Session 2213

The Vertical Integration of Design in Chemical Engineering

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Abstract

The purpose of this project is to better prepare chemical engineering students for their senior design course and for industry by exposing them to more design-oriented problems much earlier in their undergraduate careers. The feature that distinguishes engineering from the purely theoretical sciences is that of synthesis. Any meaningful synthesis requires two basic components, one that arises from the order of our scientific knowledge and another that arises from the spontaneous thought of the individual performing the synthesis. Until now, the undergraduate chemical engineering curriculum at Penn State University has focused almost entirely on the former; this project requires students to recognize the latter. Two entire chemical process plants have been divided into several design projects to be used in the core undergraduate chemical engineering courses, and each design project requires that the students use concepts learned in a given chemical engineering course (e.g. heat transfer, mass transfer, kinetics, etc.) to arrive at a fully specified design. The students will follow the same or similar chemical process plants throughout their undergraduate careers so that, by the end, they will understand many of the details of designing the plant without losing focus of the ultimate goal of the process. Most importantly, however, at some point in the project they will have to make some of their own decisions. There will be more than one way to attack the problem, and the students will have to make appropriate assumptions, research several alternatives, use common sense and think both logically and physically in order to arrive at a practical solution. If this project accomplishes its goal, the chemical engineering curriculum at Penn State University will take a step away from being a mere extension of theoretical science and a step toward being an actual preparation for a career in thoughtful problem-solving and design.

1 Introduction

Like many of its counterparts across the country, the Chemical Engineering program at Penn State University provides undergraduate students with a solid background in the theoretical aspects of the chemical engineering discipline. Students learn fundamentals in a series of six core courses and then are asked to apply this knowledge in a capstone design course where they design a full-scale chemical production facility. Although students typically have a relatively firm theoretical grasp of the relevant subject matter, the senior design course shows them they have been exposed to little or no design work throughout the curriculum. This deficiency leaves them overwhelmed at the prospect of developing a fully-specified chemical plant with only a product purity and demand specification to go on. The goal of the project described here is to enhance the current curriculum in order to better prepare students for this senior design course, which will in turn help them to better understand the application of chemical engineering knowledge in general.

Rather than add new courses or completely change the curriculum in place, we propose that design projects be included within the six core courses of the chemical engineering curriculum. This "vertical integration of design" will expose students to the concepts of applied design while they are learning about a particular topic. There are several reasons for choosing this method of curriculum improvement. First, changing a few homework assignments or adding a case study project is much easier to implement than designing an entirely new course from the start. Second, there is not a problem with the theoretical concepts that are currently being taught. The instructors for these courses have done an excellent job of selecting appropriate material and organizing it in a logical fashion. We only wish to reinforce this theoretical knowledge with applied design projects that will help students to understand the relevance of this knowledge as they learn it. In addition to solidifying and grounding the students' understanding of the discipline, these slight changes to the core curriculum will also provide a strong source of motivation to learn by increasing the students' understanding of the relevance each topic has to realistic design problems, and thus to becoming better engineers. Educational benefits of these case study projects include:

1. The students immediately see how the information they learn applies to tasks they might be asked to perform in the workplace.
2. Almost no practicing engineers work alone. Case study project work is conducted in teams. This means the students will have to learn to communicate their ideas effectively without neglecting human factors such as conflict, envy and ego. Such experience is both invaluable and conspicuously absent in the current chemical engineering curriculum.
3. The students will have to make extensive use of the same tools to which they would turn in their professional careers. Supplementary textbooks, journal articles, reference materials and computer spreadsheets will greatly facilitate, and, in most cases, be practically essential to, the design process.
4. It may not be possible to teach people how to be creative, but the opportunity to see precisely what role theory plays in the design process will make students critically aware of a need for what might be termed reasonable inspiration.

These case study projects have been developed based on the 1986 and 1989 AIChE Student Contest Problems. Each year, the American Institute of Chemical Engineers (AIChE) distributes a chemical plant design problem which is developed in collaboration with an industrial chemical manufacturer. The AIChE holds an annual contest where senior chemical engineers are given the problem and are expected to solve it during an eight-week time period. This problem is intended to be a part of the senior design course, but no interaction with any instructors is permitted regarding the design problem while students are working on it. The final design project is then submitted at the end of the eight-week period. The instructors send in the best 2 or 3 projects, which are then graded (or judged) by the AIChE, and the AIChE then selects a first, second and third place winner for the design project. Penn State is not among the schools that participate in the contest.

