

A New Course in Green Chemistry and Benign Processing

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Introduction

The material and energy demands of modern society hinge critically on the viability and progress of the chemical and allied industries, which both provide consumer products and support other industrial sectors. The burgeoning world population over the past one hundred years, augmented by enhanced life expectancy and improved quality of life, can be tied to a significant degree to products of the chemical and allied industries. Unfortunately, the public perception of these industries is hopelessly negative for a variety of reasons, most particularly environmental issues. Consequently, the U.S. and world chemical industries are at a crossroads as we enter the first decade of the 21st century. Commodity chemical manufacture is migrating increasingly toward developing countries, where labor and raw material costs are low and negative public sentiment is tempered by economic gain. The U.S. and other developed countries are increasingly focused on higher-value specialty products such as pharmaceuticals, foods, cosmetics, electronics, and agricultural products where technology and new products drive the marketplace. Yet even as these changes shield developed countries to a degree, there is an increasing global voice that chemicals manufacture ought to have less impact on the world environment and that it moves toward long-term sustainability (e.g. without depletion of resources). Treaties such as the Kyoto agreement, which intend to set emissions limits on a worldwide basis, legislation in Europe regarding recycling, reuse, and alternate resources, and research programs in the U.S. directed at energy efficiency and bio-based feedstocks lend further impetus to the global movement to reduce waste and develop sustainable production.

The emerging focus on environment and sustainability has popularized terms such as “atom economy”, “eco-efficiency”, “E factor” and in particular “green chemistry” that define strategies and methods to develop sustainable processes, quantify waste generation, and implement the use of alternate resources. Although chemical engineering programs have been teaching material and energy balance right from the inception of the discipline, the emphasis on resource conservation, waste minimization and hazard reduction was not apparent. During the past two decades, spectacular progress has been made in understanding chemicals as molecules and the structure-activity relationships with reference to their properties which are exploited for specific end uses. As these concepts and their applications – which we term “green engineering”- infiltrate the chemical and allied industry, today’s engineering graduates must gain familiarity with and be able to apply them. Further, the paradigm shift within the U.S. from commodities to specialties

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requires a broader perspective of process chemistry and global aspects of the industry than has traditionally been part of an undergraduate engineering education. In response to these changes, we have developed a new interdisciplinary course at Michigan State University that focuses on process chemistry and processing strategies leading to a clean, sustainable chemical industry. As described herein, the course provides a broad knowledge base of the existing chemical industry and the new directions the global industry is taking regarding sustainability and waste minimization. More importantly, the course provides a suite of tools such as life cycle assessment, green chemistry principles, atom economies, and economic evaluation that can be applied universally. Equipped with the information and skills from the course, the graduating engineers will have the ability to make immediate contributions to their company's efforts in this area.

Course content

Process chemistry- A major emphasis of the course is developing a strong basis of industrial process chemistry and catalysis. Knowledge of process chemistry, including stereochemistry, chirality vis-à-vis named reactions is important to understand both energy requirements and waste generation, and also to provide the capability of generating potential novel reaction pathways that improve overall sustainability. Here different types of selectivities and the possible role of retro-synthesis with reference to feedstock is brought out. The petrochemical industry is first reviewed, emphasizing traditional C₁ – C₄ and aromatic building blocks for producing commodity chemicals and polymeric materials. Next, a number of industrially important reactions (hydrogenation, condensation, esterification, oxidation, alkylation, acylation, nitration, etc.) and the catalysts materials that accelerate them are examined in order to provide the student with a basic understanding of manipulating molecules. After that, the chemistry involved in manufacturing a number of specialty products is examined in the form of case studies, most often to facilitate comparative analysis of sustainability and waste generation.

Principles of green engineering- Engineering students must take with them not only knowledge of process chemistry and catalysis but tools useful in designing benign and sustainable processes. We thus invest considerable effort in presenting principles of life cycle assessment (also known as “cradle-to-grave” analysis) to set forth concepts of including all possible energy and raw material requirements and accounting for all processing wastes and ultimate product disposal. We also examine atom economy, which is a means to quantify the chemical efficiency by which a product is formed, and quantification of waste generation from all sources. Students are required to apply the twelve principles of green chemistry (1), first proposed by Anastos, to the design of one or more “greener” processes. Underlying all of this is a careful and thorough inclusion of catalysis and reaction engineering principles that elevate the technical content of the course. Another aspect covered is the integration of different plants on a site wherein an unavoidable waste generated in a so-called green process, becomes a feed for another with value addition, thereby making the entire site “greener”.

Biobased feedstocks - Fueled by the projection that worldwide petroleum production will peak sometime around 2020 and thereafter decline, the prospect of alternative sources for fuels and chemicals is gaining prominence and is beginning to be realized commercially. As the logical

source of most existing process chemicals, renewable biomass feedstocks are extensively discussed in our course. Both crop-based materials (corn, grains, soybeans, etc..) and woody or

herbaceous cellulosic biomass (wood, switchgrass, etc.) are examined for their potential in chemicals production. Comparative economic evaluations are done between crop-based feeds, cellulosic feeds, and petroleum and coal, both in the current economic scenario and in the future based on projections of availability, new technology, and applications.

Case studies – Once the basic principles of the course have been described, classroom discussions and student involvement center around case studies and examples of a number of processes. These case studies may involve comparison of traditional, petroleum-based routes with proposed or available bio-based routes; they may involve two petroleum-based routes, one of which offers substantial waste reduction or improved product yields or properties; or they may involve development of an entirely new, green product and evaluation of how it will compete with existing products in the marketplace. These case studies often form the basis for student assignments and projects, and bring the above “green engineering” principles to life. All important industries are covered and the students are given assignments to develop a “speculative” green process for a chemical and justify their choice of the route with reference to available laboratory studies and market forces. Although no attempt is made to cover a plethora of environmental legislation to define “acceptable” emissions, the important aspect taught to the students is that whether zero material waste and zero energy processes could be developed which are inherently safe and environmentally benign.

Course presentation

Both undergraduate and graduate students in chemical engineering and chemistry take the course as an elective in their programs. The course presentation consists of three lectures per week. In addition to the primary instructors, at least three other faculty members give lectures on their particular area of interest over the course of the semester. Thus, in addition to being a valuable resource for students, the course brings together faculty who have common interest in green processing and bio-based feedstocks and provides a forum for discussion of ideas and concepts.

Students are assigned a number of homework problems over the course of the semester, many of which are focused on comparing one technology or raw material with another. They are also asked to complete two projects during the semester, for which they submit a written report and present at least one oral report.

Conclusions

We have developed a new interdisciplinary course that provides students an introduction to emerging principles of green engineering. The course differs from prior industrial chemistry courses in that the emphasis goes beyond simple chemistry to philosophy and methodologies for assessing the overall impact that the industry has on our society and our environment. We involve significant technical content in the course, particularly related to reaction engineering and catalysis of chemicals manufacturing. The interdisciplinary team of instructors, with international perspective, gives students a unique view of the chemical industry on a global basis.