Integrating Chemical Engineering into High School Science Classrooms

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Abstract

Engineering and Engineering Technology education are essential today and influence almost every aspect of our society. Yet, engineering enrollments and engineering degrees continue to decline nationwide. The Pre-Engineering Instructional and Outreach Program (PrE-IOP) seeks to enlarge the future pool of qualified high-tech workers, including those who have been historically underrepresented (minorities and women). This is being accomplished through two components:

1) The implementation of pre-engineering curriculum in middle and high schools.
2) A comprehensive information campaign about the rewards of engineering and technology professions.

A chemical engineering curriculum module has been designed to create connections between the science used in engineering applications in the modern workplace and the high school science classroom. Chemical engineering concepts are selected that support the topics taught in high school science and are the basis for the design of an industrial plant. Also, the materials are meant to fit the instructional classroom needs of high school teachers by addressing the state content standards. The adoption, adaptation and where necessary the development of appropriate pre-engineering curriculum for use in high school science classrooms is being accompanied by sustained, long-term teacher training and support. Summer institutes, with hands-on workshops are designed to familiarize the teachers with the curriculum and the associated pedagogy. Evaluation includes the teacher training, and the implementation of the curriculum materials.

Introduction and Background

The number of students selecting engineering is declining, nationally and in New Jersey, while our society's need for engineering and engineering related professionals is rising. For instance, the United States Department of Labor forecasts that new science, engineering, and technology jobs will increase significantly by 2010[1], increasing over 50%. According to the National Science Board, new engineering, technology and science jobs will increase at almost four times the rate for all occupations[2]. The rising demands on these professions, caused by a rising population in a fixed environment, represent a major problem for all worldwide societies.

There has been a growing interest by higher education institutions to bring engineering and technology principles and applications to the secondary grade level classrooms. Most of the programs for teachers have included training and curriculum development that integrates engineering design applications with scientific principles.[3-18] One reported teacher training program has included web-based support beyond the in-person workshops.[10] Some outreach programs have focused on specific engineering disciplines.[9, 11, 17-20]

The Pre-Engineering Instructional and Outreach Program (PrE-IOP) has been initiated to enlarge the future pool of qualified high-tech workers in New Jersey, including those who have been historically underrepresented (such as minorities and women). A collaboration of the Newark College of Engineering of New Jersey Institute of Technology and the Institute's Center for Pre-College Programs, this comprehensive program has two major components. The Instructional component, under the auspices of an Education and Training Institute, includes the adaptation and/or development of pre-engineering curricula for use in middle and high school science and math classrooms and the provision of summer institutes for teacher professional development.[3] The Outreach component involves the implementation of an "Engineering the Future" outreach program and the formation of alliances with three groups of stakeholders: educators, counselors and parents.[21]

Science courses can provide the opportunity to generate an interest in engineering and technology. A study of science and technology should be intended to help students develop abilities associated with technological design and problem solving. The instructional component includes the development and implementation of what we call Curriculum Integrated Modules. These modules are adaptations, enhancements, or newly developed units, meant to create connections between the science and mathematics used in engineering applications in the modern workplace and standards-based science. The curriculum materials are designed to fit the instructional classroom needs of grades 6-12 teachers by addressing the content standards in science, mathematics and technology. They focus on teaching the pre-engineering skills of design and problem solving needed to convey the skills and knowledge required for successful admission to undergraduate engineering education programs. Summer institutes are designed to familiarize the teachers with the curriculum and the associated pedagogy. Appropriate follow-up and support, both in-person and electronic, are provided during the school year.

Training teachers is considered a critical element in the successful implementation of curriculum modules.[22] First, they must see how the integration of principles of engineering and design into their teaching practice is a vehicle that can help their students learn the skills and knowledge of the standards. In addition, the teachers must be exposed to engineering principles and design in formal classes if this integration is to be institutionalized in the curriculum for the time beyond the training period. Teacher training programs and curriculum development have been implemented with the emphasis on engineering design, and on specific engineering disciplines including electrical[9] and mechanical[11, 19] engineering.

