical engineering course	Green engineering topic
Freshman engineering clinic	Green engineering project drip coffee maker Introduction to environmental regulations Introduction to life cycle assessment
Sophomore engineering clinic	Life cycle assessment of a product Environmental regulations
Material & energy balances	Emissions terminology/calculations Green material and energy balances
Mass transfer/equilibrium stage separations	Mass separating agent Risk assessment
Material science	Estimation of properties Life cycle assessment
Heat transfer	Introduction to heat integration
Chemical thermodynamics	Estimation of chemical properties
Separation processes	Pollution prevention strategies Novel green separation process integration
Chemical reaction engineering	Pollution prevention strategies Green chemistry
Process/product/plant design	Heat integration & mass integration Flow sheet analysis Life cycle assessment
Process dynamics and control	Pollution prevention modeling and control
Unit operations laboratory	Green engineering experiments
Technical elective: design for pollution prevention	Heat and mass integration Process analysis
Senior engineering research / senior project	Real industrial projects in green engineering

engineering concepts can be integrated into the course topics. A matrix, tabular or index of topics is provided. This helps an instructor who may just want to add a couple of green engineering problems the first time they teach a course or coordinate green engineering curriculum integration with other faculty in a program and cover as many topics in a optimal way. Not every module covers all green engineering topics, but the mapping is done in a very generic way so that an instructor can see the general outline of the topics taught in a course and some of the general areas of green engineering concepts. Not all of the concepts covered in a course have a green engineering analog and vice versa. An example of how these topics map for several courses are shown in the following section.

To illustrate more clearly what these modules contain, the following examples drawn from several course modules that span the curriculum have are provided. Full details on the modules for other chemical engineering courses are available at the green engineering Web site (www.rowan.edu/greenengineering) [8].

Material and energy balances

This module is for introducing green engineering principles early in the chemical engineering curriculum, as the green engineering subject matter covered is introductory in nature [13]. Twenty-five problems were developed to introduce certain terminology or basic concepts that lay the groundwork for a more extensive incorporation of green engineering in subsequent courses. Problems were developed within the framework of a material and energy balance course and teach students about topics like workplace exposure routes/limits, recycle and recovery processes, green chemistry, combustion, mass and energy integration. The conceptual mapping of the green engineering material found in the module to a Material and Energy Balance course following the various chapters of the widely used text by Felder and Rousseau [14] is shown in Table 3.

Table 3. Conceptual mapping of green engineering topics in a Material and Energy Balance course

Green engineering topic	Material and energy balance topic (follows **Elem. Principles of Chemical Processes, 3rd**)
How green engineering is utilized by chemical engineers in the profession	Chapter 1. What Some Chemical Engineers Do for a Living
Unit conversions typically used in green engineering process calculations	Chapter 2. Introduction to Engineering Calculations
Various defining equations used in green engineering	
Typical method of representing concentrations of pollutants in a process (%, fractions, ppm, etc.)	Chapter 3. Process and Process Variables
Overall closing the balance of a chemical manufacturing process.	Chapter 4. Fundamentals of Material Balances
Balances on recycle operations in green engineered processes	
Green chemistry in stoichiometry	
Combustion processes and environmental impact	
Use of various equations of state in green engineering design calculations for gas systems.	Chapter 5. Single Phase Systems
Pollutant concentrations in gaseous form	
Representation and calculation of pollutant volatility using vapor pressure.	Chapter 6. Multiphase Systems
Condensation calculations (gas–liquid equilibrium) for vapor recovery systems.	
Liquid–liquid extraction balances for pollutant recovery systems	
Representation of various forms of energy in a green engineering process	Chapter 7. Energy and Energy Balances
Recovery of energy in a process—energy integration	Chapter 8. Balances on Nonreactive Processes
Use of heat capacity and phase change calculations.	
Mixing and solutions issues in green engineering	
Energy use in green chemistry reactions, combustion processes	Chapter 9. Balances on Reactive Processes
Overall integration of mass and energy balances in green engineering on a overall plant design basis	
Use of various simulation tools and specifically designed software for green engineering design	Chapter 10. Computer-Aided Calculations
Representation of mass and energy flows for transient processes with green engineering significance	Chapter 11. Balances on Transient Processes
Industrial cases studies of green engineered manufacturing processes, Intro to life cycle analysis	Chapters 12–14. Case Studies

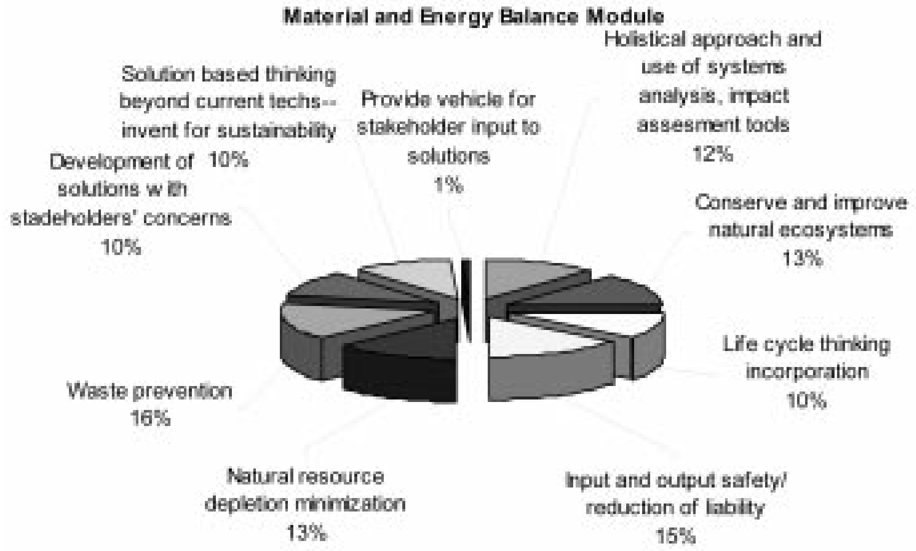


Fig. 1. Distribution on the problems from the Material and Energy Balances module among the nine green engineering principles.