2 Penn State Core Undergraduate Chemical Engineering Curriculum

The core undergraduate chemical engineering curriculum at Penn State currently includes the following courses on the following subjects. More in-depth explanations are given below.

Chem E 301	Material Balances
Chem E 302	Fluid Flow and Heat Transfer
Chem E 303	Thermodynamics
Chem E 304	Phase and Chemical Equilibria
Chem E 413	Mass Transfer Operations
Chem E 414	Kinetics and Industrial Chemistry

All the courses involve two to five lectures a week, during which the principles relevant to the treatment of the subject matter are explained and large numbers of examples are demonstrated for reinforcement. Each course requires the student to complete approximately 10 homework assignments and two or three examinations, each of which is one to two hours. Although the courses are to be taken in sequence, and generally build upon material learned in previous courses, they are taught independently, and students are made aware of the interconnections only as much as is necessary to understand the material currently under study. For example, the derivation of the design equation for plug-flow reactors is based on a material balance, or basic phase equilibrium is reviewed as preparation to explaining the operation of a distillation column.

At no point are the students made aware of the direct relevance or application this material might have on the design of chemical plants. After taking these courses with no sense of their utility, students are then required to enroll in a capstone plant design course where they are divided into project teams and asked to apply the knowledge they have learned to design an entire chemical plant using one of the several commercially available chemical process simulation software packages. The shortcoming of this arrangement is that the students are not at all prepared to make the leap from self-contained problems with well-specified assumptions, operating conditions and objectives to the collection of inextricably related, open-ended and underspecified design problems that constitutes an industrial chemical plant.

2.1 ChE 301: Material Balances

This course covers stoichiometry, unit analysis, the fundamentals of batch, semi-batch and continuous processes, steady-state and unsteady-state material balances on unreactive and reactive systems, and Raoult's and Henry's Laws. Students are also introduced to the use of computer spreadsheets for solving material balance problems. Most of the examples used in ChE 301 come from the chemical industry, but emphasis is placed on the fundamental principle of conservation mass in non-nuclear systems and the input-output process approach so that the analytical techniques learned here can be applied to virtually any process, including many that are not typically considered germane to chemical engineering.

2.2 ChE 302: Fluid Flow and Heat Transfer

The goal of this course is to acquaint chemical engineering students with the fundamentals of the two broad disciplines of fluid dynamics and heat transfer, particularly as they apply to the chemical process industry. The two topics are each treated using the three basic techniques of integral or macroscopic analysis, differential or microscopic analysis and dimensional analysis. In addition, there are two units at the end of the course dedicated to the analysis and design of heat exchangers and to radiation heat transfer. The course also emphasizes the importance of being able to convert among the various systems of units, of deriving generalized symbolic solutions to systems of algebraic or differential equations before obtaining numerical answers and of reaching a fundamental understanding of the few, but extremely important, principles that govern all physical and chemical systems.

2.3 ChE 303: Thermodynamics

This course is an introduction to the topic of thermodynamics primarily as it applies to chemical processes. The topics covered in ChE 303 include equations of state, thermodynamic properties of real fluids and their mixtures, the first and second laws of thermodynamics and cycles. The general organization of the course is as follows: (1) Energy Balances and the First Law of Thermodynamics, (2) Generalized, Theoretical and Empirical Equations of State, (3) Thermodynamic Properties of Real Fluids, (4) Entropy and the Second Law Thermodynamics, (5) Engines, Compressors, Refrigeration and Liquefaction, and (6) Chemical Process Thermodynamics.

2.4 ChE 304: Phase and Chemical Equilibria

This is a course on the physical and chemical properties of pure substances and solutions. The topics treated include pure component phase properties, solution properties, physical equilibria among phases, with emphasis on vapor-liquid equilibria, and chemical equilibria. Students must understand the theoretical significance and use of chemical potential, fugacity coefficients and activity coefficients to account for liquid and vapor phase non-ideality. Finally, the students are exposed to various equations of state and liquid-phase equilibrium models.