But the creation of connections between the science used in engineering applications in the modern workplace and standards-based science is perhaps best seen in the relationship between chemical engineering and high school science instruction.[17, 18, 23] Most of the principles of chemical engineering have applications in chemistry, physics, and mathematics. By using these connections, students can select and retrieve from the acquired science concepts those that are relevant to the given problem, to be able to assemble the concepts, and then to apply them to solve the problem. For example, the chemical engineering topic of material balances can be directly related to the study of chemical stoichiometry, introduced in high school chemistry. The study of stoichiometry is greatly enhanced by applying species, molar, and element balance techniques to batch and flow processes. Solving the species balance for processes can extend the students' capability for solving single-unit design, and allows them to explore the design of processes that are environmentally responsible right from the beginning of the design. A consideration of gaseous processes can provide students with an introduction to the behavior of ideal and real gases (concepts taught in both chemistry and physics courses). Students then can gain an understanding of how process variables and properties are affected by the nature and properties of ideal and real gases. The connections between the scientific concepts and engineering applications are the focus of this paper.

New Jersey Institute of Technology (NJIT) is an inner city, urban institution located in Newark, New Jersey with a social, economic, and academically diverse student body consisting of approximately 5800 undergraduate and 3000 graduate students. NJIT has a long history of outreach programs for elementary through college level students. The Center of Pre-College Programs had its origins with faculty in the Department of Chemical Engineering and Chemistry. The Center offers initiatives and programs designed to increase educational opportunities for inner-city youngsters, and to improve the quality of education at the elementary and secondary grades in the City of Newark, and its environs.[24] Since its inception, the Center for Pre-College Programs has sought to become a driving force in providing increasing access to scientific and technological fields among traditionally underrepresented populations. In recognition of the need to reach both current and future generations, the Center provides professional development programs for practicing teachers and counselors. Combined with the modification of current curricula and/or development of new curriculum materials it seeks to strengthen the quality of elementary and secondary schools teaching and counseling methodology in engineering, science, math and related technological subjects.[3, 22] All pre-college initiatives are fully incorporated into NJIT's community mission.

Summer 2002 - A Pilot Study

As a means to interact with high school science teachers so as to gain their input, a pilot summer workshop was held in July 2002. Chemistry teachers were introduced to chemical engineering topics, related to scientific concepts taught in the high school science courses. The content material was supplemented and enhanced with hands-on experiments, some of which were performed in the chemical engineering laboratories. Interactive CDs on

"Material and Energy Balances" [25] and "Visual Encyclopedia of Chemical Engineering Equipment" [26] were also provided.

The chemistry teachers evaluated the program and provided information for its revision. Feedback was provided on the suitability of the chemical engineering topics for the high school science classroom and the appropriateness of the hands-on experiments for the students and for the high school facilities. As a result suggestions were provided for the development of the chemical engineering module and its implementation in teacher workshops and in high school classrooms. Some of the specific suggestions included:

- There should be more problems that they could try to solve together in class in addition to the example problems.
- Problems should be chosen to have more meaning to high school students such as the problems on the interactive material balance disc.[25]
- In general, they liked computer simulation and interactive discs which high school high school students should very well receive. Simulations of fluid flow and chemical reaction kinetics would be very useful.
- The discussions on Chemical Processes and the real life Chemical Plant experiences were considered valuable. The discussions of Heat and Mass Transfer were good but the material in Equilibrium Stage Operations should be reduced or eliminated.
- The short introduction to plant design (a cookie factory) using an interactive disc and the operation of the Senior Chemical Engineering Laboratory computerized experiment on fluid flow was very enjoyable.

Connecting the Scientific Concepts with Engineering Applications

As a result of the pilot program, it was determined that the processes for the manufacturing of a commonly available and well-known product would be selected as the vehicle for relating the concepts taught in the high school science classroom to the applications to chemical engineering practice. Since the typical plant involves multi-step processes, an overview of chemical processes starts with the examination of what a process is. To understand the overall concept of a process, simple processes are explored which take place in well-known things, such as a restaurant or a popcorn machine. Explorations of things like the automobile, an animal, or the human body allows for the further analysis of the characteristics of a process and discussion of sub-processes within the overall process. These things provide the opportunity to look at both physical and chemical processes. In all cases, we want to look at the entire process of the chosen thing from start to finish.

We are then ready to look at the manufacture of the well-known product. The selected product would be a pharmaceutical, aspirin. A simplified process flow diagram of an aspirin manufacturing facility is used to illustrate the various Unit Operations. Related chemical and physical concepts are identified. A chemical process flow diagram of something like the human body can show the various elements of a Chemical Processing Plant. We identify the chemical processes and chemical and physical concepts that are involved. At the end of the exercise a more detailed process flow diagram of the human body is presented and the chemical and physical concepts are then discussed.