The following graph, (Fig. 1) illustrates how the problems in this module distribute between the nine green engineering principles.

Material and energy balance example, Problem 1—Ecosystem risk measurement using lethal dose 50. (Felder and Rousseau Ch. 2.2, 2.3, 2.6; Shonnard and Allen Ch. 5.4)

Ecosystem risk due to chemical toxicity can be expressed in several ways. One of the expressions developed for the toxicity of fish to acrylate compounds is given below:

$$\log LC_{50} = -1.46 - 0.18 \log K_{ow} \quad (1)$$

where Lethal Concentration 50, LC_{50}, represents the concentration of the chemical compound that is lethal to 50% of the population over a 96-hour period. The constant, K_{ow} is the octanol–water partition coefficient, which depends on the chemical compound. This equation as written, solves for LC_{50} in the units of millimoles/liter.

(a) Write this equation to solve explicitly for LC_{50}.
(b) Determine LC_{50} (mM/liter) for fish exposure to methyl methacrylate, $K_{ow} = 1.28$.
(c) Write the equation to solve for LC_{50} in M/liter and μM/liter.
(d) What are other hazards related to methyl methacrylate release into the environment?

The solution to this problem helps introduce a fundamental green engineering metric to the students by using course material on unit conversions and dimensional homogeneity. This illustrates how a simple topic can have a green engineering problem created for it. In the solution, the instructor should introduce the concept of environmental metrics and describe some of the other frequently measured concentration parameters and their implication on the ecosystem. The problem also gets the students to go to another source (library or Web) to look up toxic release information on methyl methacrylate.

Material and energy balance example, Problem 2—Air quality problems resulting from the combustion of various fuels. (Felder and Rousseau Ch. 4.8; Shonnard and Allen Ch. 1.5, 9.2)

The combustion of fuels in power plants and industries has lead to several air quality problems. SO_2 is a common air pollutant formed from the combustion of the sulfur-containing fuels–coal and oil. SO_2 is generated as a result of power production from utilities and industrial processes. After being emitted in the exhaust or flue from the power plant, SO_2 can be transported into the atmosphere and transformed from a gaseous pollutant to liquid H_2SO_4 by various reactions. Thus so-called acid rain, which is a major air quality problem, can occur.

(a) Investigate the environmental consequences of SO_2 and acid rain.
(b) Propose some methods to reduce SO_2 in power plant emissions.
(c) The flue gas from an industrial power plant burning fuel oil that contains elemental C, H, N, O and S, has the following composition (mass %): 74.85% N_2, 10.31% CO_2, 9.10% H_2O, 5.15% O_2, 0.590% SO_2. Determine the composition of this stack gas on a 'wet' and 'dry' basis.
(d) Fuel oil is classified by grades, which have various commercial uses. Number 2 fuel oil is used for diesel fuels and home heating oil. Numbers 4 and 6 fuel oils are used in more industrial applications. Data from Perry's Handbook, 7th ed., Table 27–6 indicates that number 2 fuel oil contains 0.22% S and number 4 fuel oil contains 1.35% S (both on a mass basis). Compare these two fuel oils in the amount (kg) of SO_2 emitted from burning these at the same rate.
(e) Assuming that the power plant has a design option to burn natural gas as an alternate fuel, what environmental impact would this have?

This problem combines the analysis of combustion processes with the impact of sulfur-containing fuels on the environment. Sulfur content is a contemporary issue in fuel formulations so this problem has specific application to showing consequences related to ecosystem impact. The use of natural gas versus oil-based fuels in a comparison is also of interest is energy systems.

Separation processes

Separation process topics covered can be applied in a green engineering way in an overall role in pollution prevention such as in the reduction of by-products, waste minimization, emissions reduction, etc. The choice of the proper mass-separating agent from a green engineering standpoint for the particular industrial separation is a key criterion to be presented. Ultimately a separation course should present sound rationale for the green integration of separation technologies in a reuse/recovery mode where valuable material(s) may be recovered and reused in the overall process. These approaches should be applied in the discussion of design and application of the various separation methods to the system being purified, fractionated or concentrated. Separation processes courses also need to encompass a broad range of both traditional and novel unit operations such that a student can see the pros and cons in their application from a green engineering standpoint.

These problems can be used to accompany courses teaching separation processes in various courses. Some schools teach these topics in a Mass Transfer course covering some of the traditional separation processes of distillation, absorption and extraction. At many schools these equilibrium-staged processes are frequently grouped together in a course with suitable name. The problems can also be used to supplement courses in advanced separations or rate-controlled separations. Such as the membrane based operation problems developed for this module. Regardless of the type of course, text used, or curricular level, this module presents problems in many of the separation processes that can readily be integrated.