2.5 ChE 413: Mass Transfer Operations

Mass transfer refers to the purification and recovery of one or more chemicals from a mixture of one or more other chemicals. Such separation can be accomplished by a wide variety of physical and chemical operations including, but by no means limited to, distillation, liquid extraction, gas absorption, humidification/dehumidification, adsorption, membranes and crystallization. While examples and design techniques illustrated in ChE 413 emphasize those mass-transfer operations most commonly encountered in industry, the fundamental principles, namely the material balance implications of counter-current, co-current and cross-current staging and the analytical tools provided by diffusion and phase equilibria, can be applied to any mass-transfer operation.

2.6 ChE 414: Kinetics and Industrial Chemistry

In this course, students are taught all of the principles required to analyze and design industrial chemical reactors. Students begin by learning how to derive the design equations for ideal PFRs, CSTRs and batch reactors and then progressively lift assumptions of ideality to understand realistic chemical reaction engineering problems. Topics covered include various rate expressions and their mechanistic origins, Arrhenius and non-Arrhenius behavior of rate constants, collection and analysis of rate data, nonisothermal reactor design and determination of mechanisms, diffusion effects and rate-limiting steps for catalytic systems.

3 Case Study Process Descriptions

The following are process descriptions of the two plants upon which the case study projects are based.

3.1 Acrylic Acid Process Description

This project is based on the 1986 AIChE Student Contest Problem. A schematic diagram of the process, which is described below, can be found in Figure 1.

Projected demands of acrylic acid over the next 10 years indicate that a new production facility must be built and on stream in 2000. Acrylic acid (AA) is produced via air oxidation of propylene and is purified via solvent extraction and distillation to remove water and by-product acetic acid (HAc). An existing plant is already in operation using this basic technology, but the Research Department has developed some alternative extraction solvents that must be considered, and there is a common belief that the purification section distillation system in the new facility can be more efficiently designed. In addition, a new catalyst has been developed that will allow us to consolidate the two-stage reactor system into a single reactor. In order to facilitate economic evaluation of the implementation of these design enhancements, we must arrive at a completely specified design for the new acrylic acid production plant.

Acrylic acid is currently produced via the oxidation of propylene using two reactors. Air, propylene and steam are fed to reactors consisting of catalyst filled tubes with molten salt circulating on the shell side for removal of the heat of reaction. The salt passes through a steam boiler to produce steam for heat recovery. In the first reactor, the propylene is converted into acrolein.

$$C_3H_6 + O_2 \rightarrow C_3H_4O + H_2O \qquad (1)$$

In the second reactor, the acrolein is converted into acrylic acid.

$$C_3H_4O + \tfrac{1}{2} O_2 \rightarrow C_3H_4O_2 \qquad (2)$$

Thus, the net reaction is:

