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Educating Chemical Engineers in Product Design*

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Historically, chemical engineers have worked on continuous chemical processes that run 24 hours per day for most of the year, characterized by large units such as distillation columns and reactors. The capstone design class has traditionally involved design and economic analysis of such a process. However, the future of chemical engineering may not be in the traditional, large, continuously operating chemical plant. Rather, the future may be in the development and design of what can be termed chemical products. To introduce students to this new paradigm, a capstone experience involving chemical product design was implemented on an experimental basis. The results were three designs, involving either application of chemical engineering principles to a new technology or the design of a device using chemical engineering principles. Assessment results suggest that this experiment was successful and that students appreciated the unique design experience.

INTRODUCTION

CHEMICAL ENGINEERS have always been masters of their universe. Historically, the vast majority of jobs have been in the petroleum refining and chemical manufacturing (petrochemical) industry. In general, this involved working with chemists and also with engineers from other disciplines. However, the few non-chemical engineers working in chemical plants generally had subordinate roles such as instrumentation, mechanical systems, and waste management. As a result of this culture, the typical capstone experience for an undergraduate chemical engineer has been to design a chemical process, usually a well-known one. In most cases, this chemical process was designed to run continuously and to produce chemicals that were either used elsewhere in the same company or somewhere else within the petrochemical industry. The 'product' of the design was a chemical process to manufacture a well-known, commodity chemical. The specifications for the chemical produced by the process were well defined by the unit operations under control of the chemical engineer. The chemical engineer's role was disconnected from the ultimate consumer.

There is a new paradigm evolving for chemical engineers. There are few new chemical plants being built in the US. Those that are being built in developing countries are often designed and staffed by local personnel. There will always be a demand for chemical engineers to work in existing chemical plants. However, there is a strong argument to be made that the future of chemical engineering is in chemical product design. Chemical products may be defined to include new chemicals (e.g., new drugs), new devices (e.g., fuel cells), and new technology (e.g., new software). Informal studies have shown that the number of students taking jobs with companies that manufacture chemical products is on the rise [1].

Among the technical issues with which chemical engineers must become familiar are batch processing, identifying customer needs, evaluating alternatives, estimating the cost of a prototype, manufacturability, and estimating the cost of a product once it is mass produced. The inclusion of non-chemical engineering technology in a chemical product design is also a necessity. While these issues may be familiar to other engineering disciplines, they are foreign to the traditional chemical engineer.

Therefore, it is valid to ask how (or if) chemical engineering education will respond to this changing paradigm. In this paper, the experiences of our program's attempt to introduce product design in the capstone class are presented.

CHEMICAL PRODUCT DESIGN BACKGROUND

Cussler and Moggridge [2] define four types of chemical products. They are:

- new specialty chemicals;
- products whose microstructure rather than molecular structure creates value (e.g., paint);
- devices causing chemical change (e.g., a blood oxygenator or the electrolytic device described later in this paper);
- virtual chemical products (e.g., software to simulate chemical processes or estimate physical properties).

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In this paper, a fifth category of chemical products is included:

- technology that uses chemical engineering principles.

We define one possible framework for the product design process [2]. It contains four steps:

1. Identify customer need.
2. Generate ideas to meet need.
3. Select among ideas.
4. Manufacture.

This framework for product design is similar, but less detailed, than other such models [3, 4]. Cussler and Moggridge also suggest that one key difference between process design and product design is the entrepreneurial skills required of the engineer in product design. In process design, the decision on what to manufacture does not usually involve the process engineer. He or she usually focuses on the calculations and engineering judgment necessary to design and to optimize the process and/or keep it running smoothly and efficiently. In product design, a combination of business and technology skills is required. The engineer shares responsibility for identifying the product and for its design and manufacture. The responsibility for identifying the product may be shared with those with business backgrounds, and the responsibility for its design and manufacture may be shared with other types of engineers. This is the type of interdisciplinary effort that companies now require.

If product design is to be a component of the undergraduate chemical engineering curriculum, it will be necessary for both faculty and students to broaden their horizons. Faculty and students will have to interact more with those outside their discipline. This includes those with business backgrounds as well as other engineers. Part of the paradigm shift clearly involves the need for more interdisciplinary interactions.

CHEMICAL PRODUCT DESIGN IN A CAPSTONE CLASS

As an example of trying to broaden students' horizons and make them aware of the changing roles of chemical engineers, in our capstone design class in chemical engineering at West Virginia University, we have used chemical product designs for the previous two academic years. One goal of this student assignment was to give students an experience in chemical product design. A second goal was to determine whether chemical product designs could be used successfully as capstone projects. The framework for the student assignment was our unique, year-long design experience led by a student chief engineer [5]. In this case, a group of 14 students under the direction of one student selected as a chief engineer was given the very open-ended assignment of identifying product design opportunities. The goal for the first semester was to identify as many opportunities as possible and then progressively narrow the field until one or more would be selected for design during the second semester. Faculty played roles in this assignment, and one of us was the 'client' (JAS), and the other was the 'vice-president of the students' company' (RT).