When each of these processes is discussed a particular problem or case study can be employed showing an application for material recovery/reuse or related pollution prevention. For example, reverse osmosis applications in pollution prevention, reuse/recovery and mass integration in a variety of manufacturing processes can be described. Reverse osmosis use in electroplating industry to recover and reuse purified water and recover and reuse concentrated plating metals is an excellent example from an environmental and economic standpoint, since both separated streams can be reused. For a more advanced topic, students can investigate the integration of a novel technology, membrane pervaporation, with a traditional separation, distillation, in azeotropic separation. A good design case here is replacing the entrainer benzene in ethanol–water separation with the pervaporation technique, since the potential release of benzene in the environment is removed. In the above cases, students can perform calculations to quantify the environmental improvements.

Separation processes example Problem 1—use of membrane pervaporation or molecular sieve adsorption in ethanol purification.

> As the new process engineer for Bio-Blend Co., you are asked to evaluate some planned upgrades to the ethanol plant that uses renewable feedstocks such as corn to make ethanol. A customer has been proposed to use a 10% blend ethanol in gasoline fuels. The final step in the purification of ethanol–water mixture involves the separation of ethanol at its azeotropic concentration. You are to provide an analysis of the operation from a technical as well as sustainable standpoint.
>
> (a) Determine the azeotropic composition at 1 atm? Plot the vapor–liquid equilibrium data.
> (b) Describes the benefits to the environment of using ethanol produced from renewable feedstocks such as corn.
> (c) Compare two methods for purification–entrainer-based distillation and either membrane pervaporation or molecular sieve adsorption for the final dehydration step.

The solution to this problem blends a traditional separation with an examination of a green-engineered separation process. The problem combines a traditional equilibrium staged calculation–determine VLE data for distillation of a binary mixture alcohol–water mixture, with an open-ended evaluation of alterative green separation processes. The problem challenges the student to examine alternative process technologies like pervaporation and pressure swing adsorption that minimize toxic material use (no entrainer) and minimize by-product flows. The problem can also use software and simulators to analyse alternative separation processes. Comparison of material and energy flows, first step in life cycle analysis on alternative manufacturing scenarios. The problem further integrates the topic of renewable resources as the overarching premise of the problem statement in the production of renewable fuels from corn. This problem is a good example of an upper-level course type problem that requires students to do more research on their own to develop the solution—more like a mini-project or design paper.

Heat transfer

This module was designed to introduce green engineering concepts into a predominantly design oriented heat transfer course offered to undergraduate chemical engineering students. Green engineering concepts were essentially incorporated into the course via a greened heat transfer homework problem set that had been developed specifically for this purpose. A total of 24 problems were generated to cover a variety of topics found in 13 chapters in the heat transfer text *Fundamentals of Heat and Mass Transfer* by Incropera and DeWitt [15] and have a universal compatibility with other heat transfer books as well. The problem set also incorporated key green engineering concepts found in the *Green Engineering* text [7].

Overall, each green heat transfer problem was divided into two parts. The first part focused entirely on significant heat transfer design concepts such as determination of conduction and convection resistances, calculation of overall heat transfer coefficients and design of standard heat exchangers such as double pipe, shell and tube and extended surface. The second part of each problem then examined the impact of that design on the environment, as guided by the nine green engineering principles [2]. For example, the first part of a typical problem would require the student to calculate the change in resistance to heat transfer that occurs when argon replaces air in standard replacement windows. The second part of that problem would then require the student to calculate the total energy savings that corresponded to the resulting decrease in heat transfer through the windows. In addition, because the greened heat transfer problems were divided into two sections, the instructor had the option of using two different approaches to incorporate green engineering concepts into the class. For example, based on the sample problem previously cited, the instructor would provide the class with the heat transfer resistances associated with air-filled windows and argon-filled windows and the class would then complete the second part of the problem by comparing the energy saved (or lost) and the total money saved (or lost) between the two windows over the life of the windows. The impact of this energy savings on fossil fuel usage reductions can also be explored. Table 4 lists the green engineering topics that have been incorporated into the various chapters in Incropera and DeWitt to produce the greened heat transfer problem set.

Heat transfer example Problem 1—Attic insulation. (Incropera and DeWitt: Ch. 3.1.3; Allen & Shonnard: Ch. 2.8, 6.2.5; *Green Engineering Principles*: Ch. 2, 4, 5, 6)

A homeowner has decided to renovate her home. Due to the rising cost of fuel her first priority is to insulate the attic. As of now, the attic has no insulation at all and the outer wall is made of brick (k = 0.72 W/m°C). The thickness of the brick wall is 5 cm.

The insulation will have a thickness of 11 cm. The homeowner has narrowed down her choice of insulation to either fiberglass (k = 0.036 W/m°C) or cork (k = 0.039 W/m°C). Once the insulation is installed, a 2 cm thick wall of sheetrock (k = 0.118 W/m°C) will be installed on the inside of the attic to cover the insulation. The average temperature outside in the wintertime is determined to be 10°C and the temperature inside the attic will be maintained at 21°C. Assume the inside wall temperature is equal to the room temperature. One wall of the attic is measured to be 7 m wide and 2 m long. The price of the fuel that operates the furnace heating the attic is \$0.03/ MJ (\$0.03/MW-s).