$$C_3H_6 + 1.5\, O_2 \rightarrow C_3H_4O_2 + H_2O \qquad (3)$$

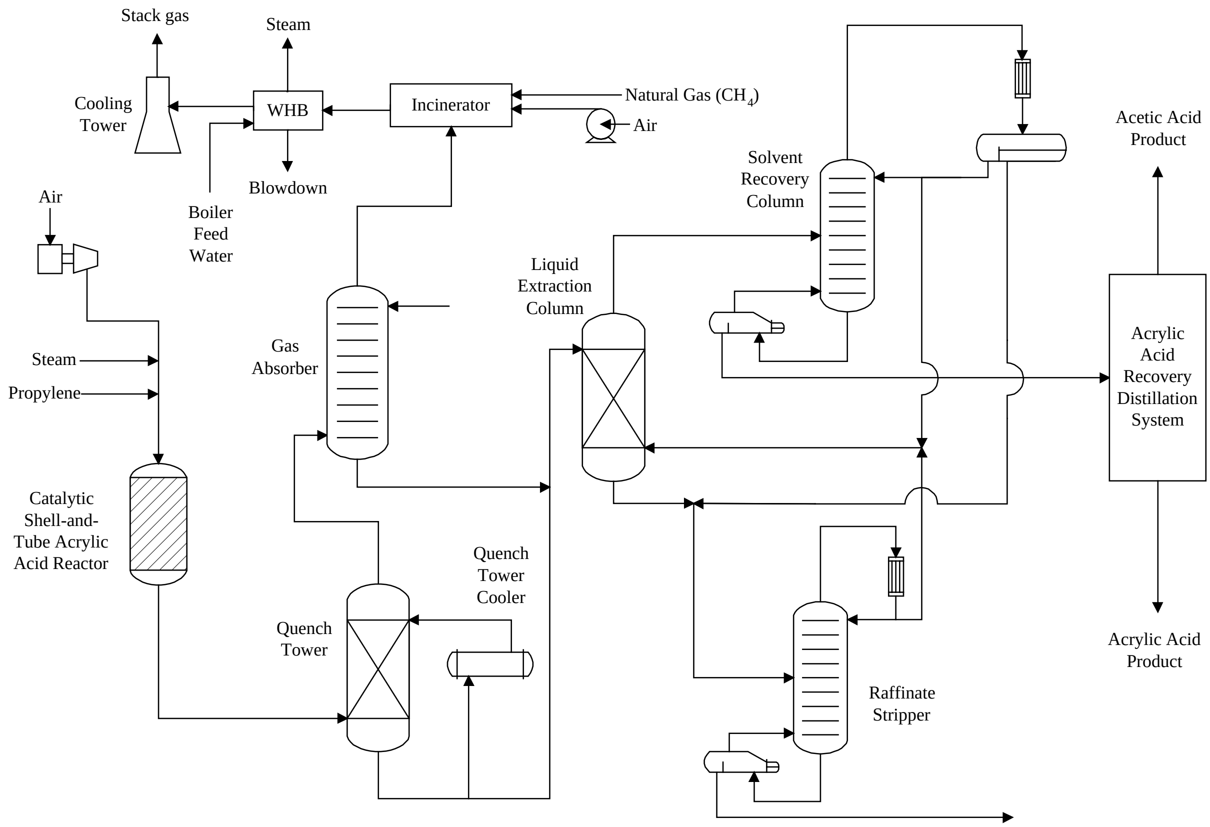

Figure 1. Acrylic Acid Production Plant

Typical yields for this reaction are 75-85%. The principal by-products of the reaction process, CO_2 and HAc, are produced according to the following reactions.

$$C_3H_6 + 2.5\,O_2 \rightarrow C_2H_4O_2 + CO_2 + H_2O \quad (4)$$

$$C_3H_6 + 4.5\,O_2 \rightarrow 3\,CO_2 + 3\,H_2O \quad (5)$$

In the new plant, these two reactors will be replaced by a single reactor with a new catalyst. All the unit operations downstream from the reactor will hereafter be collectively referred to as the separations section, and that section is further divided into a gas absorber system, an extraction/solvent recovery system and an acrylic acid recovery system.

The product stream from the oxidation reactor is quenched in the first stage of the gas absorber system, and the gas from this first stage is fed to an absorption stage where water is used to recover acrylic and acetic acids. The waste gas, principally nitrogen, excess oxygen, carbon dioxide and propylene, along with some residual AA and HAc, must be incinerated to remove all of the hydrocarbon components to meet environmental regulations. (During start-up and upset conditions, low levels of acrolein can also be present, and this material is extremely hazardous.)

The aqueous effluent from both stages of the absorber system is then fed to the liquid extraction/solvent recovery system of the plant. In the liquid extraction section, the acrylic acid and the acetic acid are first extracted with a solvent in a continuous, countercurrent, multi-stage liquid extraction column. The extract from this liquid extraction column is sent to a solvent recovery distillation column, where the solvent and water from the extract phase are removed from the mixed acid product stream. Any water that is in the extract stream from the liquid extraction column is taken overhead in the solvent recovery distillation column. Following solvent and water removal in the solvent recovery distillation column, the acrylic acid/acetic acid product mixture is separated further by distillation to produce crude acrylic acid and by-product acetic acid.