With reference to the product design framework discussed earlier, the students were required to complete the first three steps during the first semester and the fourth step during the second semester. Because the students were not working for an actual company, some liberties were taken with the definition of the customer. The client was the customer, but the client's company had no specific business. Instead, the client was a venture capitalist looking for opportunities for investment. Therefore, it was incumbent on the students to determine the potential need (customer base) for their ideas and sell these ideas to the client.

Students were given a limited background on product design. The basics were introduced at a level of detail roughly equivalent to the 'Chemical

Table 1. Product designs recommended by students

Product	Notes
Chlorine alternatives in pools	device to convert salt to chlorinated disinfectant
Magnetic refrigerator	based on magnetocaloric effect—no compressor
Zebra mussel control	removal and control of mollusks that foul water intake pipes in water treatment plants and power plants
Removal of silver by chitosan	using crustacean shells as adsorbent
Peptide production	production of kilogram quantities of peptides from amino acids
Starch-based polymers (polylactic acid)	novel product—biodegradable polymer
Ethanol-water separation using molecular sieves	method to purify past azeotrope
Asbestos removal system	filtration system to remove asbestos continuously from air
E. coli detector	on meat packaging to determine freshness
Additives to assist in garbage decomposition	enzymes, proteins, etc.
Medical disposal device	furnace to convert stainless steel needles to recyclable metal
Geothermal heat pump	home heat pump using geothermal temperature difference
Anti nerve gas injection system	automatic sensor that commences injection when nerve gas detected
Natural pesticides	naturally produced chemicals derived from plants like tobacco
Fuel cells	for cars, etc.

Product Design Background' section above. They were also provided with references 1 and 2. There were weekly client meetings, which are a standard feature of this capstone experience [5]. For the first few weeks, these meetings were used to clarify, or at least narrow, the definition of product design, determine which of their ideas qualified as product design, and suggest product design ideas for their consideration.

The student group generated over 100 ideas within the first month or so of the first semester. Many of these ideas were the result of brainstorming activities and were rejected rather quickly. By the midpoint of the first semester, 17 ideas were recommended by the students for further study, and 15 of these ideas were chosen by the client for further evaluation. These are listed in Table 1, with a brief description of each. After further evaluation, at the end of the first semester, the students recommended 7 ideas for complete designs, and these are shown in bold in Table 1. Three were chosen for complete designs, and these shown are in bold and italics in Table 1. The group of 14 students was subsequently sub-divided into three smaller groups, or teams, for the product designs, which were completed during the second semester. Each team had a leader, and the chief engineer was responsible for coordinating all three designs and representing each team to the client.

The eight ideas that were not recommended for complete designs were in that category because students determined either that these products were already readily available or that sufficient information did not exist in the open literature for a complete product design. This latter reason was the primary consideration for selection of the three products for final design. It was determined that sufficient information was available for a design, and that experiments would not be needed to determine key parameters.

A short description of the three product designs is presented below. Detailed descriptions of all of these products may be found on our website [6].

1. Zebra mussels are mollusks that attach to water intake pipes to power plants and water treatment facilities. They attach in the veliger stage (infancy) when they are of microscopic size and then grow to maturity while attached to the wall. Zebra mussels were first introduced into the United States in 1986. They were discovered in the Great Lakes, and their most likely source was the ballast water of ships coming from Europe. Their arrival became notorious when water intake pipes all over the Great Lakes region started becoming clogged with their masses. It has been determined that a 4.5 ppm aqueous alkylbenzyldimethylammonium chloride can be used for a one-time kill of zebra mussels, and that continuous addition of 3 ppm hydrogen peroxide inhibits further infestation. A grating was designed for the water intake pipes to deliver these chemicals. The project also included design of the pumping system and an analysis of the turbulent fluid mechanics at the injection point to ensure complete coverage and adequate dispersion/mixing of the injected chemicals.
2. The salt chlorination device uses an electrolytic cell to electrolyze salt into hypochlorous acid, the active pool disinfectant. This device eliminates the almost daily requirement to add chlorinated chemicals to a pool. It also reduces the chlorine smell because the device is in the 'pump room'. Additionally, the bleaching and irritating effects of chlorine in the pool are diminished because the hypochlorite is concentrated only near the electrolytic cell. It either does not exist within the pool or its concentration is much lower in the pool. In this project, the electrolytic cell and the pumping system were designed. An interesting feature of this design is the need to quantify the cost of convenience of such a device. The question is how much will a home or commercial pool owner be willing to pay for the convenience of not having to deal with adding chemicals on a daily basis. Clearly, this is a marketing issue that cannot be answered without customer surveys.
3. Magnetic refrigeration is based on the magnetocaloric effect. This effect is defined as the response of a solid to an applied magnetic field, which is manifested as a change in its temperature. This effect is obeyed by all transition metals and lanthanide-series elements. When a magnetic field is applied, these metals tend to heat up. As heat is applied, the magnetic moments align. When the field is removed, the metal cools down as the magnetic moments become randomly oriented. The main difference between a magnetic refrigerator and a conventional refrigerator is that the magnetic refrigerator needs no compressor, the most inefficient and expensive part of the conventional gas compression system. In place of the compressor are small beds containing the magnetocaloric material, a small pump to circulate the heat transfer fluid, and a drive shaft to move the beds in and out of the magnetic field. The heat transfer fluid used in this process is water mixed with ethanol instead of the traditional refrigerants that may pose a threat to the environment. One aspect of this design is the need to move two beds of this material continuously in and out of a magnetic field. The device for switching the beds requires a pulley system, which was unfamiliar to chemical engineers. While the costs of all components could be estimated, students were unfamiliar with methods for estimating the cost to assemble a prototype, the wear and lifetime of moving parts, and the cost of mass production. However, they were able to find information on the cost of mass production in the industrial engineering literature. This would have been an