The process flow diagram of the aspirin (acetyl salicylic acid) manufacturing facility is used to illustrate the various Unit Operations of the process. The basis of the process is the Kolbe-Schmitt synthesis of aspirin.

In Step 1 of the process, phenol, concentrated caustic soda, and carbon dioxide react to form sodium salicylate, which reacts further with sulfuric acid to form salicylic acid. Salicylic acid reacts with acetic anhydride in the presence of toluene in Step 2 of the process to produce acetyl salicylic acid (aspirin). The chemist first performs these operations in small, batch scale steps with very little concern initially for unreacted reactant recovery and recycle and pollution abatement and prevention. On a small scale the initial focus is on the product.

The chemical engineer must create a large-scale flow process with recycle of unreacted reactants, solvents, and their recovery. They must be concerned with the disposal of large quantities of undesirable by-products and waste, pollution abatement and prevention and an operating plant the runs for 24 hours per day, 365 days per year with periodic shutdowns for scheduled maintenance.

Using the aspirin manufacturing plant, the module focuses on those science concepts taught in high school that are relevant to chemical engineering principles. For relevant processes, the chemical processes and chemical and physical concepts that are involved are identified and related to chemical engineering principles and practices. Diverse topics such as heat transfer, mass transfer, chemical reaction and separations technology are introduced and related to scientific concepts. For example, an overall system material balance based upon stoichiometry must be made. During the discussion of Process Variables, mass, volume, flow rate, chemical composition (mass fraction and mole fraction), pressure and temperature concepts and relationships are discussed and applied in material balances. The different phases of matter and the ideal gas law come into play.

The First Law of Thermodynamics for closed and open systems is applied to problems involving non-reactive and reactive energy balances, heat effects, phase changes, heats of reaction, mixing and solution. The chemistry concepts of thermochemistry, calorimetry, chemical bonds and structure, chemical and physical equilibrium, solutions, chemical reactions, work, and heat are applied to single and multi component systems. Principles of physics, such as vectors, motion, momentum, dynamics, friction, kinetic and potential energy, conversion of work to energy and vice versa, velocity, acceleration, torque, power and gravity are also important in the plant. A few thermodynamic cycles including the Carnot engine are discussed to show the relationship of work and heat. Vapor-Liquid, Liquid-Liquid, Solid-Liquid, Solid-Vapor, and chemical reaction equilibrium concepts are also important processes in the manufacturing plant.

Chemical reactors used in chemical plants are introduced. The material and energy balance equations are used to develop the design equations for batch reactors, continuous flow stirred tank reactors, plug flow reactors and catalytic plant reactors. The collection and analysis of rate data are used to measure the rates of reactions in batch reactors. The Aspirin process illustrates the importance of understanding the transport of material from one part of a chemical process to another and through different kinds of chemical equipment. High school concepts of stress, strain, friction, viscosity are related to laminar and turbulent flow Conductive, convective and radiation heat transfer are discussed and related to the efficient use of heat in chemical processes. Thermal conductivity, heat capacity, and heat transfer coefficients are also considered as well as the concept of temperature driving forces needed in design of heat transfer plant equipment. Heat transfer involving phase change in condensation and boiling is a relevant scientific concept.

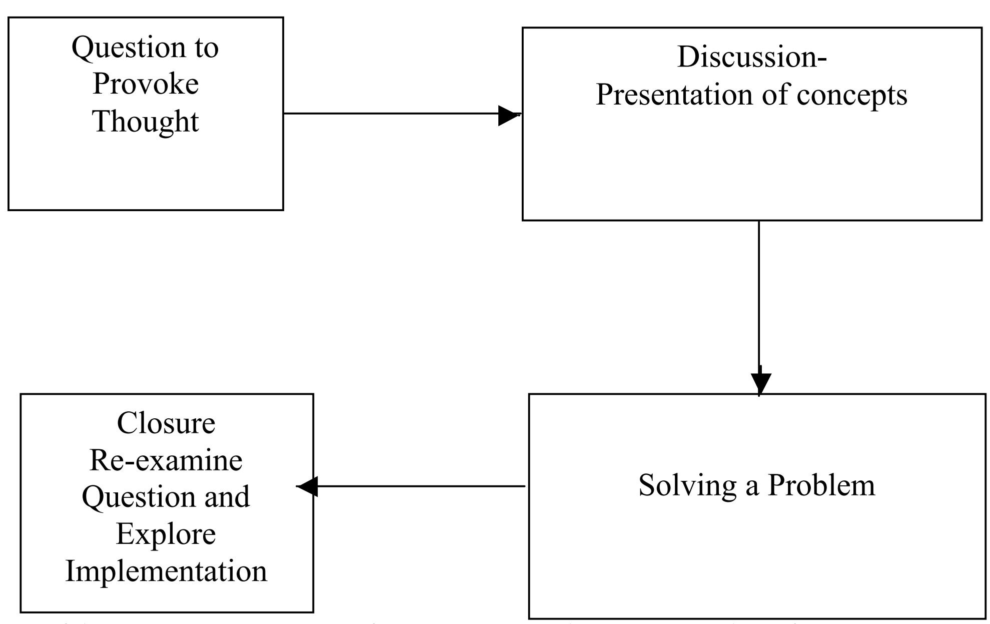
The concept of diffusion is applied to chemical plant problems. The mass transfer coefficient is introduced and the analogies between momentum, heat and mass transfer are illustrated. Concentration gradients and the various units on concentration are discussed.   For example, plant equipment involving gas absorption, which is very important in pollution abatement, is governed by the same basic concepts in mass transfer as is plant equipment related to liquid-liquid extraction.