A portion of the overhead product stream from the solvent recovery distillation column and the raffinate stream from the liquid extraction column are gathered together and sent to a raffinate stripper. The raffinate stripper is used to recover any solvent that is soluble in the solvent recovery separator water layer or that is in the raffinate stream from the extraction column. Following stripping in the raffinate stripper, the water is treated in a biological wastewater treatment facility.

The by-product acetic acid is worth recovering and selling. The wastewater from the process can be handled in the existing waste treatment plant, but the waste gas must be burned to meet environmental regulations.

3.2 Vac Resid Process Description

This plant is based on the 1989 AIChE Student Contest Problem, and a ChE 465 design project from the 1993 Fall semester at Penn State. A schematic diagram of the process, which is described below, can be found in Figure 2.

As you might already know, our Petroleum Production and Refinery Division has been combusting the bottom residue from its crude oil vacuum distillation columns as supplemental fuel and landfilling any balance for many years now. Due to a recent change in environmental regulations, however, this option will no longer be possible. Therefore, our division of the Engineering Department will be investigating the possibility of designing a plant to convert this crude oil vacuum residue into MTBE (methyl-t-butyl ether). MTBE is an oxygenated hydrocarbon which is extremely valuable as a gasoline additive under the new air pollution control regulations. The first step of the process involves using partial oxidation of the residue to form carbon monoxide and hydrogen. These intermediate products are then used to make methanol which is later converted to MTBE upon the addition of isobutylene.
There are five basic reactions that occur in the production of MTBE from crude vacuum residue. The first step is the partial oxidation of the carbon and hydrogen in the vacuum residue stream using pure oxygen:

$$C_nH_m\ (l) + n/2\ O_2\ (g) \rightarrow n\ CO\ (g) + m/2\ H_2\ (g) \qquad (1)$$