(a) How much heat was lost through the attic wall before the renovations took place? What is the daily cost of the fuel without insulation?
(b) How much heat is lost through the attic wall when using: (i) fiberglass insulation; (ii) cork insulation. What is the daily cost of the fuel for each type of insulation?
(c) Assume the homeowner did these renovations herself and decided to use the fiberglass insulation. She wore gloves on her hands, but had no protection on her arms and nothing covering her mouth. The mass fraction of exposure chemical in fiberglass is 0.5. Assume she installed one section of the fiberglass every half hour for 8 hours per day. What is the dermal exposure to her arms?
(d) What are the dangers of skin exposure and inhalation of fiberglass?
(e) How much difference in heat loss would have occurred had she used the cork insulation instead?

The example above is a typical chemical engineering heat transfer problem that shows quite simply how attic insulation decreases heat loss and increases savings—savings that can be easily adapted to engineering equipment such as a distillation column or a quartz furnace. This problem also addresses the trade-offs between cost, safety, use of renewable resources, performance of the product and toxicity when the more hazardous, low cost, low thermal conductivity fiberglass is compared to the less hazardous, more expensive cork.

Heat transfer example problem 2 – Double pipe heat exchangers and geothermal energy. (Incropera and DeWitt: 8.7; Allen & Shonnard: 1.8, 9.1; Green Eng Principles: 1, 5, 7)

Ground source heat pumps draw geothermal heat out of the ground by circulating an anti-freeze/water mixture through plastic tubing in the subsoil under and around your home. The geothermal energy drawn from this soil flows back through a water–heat exchanger and distributes the heat throughout the house. Consider a double-pipe heat exchanger, with water at 10°C that is to be heated by this antifreeze/ water mixture. The inlet and outlet temperatures of the antifreeze/water mixture remain constant at 150°C. The inner and outer tube diameters of the annular space are 5.0 cm and 8.0 cm, respectively. The water enters the tube at an average velocity of 2 cm/s. The length of the tube is 1.07 m and the outer tube is assumed to be perfectly insulated.

(a) Determine the temperature of the water leaving the heat exchanger.
(b) What are the advantages and disadvantages of using geothermal energy to heat your home?
(c) From an environmental perspective, what are the dangers of using antifreeze in the subsoil tubing below your home? Is there an alternative geothermal fluid that can be considered to replace the antifreeze that is more environmentally friendly?

The first portion of this problem, part (a), is a standard design question found in any heat transfer course. On the contrary, the second part of the problem, parts (b) and (c), are not. While geothermal energy is very common in North Atlantic countries such as Scotland and Sweden, it has yet to gain significant prominence in the United States

Table 4. Conceptual mapping of green engineering topics in a heat transfer course

Green engineering topic	Heat transfer topic (follows **Fundamentals Of Heat And Mass Transfer, Incropera and Dewitt, 5th edn)**
Recovery of energy in a process energy integration	Chapter 1. Introduction
Green engineering responsibilities for environmental protection	
Green engineering pollution prevention concepts	
Proper waste removal and pollution prevention	Chapter 2. Introduction to Conduction
Green engineering chemical exposure hazard assessments	
Global energy issues and the use of renewable energy	
Reducing the use and generation of hazardous substances	
Exposure assessment and modeling dermal exposure	Chapter 3. One-Dimensional, Steady-State Conduction
Responsibilities for chemical process safety	
Green engineering threshold limit values	
Water quality issues	
Conservation of natural ecosystems	Chapter 4 Two-Dimensional, Steady-State Conduction
Conservation of natural resources by energy savings	
The roles and responsibilities of chemical engineers—maintaining safe conditions for operating personnel	Chapter 5. Transient Conduction
Chemical process designs need to be protective of human health	Chapter 6. Introduction to Convection
Ethics—putting health, safety and environmental issues ahead of profits	
Global energy issues–oil and coal are non-renewable energy sources	Chapter 7. External Flow
Environmentally preferable pathways in chemical engineering	
Value of risk assessment in the engineering profession	
Air quality issues and diesel air pollution	Chapter 8. Internal Flow
Pollution prevention in material selection for unit operations	
Considering potential impact of human activity on the environment	Chapter 9. Free Convection
Life-cycle studies and product comparison	
Significance of melting and boiling points of various chemicals	Chapter 10. Boiling and Condensation
Global warming and ozone depletion in the stratosphere	
Environmental cause and effect chains	
Importance of recycling waste in pollution prevention	Chapter 11. Heat Exchangers
Process energy integration with heat exchangers	
The importance of integrating safety procedures into process designs	Chapter 12. Radiation: Processes and Properties
Calculation of octanol–water partition coefficients and volatility of chemicals	
Choosing alternative methods that generate less waste when designing a new system	Chapter 13. Radiation Exchange Between Surfaces
Choosing more energy efficient alternatives	
Incorporation of process mass integration	Chapter 14. Diffusion Mass Transfer

and this problem forces the student to at a minimum to educate themselves of the existence of geothermal energy and examine its positives and negatives.