excellent project for an interdisciplinary team; however, we did not understand this until the project was almost completed. Clearly, faculty education is also a key component of the paradigm change.

Another example of a chemical product that students worked on for the 2000–2001 academic year was potential applications for fuel cells. Anyone who has ever used a laptop computer where there is no source of power has probably, at one time or another, been frustrated by a battery that has run out before the desired work was completed. However, does this mean there is a need for a longer-lasting power source? Or will this be a high-end, niche market? Consider the situations when one uses a laptop computer for long periods of time away from a power source. One of the most common situations is on an airplane. However, newer aircraft, are now being fitted with power connections at every seat. As older aircraft are replaced or as they are modernized, will all aircraft used for longer flights have power available? If so, this could diminish the need for a longer-lasting power source, especially one that might require new technology and be costly. This is one of the reasons that we did not pursue this application for fuel cells.

Issues in chemical product design implementation

Clearly, these are unusual projects for a capstone chemical engineering class. They involve application of chemical engineering principles, but the applications are different from those students might expect and different from the experience of most faculty members.

The obvious question is how to foment the paradigm shift to break the historical barrier of chemical engineers as masters of their own kingdom. Faculty will have to be convinced to alter the emphasis of their courses; however, the time commitment to change what has been done for many years is always a barrier. For faculty willing to commit to the change in emphasis, it will probably be easier to educate students. They can be given the opportunity to work on interdisciplinary design problems with other engineers or with those in the business school. Or, they can be given design problems that make them wish they had other engineers or business majors to work with, because they are forced to teach themselves material from the other disciplines. These are two potential methods to educate students with different beliefs about the role of the chemical engineer so that they will be able to function in the changing chemical engineering environment. The former is ideal, but the reality of interdisciplinary barriers at universities is an impediment. The latter may be a useful alternative. It has the advantage of changing attitudes, but the resulting design may not be as complete as it might be.

In retrospect, all three of these projects would have been excellent opportunities for multidisciplinary team experiences. As was described for the magnetic refrigerator, there were aspects appropriate for mechanical and industrial engineers. The salt chorination device would have benefited from contributions from a chemist. The zebra mussel project would normally have benefited from the contributions of a biologist; however, it turned out that one of our students, who was the source of the idea, was already expert on zebra mussel biology from a high-school science project. It is also likely that any product design project would benefit from team members with a business background. Chemical engineering departments or engineering colleges wishing to implement a multidisciplinary design experience may wish to consider product design projects for this purpose.

ASSESSMENT

We believe these projects to have been a success; however, we were unsure of this outcome until late in the second semester. The assignment on the year-long project is always very open-ended, but this assignment was more open-ended than usual. Given the novelty of these projects, our level of discomfort was equivalent to that of the students early in the project. Normally, we go into one of these very open-ended assignments with at least one idea for a project direction, though we expect that students will identify many additional feasible alternatives. In the worst case scenario, the client can drive the project toward that default option. In this project, the students deserve credit for pulling these projects together. It was particularly satisfying that, for all three projects, they identified an objective function and decision variables to do optimization, even though these functions and variables were different from those usually used in traditional process designs.

After the final presentation, the group was interviewed and asked how they felt about having done this project instead of a more traditional chemical process design (as had been done by their peers in the other half of the class). All felt it was a positive experience. Their opinion is best summarized by one response: 'It was certainly more interesting than doing another process design.' This is a reflection of the design orientation in our curriculum, in which students had already completed a traditional process design in the sophomore and junior years and worked on different aspects of a traditional chemical process in another portion of the senior design class [7, 8].

CONCLUSION

A capstone experience involving chemical product design has been described. This is a unique experience for chemical engineers who are not normally involved in designs in which customer interactions are necessary. If it is true that more chemical engineers will become involved in product design in the future, a paradigm shift in the content of capstone design classes will be necessary. Faculty will have to be re-educated, and students will have to be educated differently. This involves working with different types of processes and possibly a wider variety of professionals, incorporating their expertise into the design process. It will certainly be interesting to see if and how this paradigm shift evolves.

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