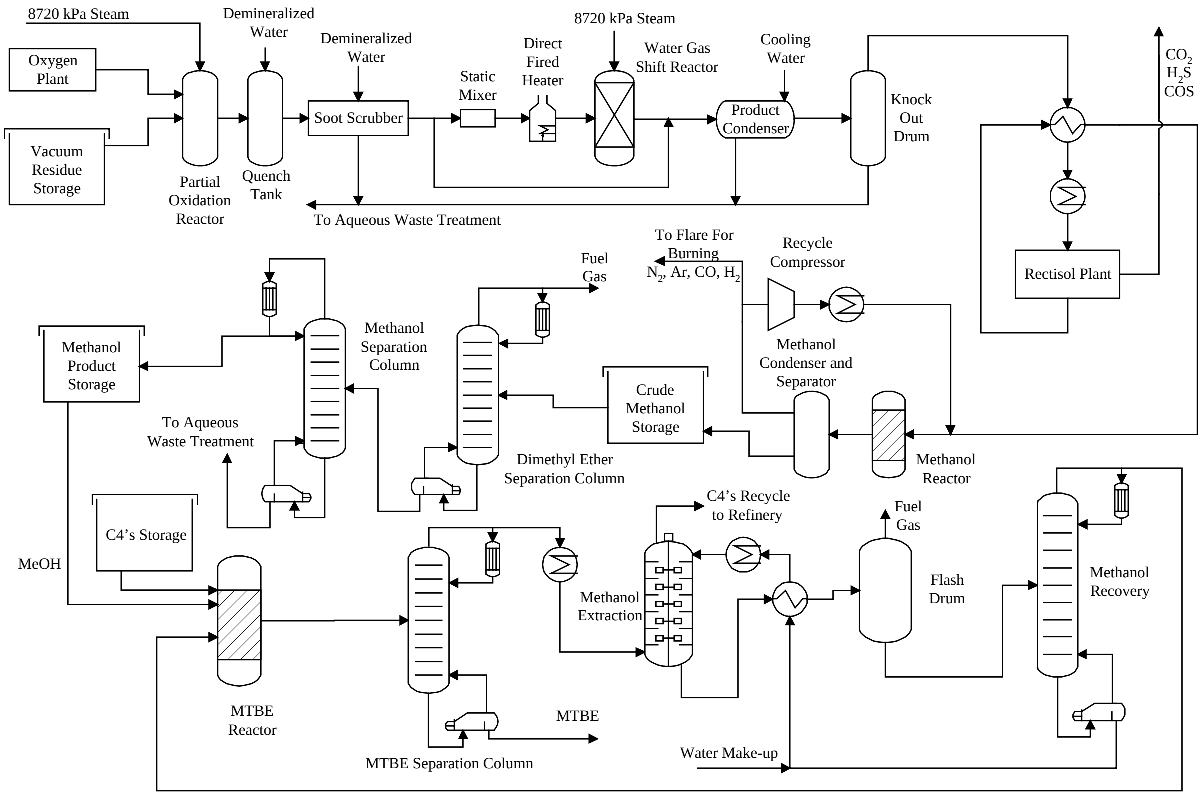

Figure 2. Methanol and MTBE Production Plant

The next reaction is the water gas shift reaction, which is used to adjust the H_2 to CO ratio for the optimal production of methanol:

$$CO\ (g) + H_2O\ (g) \rightarrow CO_2\ (g) + H_2\ (g) \qquad (2)$$

Methanol is then produced from carbon monoxide and hydrogen by the reaction:

$$CO\ (g) + 2\ H_2\ (g) \rightarrow CH_3OH\ (g) \qquad (3)$$

The formation of dimethyl ether and water from carbon monoxide and hydrogen also occurs as a side reaction when producing methanol:

$$2\ CO\ (g) + 4\ H_2\ (g) \rightarrow C_2H_6O\ (g) + H_2O\ (g) \qquad (4)$$

The final reaction involves the production of MTBE from methanol and isobutylene:

$$CH_3OH\ (l) + C_4H_8\ (l) \rightarrow C_5H_{12}O\ (l) \qquad (5)$$

4 Example Projects

The four examples that follow demonstrate how case study projects allow for the introduction of thought processes that are more typical of genuine engineering than are those typically found in conventional problem-solving exercises. The first example has been taken from a mass transfer operations case study project where students are asked to design unit operations for the acrylic acid production plant. Solutions are provided for two parts of this case study project. The remaining two examples are from the vacuum residue processing plant. One of these examples involves the design of two interacting heat exchangers, and the other involves the design of a catalytic plug-flow reactor using kinetic data.

The acrylic acid mass transfer operations case study project involves the design of a liquid-liquid extractor and four distillation columns. The case study problem statement would be handed out together with the acrylic acid process description, a list of chemical property data, a list of design guidelines and the overall plant process flow sheet from Figure 1. Approximately one week after the case study is handed out, the students should hand in their choice of solvent and the rationale for that choice. At that time, the instructor would inform the whole class that solvent A is a more economical choice than solvent B and then hand out a problem statement supplement. This supplement gives the students important data that pertains only to solvent A. From that point, the instructor would give the students approximately four to six weeks to hand in the final report. The case study problem statement follows.

4.1 Acrylic Acid Mass Transfer Operations Case Study Problem Statement

Your task is to design all mass-transfer unit operations in the extraction/solvent recovery system and the acrylic acid recovery system of the acrylic acid production plant.

The new plant should have a capacity of 50,000 metric tons per year of crude acrylic acid. An onstream availability of 88% should be assumed. Existing site facilities are sufficient to handle the additional utility requirements. No new bulk storage facilities will be required. The crude acrylic acid must be at least 99.9 wt% pure, and the by-product acetic acid can be no more than 1.0 wt% acrylic acid. Table 1 lists the flow rates which should be used as a design basis for the plant.

Table 1. Flow Rates of All Components in Stream 10

All Flows in kmol/hr	
Component	**Flow Rate**
Acetic Acid	6.597
Acrylic Acid	90.830
Water	1116.146