Reaction engineering

The chemical reaction-engineering module was authored by Neil Schweitzer and Martin Abraham of the University of Toledo. Problems in this module have been linked to the content of chapters 1 through 9 in the textbook entitled, *Elements of Chemical Reaction Engineering*, 3rd edition by Fogler [16]. In addition the 4th edition of this book has a note highlighted by the symbol of a tree at the end of each chapter. The note reminds the reader that additional homework problems in green engineering can be obtained from the Rowan Green Engineering Web site. It is envisioned that in the next edition of the text each chapter will contain new green engineering problems within the text.

The synthesis of a process design represents a hierarchical decision process, in which the choice of a particular component impacts all other process decisions. The central feature of most chemical processes is the conversion of raw materials into useful products. As a result, the reactor design is one of the central tasks in the synthesis of a chemical process. The selection of design characteristics, i.e. reactor type, conversion, temperature, use of solvent, etc. dictate many of the remaining process considerations associated with separations and recycle, heat exchange and use of utilities. Thus, it is appropriate to consider the environmental impacts of a reactor design problem in the context of green engineering [17].

Numerous traditional topics of reaction engineering can be applied to green engineering. For example, in a parallel reaction scheme wherein one reaction leads to the desired product, the reaction temperature, the concentration of the reactant, or the reactor type can often be used to control the selectivity. Similarly, the incorporation of a heterogeneous catalyst can accelerate the rate of reaction or affect the reaction selectivity. An additional element of pollution prevention in reaction engineering is the development of new reactor separator configurations. We have developed a student project using a membrane reactor for the production of ethylene from ethane resulting in lower energy consumption requirements as well as higher conversion [18].

A final area in which green engineering can be emphasized in the reactor design class is the area of green chemistry. Here, one investigates whether a new reaction route can be identified that minimizes the possibility of worker or surrounding environmental exposure? Alternatively, the question could be asked, 'can one of the products be used as a raw material for another feed stream?' In order to introduce green engineering examples, many of the homework problems are based on green chemistry. In this matter the necessary concepts of reaction engineering can be taught as in a traditional course, but they will have an emphasis in green engineering.

Table 5 shows how several problems from the module that represent introductory topics can incorporate green engineering as well as reaction engineering topics using real-world examples. The module covers all nine chapters of the reaction engineering text presenting approximately two problems per chapter.

For an example of process intensification: in chapter 3 an example is given of process intensification in which reaction and separation occur in a single vessel. In this example, an equilibrium reaction is encountered in which the conditions are engineered to remove one of the products of reaction. In using process intensification, in which reaction and separation occur in a single vessel, minimizes the costs associated with the separation, decreasing the waste produced from the unused reactant and the energy impacts associated with the process. In this problem the product is removed by condensation by controlling the reaction vessel pressure.

For examples of green engineering using renewable resources: the use of renewable resources is a central concern within green engineering. In order to make use of these resources, new reaction schemes will need to be envisioned. One opportunity is to convert waste biomass to new chemical building blocks, such as ethanol. In this series of problems the cellulose in corncobs is converted by bacteria into ethanol. The first problem linked to chapter 4 is to determine the optimum sequence of reactors, which will optimize the conversion of cellulose.

The second problem is a reaction rate determination problem from actual reaction rate data [19]. Rate data from this reaction are provided and the student is required to determine a reaction rate expression. In chapter 7, Michaelis–Menten kinetics are used to fit the enzymatic reaction rate data cellulose from corncobs reacting with the saccharomyces cerevisiae bacteria.

Concerning hydrogen economy: another prob-

Table 5. Analysis of selected problems from the reaction-engineering module

Problem	Reaction engineering course element (Fogler text chapter)	Green engineering element (Allen and Shonnard text chapter)
Automotive catalytic converter	Sec. 1.4.3 describes the mole balance for the packed bed reactor and provides an example for a first order reaction.	Sec. 1.5 describes criteria air pollutants and begins to put the issue of pollution reduction into an appropriate context.
Aerated bioreactor lagoon	Sec. 1.3 and 1.4.1 describe batch and continuous stirred tank reactors and describe the methodology for deriving the reactor design equation.	Sec. 5.3.2 and 5.3.3 describes techniques for estimating the persistence of chemicals in aquatic environments and the biodegradability of chemicals. Once the rate of decay is estimated, the reactor design equations can be used to build a system to accommodate a specific waste stream.
Membrane reactor system	Sec. 1.2, the general mole balance, is required to complete a mass balance on this reactive system.	Sec. 9.4.3 describes the opportunities that can be achieved through process intensification and in particular, the gains that can be achieved by coupling a reactor and a separator to increase the efficiency of the process.
Reactor selection	Sec. 2.4 describes operations of reactors in series and the techniques needed for calculating the conversion from complex reactor systems	Sec. 9.3 describes the techniques that can be used for reactor selection, mostly in terms of the temperature and reactor mixing properties. The current example demonstrates this concept for reactors in series.

lem for chapter 8 shows students how hydrogen is produced from hydrocarbon sources. In this problem hydrogen is produced from a reforming reaction, which produces CO and H_2. Following this reforming reaction, the CO must be removed from the gas product, since it is a poison for the fuel cell catalyst. Water–gas shift chemistry is used for this purpose with an additional benefit that greater amounts of hydrogen are produced, as the reaction converts water to hydrogen as it converts CO to CO_2. The reforming reaction is appropriate for the conversion of biomass-derived resources, as well, with the same inherent problem with CO concentration. Thus, the water–gas shift reaction is essential for the production of hydrogen regardless of the raw material.

