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Minimizing Environmental Impact of Chemical Manufacturing Processes

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Introduction

Knowledge of technologies and strategies for pollution prevention and the remediation of hazardous pollutants, as well as the environmental impact of pollutants that are released into the environment, is an increasingly important part of the average Chemical Engineer's job responsibilities. Therefore, in the Departments of Chemical Engineering at the University of Notre Dame, West Virginia University and the University of Nevada at Reno, we are implementing through courseware, research and design projects a program to 1) develop the students' appreciation of the impact of pollutant release from chemical processes and of the environmental, ecological and long-term economic benefits of pollutant minimization or elimination, 2) equip them with active knowledge of the technology that is being developed for minimizing the environmental impact of chemical manufacturing processes and 3) show students how this new technology can be implemented. The overall goal of this project is to incorporate the results of recent and ongoing research taking place at the three participating institutions, as well as elsewhere, on environmentally conscious chemical manufacturing processes into the chemical and metallurgical engineering curricula. This research includes pollution prevention, waste reduction, environmentally conscious chemical process design, and the modeling and assessment of the environmental and ecological impact of pollutant release.

The overall program includes the development of three new courses: 1) Environmentally Conscious Chemical Process Design, 2) Ecology and the Environment and 3) Environmental Flows. In addition, we are incorporating research results into instructional modules that are integrated throughout the chemical engineering curriculum, with a special emphasis on the design sequence. Information on the entire project can be found at : http://www.nd.edu/~enviro. In this paper we will discuss two aspects of the project: 1) the new course on Environmentally Conscious Chemical Process Design, which has been taught and tested at the University of Notre Dame and 2) new design projects that illustrate the minimization of the environmental impact of chemical manufacturing processes. Finally, we conclude with our methodology for assessment.

Courseware: Environmentally Conscious Chemical Process Design

Overall, our philosophy is that strategies for minimizing the environmental impact of chemical processes need to be included and integrated throughout the normal chemical engineering curriculum. However, there is also a need for a senior-level and introductory graduate-level elective course that focuses specifically on pollution prevention. The objectives of the course are 1) to educate students on the real costs of operating processes that release pollutants to the environment, 2) to provide them with strategies to minimize or reduce the environmental impact of a given chemical process, and 3) to examine the design of processes using new technologies that totally eliminate pollutants at the source.

The course includes four major components:

1. An introduction to the idea of waste elimination or reduction, and how pollution prevention differs from remediation. This introduction includes a discussion of waste inventories, life-cycle analysis and industrial ecology. The WWW is an excellent source of information on waste inventories, and several particularly useful sites are listed in Table 1. Also, we present some of the simpler procedures and process modifications that can be made to prevent pollution, such as reducing fugitive emissions and leaks and designing piping systems to drain by gravity so less solvent is need for flushing and cleaning. An excellent source for this material is the newly published book by Allen and Rosselot[1].

2. A discussion of the pertinent environmental regulations that impact the design and operating costs of chemical processes. Environmental regulations of particular interest include the Clean Air Act, the Clean Water Act, the Pollution Prevention Act, the Resource Conservation and Recovery Act, the Occupational Safety and Health Act, the Comprehensive Environmental Response, Compensation and Liability Act, the Emergency Planning and Community Right-to-Know Act, the Federal Insecticide, Fungicide and Rodenticide Act, and the Toxic Substances Control Act. These laws are the real impetus for the development of new technologies and waste management strategies and it is important that chemical engineers know their legal responsibilities. A nicely condensed version of these laws is available from the National Pollution Prevention Center[2].

3. A survey of current research efforts to develop alternative technologies that minimize waste or eliminate pollutants. Examples of some of the current research efforts that we used in the course include 1) new chemical routes to adipic acid, catechol and hydroquinone that use glucose instead of benzene as a starting material[3,4], 2) the use of supercritical CO_2 as a replacement solvent for reactions[5,6], 3) the generation of urethanes from amines and carbon dioxide,[7] and 4) the effect of mass transfer on the selectivity of catalytic reactions in a packed bed reactor[8].

4. Examination of a series of case studies that compare designs of conventional chemical processes to those using new, environmentally benign, technologies. This is the real core of the course and gives the students the opportunity to examine and optimize processes side-by-side to compare old technology to new, more environmentally friendly, technologies. The three case studies consist of ASPEN PLUS simulation models, with costing and economic evaluation, of the old and new technologies. Two of the designs use supercritical CO_2 as an environmentally benign replacement solvent for extractions. The first explores the decaffeination of coffee with CO_2 instead of via the "water process," which uses both water and methylene chloride for removal of the caffeine. There are now several commercial plants using supercritical CO_2 for tea and coffee decaffeination worldwide[9]. The second case study looks at soybean oil extraction with CO_2 and is based on the work of King and coworkers[10]. This process would replace hexane extraction, which poses both environmental and safety concerns. The third case study exploits some new chemistry developed by researchers at Monsanto[11,12]. By using nucleophilic aromatic substitution for hydrogen, they are able to eliminate the need for chlorine to activate benzene. For example, they are able to produce *p*-nitroaniline without proceeding through chlorobenzene, which is the standard technology. This third case study compares the processes using the old and new chemistries. These case studies are included in the descriptions of design projects listed in Table 2. The case studies are presented to the students in two parts. First, the processes are described to the students and they have the opportunity to develop the approximate process flowsheet themselves. Then, they are given an ASPEN PLUS model containing the basic framework of the process design and given the opportunity to investigate changing variables such as reactor or separator conditions, throughput, pollutant disposal costs, etc.