The science principles related to distillation and other separation processes are extended to those principles used the design of large-scale distillation equipment. The importance of temperature-composition, vapor-liquid equilibrium, and column and plate efficiencies is shown in the design of the distillation columns used in Aspirin production.

The principles and importance of process control in the chemical industry are considered in terms of simple concepts used in ancient civilizations and in our day living   Using the simple example of liquid level in a tank; the feedback loop is developed and discussed.

As a culminating component of the module, the concepts used in process and plant design are very nicely demonstrated on an interactive disc for the manufacture of a "Mystery Product", its scientific concepts, the economics and conclusion. The "Mystery Product" involves the manufacture of chocolate chip cookies.

Teacher Training and Classroom Implementation



Teacher training and course implementation uses cooperative learning techniques with the classes divided into teams of two or three. As much as possible, the workshop format simulates the instructional approach to be used in the high school classroom. The simple process shown above illustrates the approach being used in the teacher-training program.

As a general overview, we see that the treatment of each topic begins with a question for the teachers to answer. It should be noted that for each concept, interactive hands-on learning is emphasized. After considering the various answers to the questions, the concept under discussion is presented by the instructor. That is followed by one or more problems posed to the teachers to solve. Finally, the discussion and problem solving are related back to the initial question posed to the teachers. At this point, the high school teachers explore the implementation of the topic into their classrooms.

Discussions on classroom implementation focused on three components: alignment with standards, instructional strategies, and content. Time was spent with the teachers reviewing the N. J. Core Curriculum Content Standards. It was important for the participants to realize that teaching to the content standards requires certain instructional approaches. The standards require students to apply, demonstrate, or use specific knowledge or skills, rather than just retain facts or demonstrate basic rote knowledge. While the teachers are encouraged to develop their own strategies, one approach presented to the teachers was:

- A scientific concept is selected, a description is developed, and the concept is related it chemical engineering principles/practice.
- A hands-on activity is developed that illustrates and further develops the concept.
- For the concept, four things are developed that the teachers and students could do, for example, calculate results, draw a graph, write a report and make an oral presentation.
- Decide on four outcomes of the concept and determine what the students learned.

We can look at the overall process shown above with some examples. As a start, after an introduction to the program the question is asked "*What is engineering?*" The class is divided into teams of two each and each team is asked to list their answers to the question. The concepts are then listed and discussed. The class is then asked, "*What is the difference between a scientist and an engineer?*" "*What can you think of in your life that does not have a science or an engineering base?*" "*Can you name some famous engineers?*" Again a discussion between team members takes place and the ideas are collected. Following the discussion, the answers to the questions that have been researched are presented to the class and implementation is discussed and the outcomes are summarized. The class is then asked, "*How can this be used in your class to reinforce the concepts that you are teaching your students?*" This is followed by the questions "*What is Chemical Engineering?*" "*What do Chemical Engineers do?*" "*What are some general scientific principles that concern chemical engineers?*" and "*Where do chemical engineers work?*" which are discussed in a similar fashion.