The reaction-engineering problem is to solve a multiple reaction scheme (three reactions) with the inclusion of an energy balance. The reaction kinetics are based on actual data [20]. In addition the water gas shift reaction is a reversible reaction, in which the equilibrium concentration is dependent on the temperature at which the reaction is performed. Also, if oxygen is present in the gas stream (as it usually is), CO and H_2 can be oxidized in competition with the desired water gas shift chemistry.

System dynamics and control

The problems in dynamics and control are in five sections and 24 problem statements. These sections are called Avoid Tank Spillage, Trouble in River City, Filter-Wash System, Aerator Mixer System and Paint Spray Booth Pressure System. The first section (Avoid Tank Spillage) contains a modeling example of the transients of liquid level in a storage tank. It presents a common engineering text modeling problem within a context of applicability to pollution prevention. This example is suggestive of how any of our common textbook modeling assignments can be framed in a green engineering context. We believe that any of the problems we assign can be couched in a green engineering context to the benefit of our students.

The other sections of this module have a unique feature of linking to a Web site where the student can run real experiments on pilot plant equipment and are interactive for the student. The problems in this section allow the student to perform on-line system identification, model fitting and design and testing of feedback controllers for the problems. The experimental equipment is on-line 24 hours a day, 7 days a week for student experimentation. There are three pilot plants now used in these modules. These are pilot plants for a sewerage treatment plant's filtration system and its aerator mixers and for the spray paint booths in a manufacturing facility. The message here intends to convey that the experiments that we run (whether through this site or in our own labs) are teaching tools that are applicable in all kinds of green-engineering situations. Similar to what was stated above, we believe that any of the experiments we assign can be couched in a green engineering context to the benefit of our students. An example problem for this section is given below for the filter-wash system in a sewage treatment plant.

System dynamics and control example problem— Flow control for a filter-wash system in sewage treatment.

Our POTW (Publicly Owned Treatment Works) sewerage treatment plant in Chattanooga, TN, has a large filter press to filter out the sewerage sludge solids in order to send the solids to the city landfill. The filtrate water is then processed further before returning to the Tennessee River. The filter press operates in a repeating batch mode. Between batches, the filter media and plates must be washed. The manufacturer of the press specifies that the water flow rate to the washing nozzles have to be maintained between 7 and 10 lb/min.

The flow rate of the wash water is maintained by a variable speed centrifugal pump. The motor driving the pump is a variable-speed motor. The speed of the pump is under feedback control to maintain the desired flow rate to the washing nozzles. The controller is a proportional-integral controller. A diagram of the pump, washing nozzles and control system is

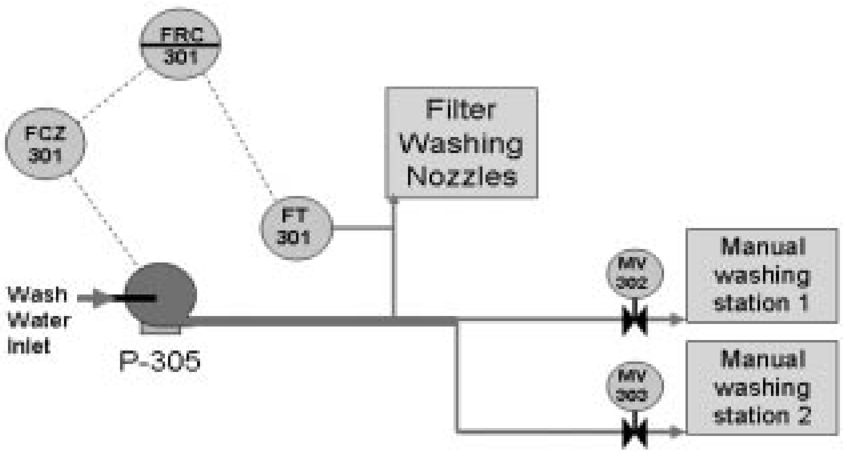


Fig. 2: Schematic diagram of the filter wash system.

shown below. Also shown on the diagram are two other manual or auxiliary wash lines that are used by operators in the plant to wash up spills when needed.

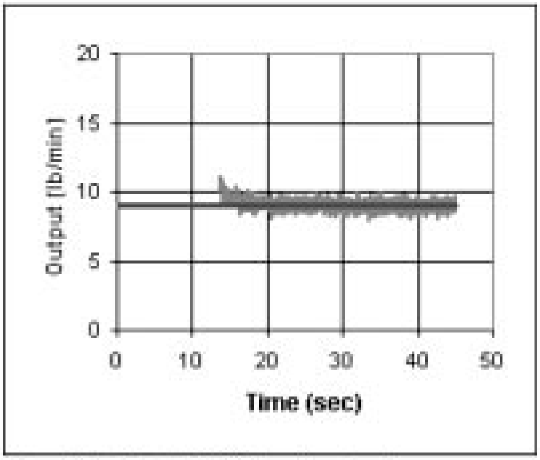
Operational situation: plant personnel have been happy with the system (including the control system) for years. Ever since plant start-up, we have been able to maintain the wash-water flow rate within specifications. Figures 3 and 4 are graphs of the wash water flow rate (sampled by FT-301) and Pump Speed (from FRC-301 output, expressed as %) under closed-loop feedback control for two recent periods.