This course provides practical information, as well as exposure to the new technologies that are currently being developed for pollution prevention. With this course, the goal is for our graduates to become chemical engineering professionals who are equipped with the awareness, knowledge, and ability to minimize the environmental impact of the chemical manufacturing processes that they oversee.

Design Projects

Several design projects that emphasize new technology for minimizing the environmental impact of chemical manufacturing processes are being developed and tested in the required senior design courses at West Virginia University and the University of Notre Dame. Project characteristics include solvent substitution, waste water stream treatment, production of an environmentally-friendly replacement chemical, alternative, "green" reaction paths, and a less energy-intensive process. Some of the projects (i.e., the ones ultimately used in the Environmentally Conscious Chemical Process Design course described above) develop both the new technology and the conventional technology so that side-by-side comparisons can be made. A summary of the available projects is in Table 2. More detailed descriptions of these projects, as well as some reports and simulation files that can be downloaded, can be found on the project website at : http://www.nd.edu/~enviro.

Assessment

Assessment of the success of this program and its impact on student learning outcomes will be done in conjunction with existing assessment activities at all three universities involved in this project. An assessment plan has three components: (1) goals, (2) measures, and (3) feedback. The goals of this work are to give students an appreciation of environmental regulations and environmental consequences of chemical manufacturing processes, and for students to understand basic methods for minimizing environmental impact. The performance criteria that will be taken into consideration include understanding of a) the environmental impact of chemical engineering, b) the key regulations, c) the need for and methods for waste treatment, and d) the need for and strategies for waste minimization and pollution prevention. These skills will be developed in a) core chemical engineering classes that use companion problems, modules and lectures, b) elective courses, and c) sophomore, junior and senior level design projects. The measures of these goals will be slightly different at the three universities. In general, they will involve the development of portfolios of student work, faculty evaluation of student performance in classes and projects, student self-evaluation (in exit questionnaires and interviews), alumni questionnaires and employer questionnaires. Assessment instruments already in use at the three universities are being modified to include environmentally-related questions and additional components relevant to pollution prevention. Additional measures may be added as the project progresses. Finally, feedback will be given to the project principal investigators, as well as to other faculty who have been using the environmentally-related design projects and homework problems. This feedback will make faculty aware of the degree of success reached in achieving the stated goals of the project and facilitate continuous improvement of the project. In particular, feedback will provide the impetus for modification of existing course material, development of new materials, and modification of the students' experiences. Continuing assessment and corrective action will ensure that the goals of this project are achieved. We will report on assessment results in a future publication.

Summary

In this paper, we have described two aspects of an overall project to integrate the ideas, strategies and technologies associated with minimizing the environmental impact of chemical manufacturing processes into the undergraduate chemical engineering and metallurgical engineering curricula. In particular, we described a senior level elective course entitled Environmentally Conscious Chemical Process Design that emphasizes pollution prevention. In addition, we described a number of environmentally-related design projects that we have used in our capstone senior design courses. Finally, we have indicated how we plan to assess the impact of the new course materials, new courses and design projects.

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Biographical Sketches

JOAN F. BRENNECKE received her B.S. Ch.E. from the University of Texas at Austin and her M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign. Her research interests are in the application of supercritical fluid technology for pollution prevention and environmental remediation, spectroscopic methods and high pressure phase equilibrium.

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Table 1
Websites used in Environmentally Conscious Chemical Process Design Course

http://www.rtk.net/www.data/tri_gen.html	Toxic Release Inventory area, facility or industry searches
http://www.rtk.net/www.data/brs_gen.html	Biennial Reporting System area, facility or industry searches
http://ttnwww.rtpnc.epa.gov/naaqspro	National ambient air quality standards

Table 2
Summary of Design Projects Illustrating the Minimization of the Environmental Impact of Chemical Manufacturing Processes

Project	Type	Comments	Contact
Extraction of gingerol from ginger root using supercritical carbon dioxide	Solvent substitution	Batch extraction from ginger root, mass transfer modeling is key to extractor design to obtain contact times	Shaeiwitz
Decaffeination of coffee using supercritical carbon dioxide	Solvent substitution	Two processes, WVU: mass transfer modeling for extraction of caffeine followed by reverse osmosis to concentrate caffeine, ND: comparison of supercritical and conventional processes, nitrogen stripping to concentrate caffeine	Shaeiwitz or Stadtherr
Soybean oil extraction using supercritical carbon dioxide	Solvent substitution	Comparison of conventional and new processes	Brennecke
Removal of phenol from waste water stream using supercritical carbon dioxide	Waste stream treatment	Extraction of phenol from water followed by phenol recovery and carbon dioxide recycle	Shaeiwitz
Removal of phenol from waste water stream using supercritical water oxidation	Waste stream treatment	Phenol destroyed by oxidation in supercritical water as solvent	Stadtherr
Concentration of ethanol using supercritical carbon dioxide	Alternative, less energy-intensive process	Alternative to distillation, reduced energy costs so less fossil fuel use	Brennecke
Production of refrigerant R-134a	Environmentally-friendly replacement chemical	This is one of the processes currently used to manufacture the new refrigerant	Shaeiwitz
New route for production of *p*-nitroaniline	Alternative reaction path	Eliminates need for chlorine and chlorinated organics	Brennecke
Production of dimethyl carbonate	Alternative reaction path	DMC is a potential oxygenated fuel additive, it can also replace phosgene as raw material, alternative reaction path does not use phosgene as raw material for DMC	Shaeiwitz
Production of polyurethanes from dimethyl carbonate	Alternative reaction path	Phosgene replaced as raw material	Shaeiwitz