The aqueous acid solutions from the bottoms of both gas absorption stages are sent to the extraction/solvent recovery portion of the separations section. Here they are contacted with an acid-free water-saturated solvent for extraction of the acids in a continuous, countercurrent, multi-stage mixer column extractor. The extract from the liquid extraction column is fed to a distillation column for recovery of the solvent and the water remaining in the extract phase. The distillate from this solvent recovery distillation column is separated into an organic solvent layer and an aqueous layer in a reflux holding vessel. Part of the solvent layer is used for reflux, while the remainder is recycled to the extractor. The water layer from the reflux holding vessel is combined with the raffinate from the extractor and sent to a raffinate stripper for removal of the solvent from the raffinate waste stream. Assume 100% recovery of the combined acids to the extract solvent recovery distillation column bottoms and negligible amounts of water and solvent in this stream for material balance purposes. The solvent recovery column should be designed on a pseudo-binary basis with solvent and acrylic acid as the key components. In determining the number of stages required to recover the solvent from the acid, it can be assumed that the pseudo-binary composition of solvent in the bottoms is 0.01 mol% and in the overhead is 99.99 mol%. The raffinate stripper, which should be designed as a solvent/water pseudo-binary distillation column, should produce acid-free water-saturated solvent as overhead product and a bottoms that is 0.01 mol% solvent on a pseudo-binary basis. Again, assume complete recovery of the solvent for material balance purposes.

The final separation of acrylic acid from acetic acid is done using distillation. Because of the tendency of acrylic acid to polymerize at high temperatures, it is necessary to maintain the temperature of the material below 90°C at all times. In developing the distillation column recovery system for producing product acrylic acid and by-product acetic acid, the following assumptions should be made.

The project has been divided into two parts. A process flowsheet of the extraction/solvent recovery and acrylic acid recovery systems can be found in Figure 3.

Part I (10%).

Choose the best solvent based on overall economic considerations, and write a one-page report to explain the reasoning behind your solvent choice. The Research Department will then use this solvent to perform pilot-scale liquid-liquid extraction and vapor-liquid equilibrium experiments to aid in design of the liquid-liquid extraction column and the raffinate stripping distillation column. You can expect their results within a few days.

Part II (90%).

1. Briefly explain the purpose of each mass-transfer operation in the extraction/solvent recovery and acrylic acid recovery systems.
2. Calculate the size (height and diameter) of each mass-transfer operation in the extraction/solvent recovery and acrylic acid recovery systems. Show all steps in arriving at these sizes by documenting all equations and explaining the design procedure for each unit.
3. Determine what you think would be an operationally practical and reasonable design for the acrylic acid recovery system, and include a flow sheet and detailed explanation of this design. Also explain how you arrived at the design.
4. Make a set of detailed material balance calculations including flow rates and compositions of all streams in the extraction/solvent recovery and acrylic acid recovery systems. Report your numerical results in tabular form with the components listed by row in alphabetical order and

the streams listed by column as shown in Table 2 below. List all the components shown below for every stream, and use a dash to indicate that a stream does not contain a particular component.

Table 2. Sample Material Balance Table

All Flows in kmol/hr				
Component	**MW**	**Stream 1**	**Stream 2**	**Etc.**
Acetic Acid	--	--	--	--
Acrylic Acid	--	--	--	--
Solvent	--	--	--	--
Water	--	--	--	--
Total	--	--	--	--

4.2 Acrylic Acid Mass Transfer Operations Case Study Partial Solution

The 76-page solution that is also given to the professor who makes use of this case study project is beyond the scope of this document. However, it is worthwhile to focus on two of the most important and most practical engineering judgments that must be made in designing this section of the acrylic acid production plant.

4.2.1 Choice of Solvent

Before the liquid-liquid extractor can be designed, it is necessary to decide which solvent to use. One obvious consideration is the affinity each solvent has for the acids. This is represented by the slopes of the tie lines on the ternary diagrams found in Figures 4 and 5. The steeper the tie lines, the better the solvent dissolves the acids, and the fewer the number of stages that will be required in the liquid-liquid extractor. However, an even more important concern in choosing the better solvent requires consideration of downstream steps in the separation process. The more miscible a given solvent is with the diluent in the extractor (in this case water), the more solvent that will need to be removed in the raffinate distillation column, and the greater the amount of water that will be in the solvent recovery column. This water will inflate not only the size of these columns (capital cost), but also the energy requirements for their associated heat-transfer equipment (operating costs). One can judge each solvent's miscibility by noting the solubility curve's proximity to the edges of the triangle on the ternary diagram. The closer the curve is to the edges, the less miscible the solvent is with the diluent, and the better the solvent is for this extraction. While Solvent B's tie lines are slightly steeper than those for Solvent A (particularly at the bottom), this small savings in capital cost will easily be outweighed by the greatly diminished energy costs for Solvent A. Thus Solvent A is the better choice for this extraction.