The controller tuning parameters were set by installation contractor and have not been adjusted. The value of Controller gain is 4.0 %/lb/min; the integral (reset) time value is 1.0 s.

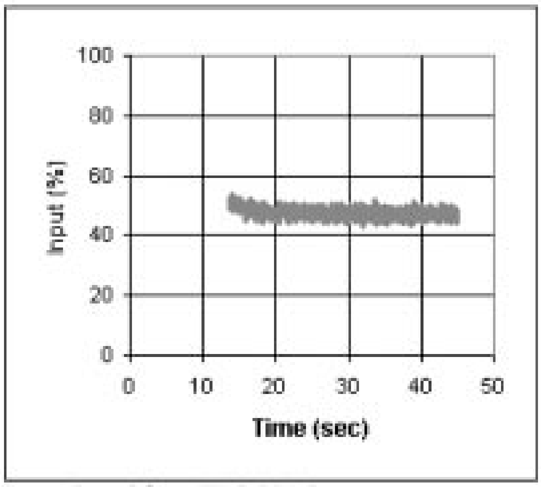
Unfortunately, with a recent improvement in operating procedures and equipment upgrades, we frequently have no need for either auxiliary washing station to be used. When neither auxiliary washing station is in use, our operators tell us that the wash-water flow rate is very erratic. The objectives of this assignment are:

(a) To observe the operation and behavior of the recommended design of a proportional control system.
(b) To observe the effect of the value of the proportional feedback gain, K_c.
(c) To observe the response to a closed loop controlled system to a set point change.
(d) To determine the ultimate gain and ultimate period for the closed-loop system.
(e) To tune the controller for critically damped response, quarter decay and at the limit of stability.
(f) To observe the response of the closed-loop system to one or more disturbances.

This problem is typical of a real control problem that may arise in an engineer's assignment in a green engineering environment. Process dynamics and controls is also an integral part of green engineering. Steady state or pseudo steady state processes are important in improving the efficiency and conserving resources for processes. Having a

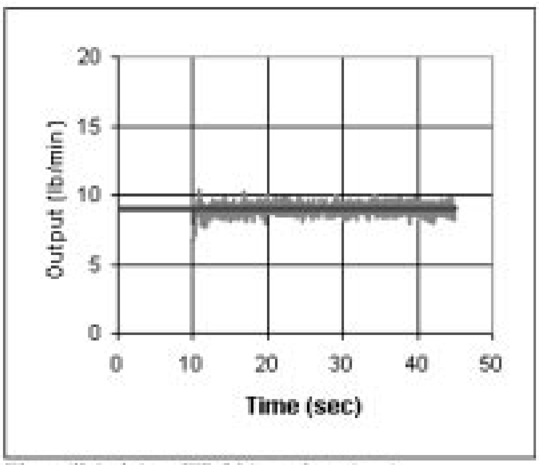


Flow (lb/min) at FT-301 vs time (sec)

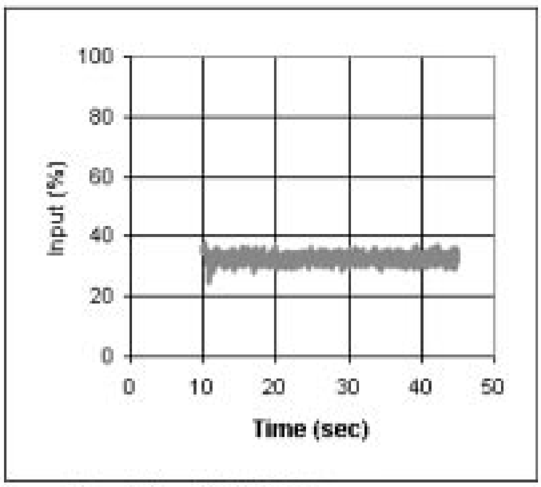


Pump Speed from FRC-301 Output

Fig. 3. Performance while 2 auxiliary washing stations are in use.



Flow (lb/min) at FT-301 vs time (sec)



Pump Speed from FRC-301 Output

Fig. 4. Performance while 1 auxiliary washing station is in use.

process 'in control' is critical in meeting many EPA requirements, such as the amounts of pollutants in air and water, decreasing the amount of waste in a process and not producing hazardous by-products in a reactor. The example problem was designed to show how various tuning parameters affect the flow rate for the pump over a period of time.

When a controller has improper tuning parameters, it will operate inefficiently which will lead to an increase in operating energy for the controller and also a waste in material. For this problem, improper tuning parameters will lead to the controller over adjusting the pump flow rate frequently, a waste of water due to rapid flow rate fluctuation and possibly improper cleaning of the filter. This example problem covers some of the green engineering principles described by Allen and Shonnard [7] such as waste prevention and conservation of natural resources.

ASSESSMENT

Faculty using these modules have continuously improved their content, modified and improved content and assessed their impact in various ways. Every program and/or instructor assesses their courses differently (as is true with the ABET process) and a representative example of an assessment method used by Manhattan College is presented here to show how one of the green engineering modules was assessed. Again, as with the majority of the green engineering modules developed this has applicability to other green/ sustainable areas as well.