We then start the exploration of what a process is, starting with the nature of a simple process. The question is asked as to "*What is a process?*" The ideas are collected and the class is asked to think about the processes taking place in an automobile. The class is asked to show an overall material and energy balance for the automobile and the scientific principles that are involved in an automobile process. After some discussion, the class is shown an overall process and a process flow sheet of the various process units which are a part of the overall process of the automobile with the following unit processes:

- The flow of fuel and air, the ignition, combustion reactions and the exhaust of combustion products to the atmosphere,
- The heat transfer process in cooling the engine,
- The battery processes in starting ignition, generation of electricity and recharging the battery,
- The heating and air conditioning system and the refrigeration cycle.

Once the group has obtained a feel for a process analysis, each team is asked to repeat the exercise for the human body, which has various elements of a Chemical Processing Plant and asked to identify the chemical processes and chemical and physical concepts that are involved. The teams are asked to develop an overall process diagram with the input and output of materials and energy. Then the flow process diagram of the body is developed including the various process units in the human body, the mouth, lungs, stomach liver, small intestine, large intestine, gall bladder, bladder, heart, brain, pancreas, kidneys, and the functions of the nerves, etc. Process control is introduced using the principle of feedback control of the body's reaction to temperature control in a shower. The analogy of temperature control in exothermic or endothermic reactions in chemical reactors is shown. At the end of the exercise a more detailed process flow diagram of the human body is presented and the chemical and physical concepts that are involved are discussed.

We than move on to an "*Overview of Chemical Processes*". A simplified chemical; process flow diagram of an Aspirin Manufacturing Facility is used to identify the concepts taught in high school science and show how these concepts are used in chemical engineering principles and practice. The basis of the process is the Kolbe-Schmitt synthesis of aspirin. The principle reactions that are involved are discussed with the class. The process steps involved in the chemistry laboratory, where the process was first developed are discussed. It is then shown why it is necessary to take these laboratory steps and convert them into a flow process. The class then begins thinking of "designing" the plant. First, an overall system material balance based upon stoichiometry can be made. This material balance, however, involves a basis of calculation. Each team will be asked to think about the basis of the calculation. The basis of calculation for the material balance is dependent upon the size of the production facility. The problem is initially economic in nature and will be presented as follows:

- Determine the size of the production facility.
- One method to estimate the size of the production facility is based upon the growth of the population in the United States.
- The growth of Aspirin production in the United States.
- Estimate the amount of Aspirin needed in the United States in the year 2015.
- Estimate what share of this market you hope to capture.
- Determine the size of your production facility.

- Determine the overall material balance for your process including all input and output streams for the products and by-products assuming a 100 percent conversion in each step of the two-step process, and a 95 per cent yield in each step.
- Determine the necessary recycle streams and waste streams.
- Suggest recovery methods for the valuable raw materials to be recycled and the disposal methods for the waste streams.
- Suggest any pollution prevention or pollution abatement technologies.

The remaining topics related to the manufacture of aspirin are introduced in an analogous fashion. For example, energy balances are introduced at the reflux condenser on the Step 2 chemical reactor, or the teachers are guided into the transport of material from one process unit to another. Discussions of topics are guided by the content of the curriculum modules.

Throughout the program, hands-on laboratory experiments and demonstrations relating to the principles taught in high school science classrooms are used to actively engage the teachers. They include but are not limited to:

- The demonstration of the Drinking Bird. [27]
- The Rolling Coffee Can classroom demonstrator.
- Experiments with the coffee cup calorimeter.
- Experiments in liquid-liquid equilibrium using simple systems.
- A classroom demonstration of Reynolds Experiment.
- Experiments illustrating reaction kinetics.[28]
- Momentum transfer – fluid flow. [28]
- "Watching Time Go By"[29], is based on the concepts of efflux time from a tank. The water flowing by the force of gravity is used as a time measurement paralleling the use of flowing water and sand in ancient history to measure time.

In addition, simulations are also used to illustrate the concepts. For example in the 2002 pilot program, teachers were exposed to an interactive material balance disc[25] to perform material balance calculations and to the "Visual Encyclopedia of Chemical Engineering Equipment"[26].

Conclusions

The major issues addressed were

- The instructional approach, that is interactive discussion/inquiry or traditional lecture approach and discuss.
- The course content, that is integrating chemical engineering concepts and their relations to high school science rather than actually teaching chemical engineering. Where do chemistry, mathematics and physics fit in the content?

A four-step process was implemented for the teacher training which could be translated into the high school classroom. The objective of the program is not to simply lecture on chemical engineering principles but to show the high school teachers, how the concepts that they teach in their science courses are applied in chemical engineering theory and practice. It is meant to give the students a feel of chemical engineering practice.

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