The greened heat transfer problem set was first introduced to a class of 27 chemical engineering students in the fall semester of their junior year. Over the period of a 14-week semester students were given eight homework assignments–typically one week was allowed for completion of each assignment. Each assignment varied in length from one problem to five problems, depending on the difficulty of each problem. The students completed a total of 27 heat transfer problems over the course of the semester of which 11 problems (approximately 40%) were taken from the newly developed greened heat transfer problem set. A variety of assessment tools were used to evaluate the effectiveness of the greened heat transfer problem set as a technique for introducing green engineering principles into a predominantly design-oriented course. A complete analysis of the assessment is presented elsewhere but a summary is presented below [21].

Green engineering IQ—each student was asked to rate their own awareness of green engineering concepts on a scale of 0–10 at both the beginning of the semester and at the end of the semester after the students had been exposed to a range of greened heat transfer problems. Of the 27 students in the class, 25 students successfully completed the green engineering IQ evaluation. The results showed that the average green engineering IQ of the class at the beginning of the semester was 3.0 and more than doubled to 6.7 by the end of the semester. This was found to be a very simple, effective and useful tool by the instructor and will be used when the greened class is taught again.

Student evaluation of green engineering problems—each student was asked to evaluate the greened heat transfer problems that they were asked to complete on a scale of 0–10 with respect to how effective it was towards increasing the students green engineering IQ. The results showed that the greened homework problems taken from the early chapters (simpler and more fundamental) received lower ratings than the greened homework problems taken from the later chapters (more in-depth and complicated). For example, greened problems for early topics in Incropera and DeWitt tended to be very general and introductory in nature. Problem titles included: Green Engineering Responsibilities (Avg Rating = 2.2), Energy Savings and Environmental Awareness (Avg Rating = 3.3), Proper Disposal of Spent Fuel (Avg Rating = 3.4).

Student responses to these early problems in the green engineering analyses that was submitted at the end of the semester included: 'waste of time', 'only common sense', 'busy work'. The difficulty arose in the fact that early on in the semester, the students had little in the way of heat transfer design capability and the greened heat transfer problems tended to be qualitative in nature out of necessity. Overall, the ratings for the early greened problems were low and the comments were relatively negative. In contrast, the numerical ratings given to the problems that were distributed to the students towards the end of the semester were rated slightly higher by the students and garnered extremely positive comments in the green engineering analyses. For example, of the 27 students that submitted a green engineering analysis, 27/27 sited the 'rainforest' problem (Avg Rating = 5.1) as a favorite and 23/27 sited the 'argon-filled windows' as a favourite (Avg Rating = 4.7). Sample student comments included: 'inspiring', 'why can't all homework problems be like this', 'changed the way I think about green engineering', 'made me think I can make a difference'. As result of this assessment tool, the instructor will eliminate some of the earlier, more introductory green problems from the course when it is taught again.

Green engineering analysis—each student was required to submit a two-page written analysis of using the greened heat transfer problem set as a technique for introducing green engineering concepts into a design course. Each student was also required to cite specific greened heat transfer problems as examples. Student comments included:

> In my own experience with solving these problems I feel that I have gained a greater knowledge of what indeed green engineering is and they have influenced me to pursue a career in the green engineering field.

> Pollution exists in many forms and avenues of which people are ignorant. The green problems counteract this general lack of knowledge by introducing real-life situations in which the environment is involved. When considering the problems concerning the environment, ignorance is the greatest problem and knowledge is the greatest weapon.

This was also found to be a very useful tool by the instructor and will be used again when the course is taught in the future.

Course objectives survey—students were asked to rate the following objective: to develop an awareness of the concept of green engineering, to become aware of the impact that heat transfer and heat exchanger design can have on the environment. The results showed that 20/26 (77%) of the students rated this course objective as either excellent or good with respect to how the objective was met. 4/26 (15%) said that this objective was met 'adequately' and 2/26 (8%) said that this objective was met poorly. Overall, 92% of the students were satisfied with the outcome.

In addition to the instructor's assessment of the newly greened heat transfer course, a student task force was also set up to evaluate and assess the course and the following tools were used:

- student survey developed by the student task force;
  - section i: homework assessment;
  - section ii: topics for future homework problems;
  - section iii: classroom discussion and suggestions for course improvement;
- student forum;
- student task force assessment of instructor's proposed modifications to greened course.

The task force determined that five critical elements exist that should be part of any greened engineering design course. A detailed discussion of these five critical elements is presented elsewhere but a summary is presented below [22].

- Provide students with a very short, introductory green engineering text.
- Periodically test students on their green engineering knowledge.
- Include significant classroom discussion before and after green homework assignments have been completed.
- Assign group research projects based on green engineering concepts.
- Include green homework assignments that focus more on world issues and are industry based.

Based on the instructor's assessment and the assessment of the greened heat transfer course by the student task force, introduction of green engineering concepts into a predominantly design-oriented heat transfer course via greened homework problems was a success. Some slight modifications will be made in the future, but overall, the greened course will remain unchanged.

CONCLUSIONS

The engineer, as the designer of products and processes, also has a central role in designing chemical processes that have a minimal impact on the environment. We as educators can prepare our students to use the risk assessment tools of green engineering to design new processes and modify existing processes. As a result, green engineering could become a central component of the engineering curriculum. This paper presents some methods currently being used to teach green engineering within engineering programs. Examples in which green engineering is integrated throughout a curriculum as well as examples problems used in several chemical engineering courses are presented.

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