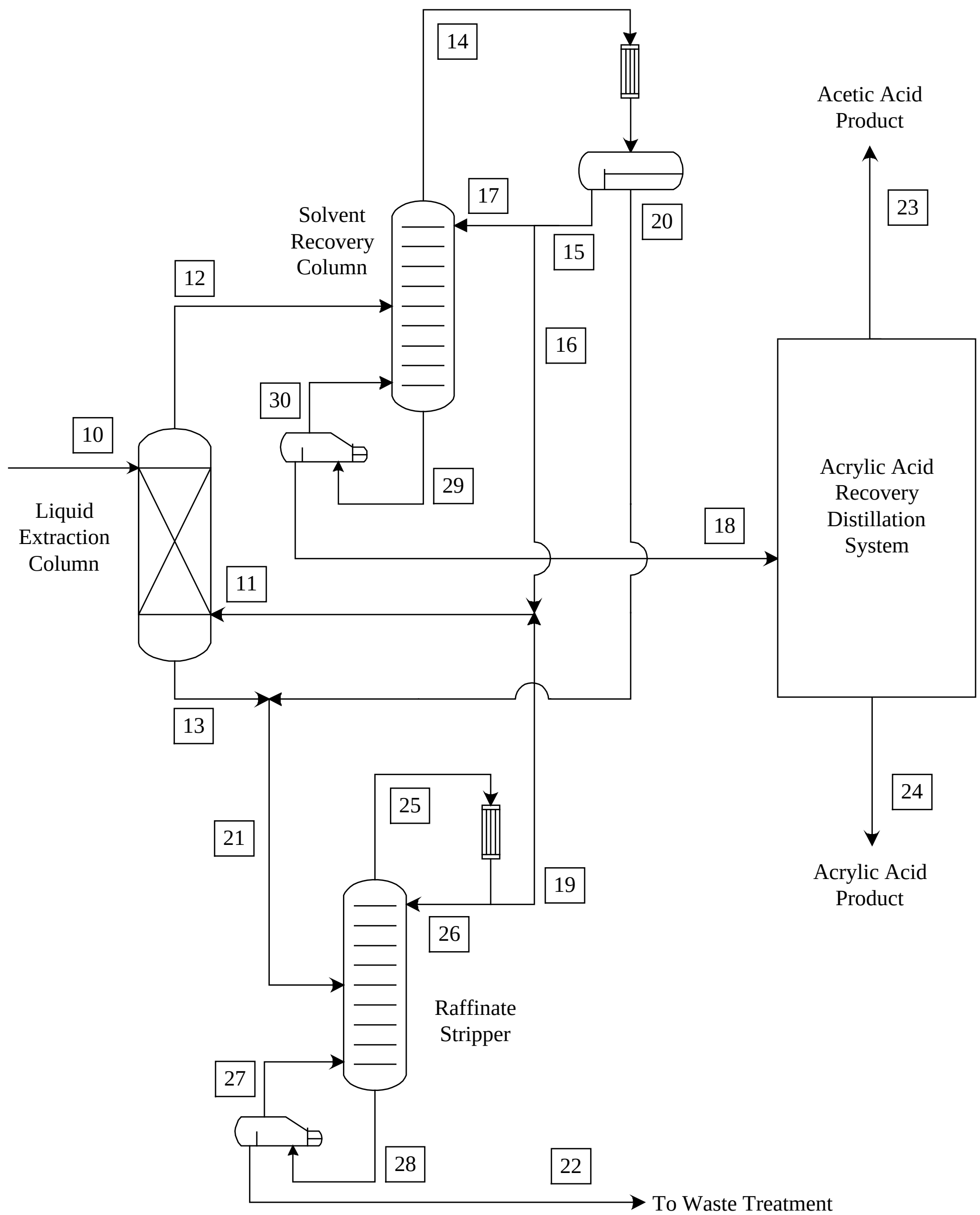

Figure 3. Liquid-Liquid Extraction System for the Acrylic Acid Production Plant

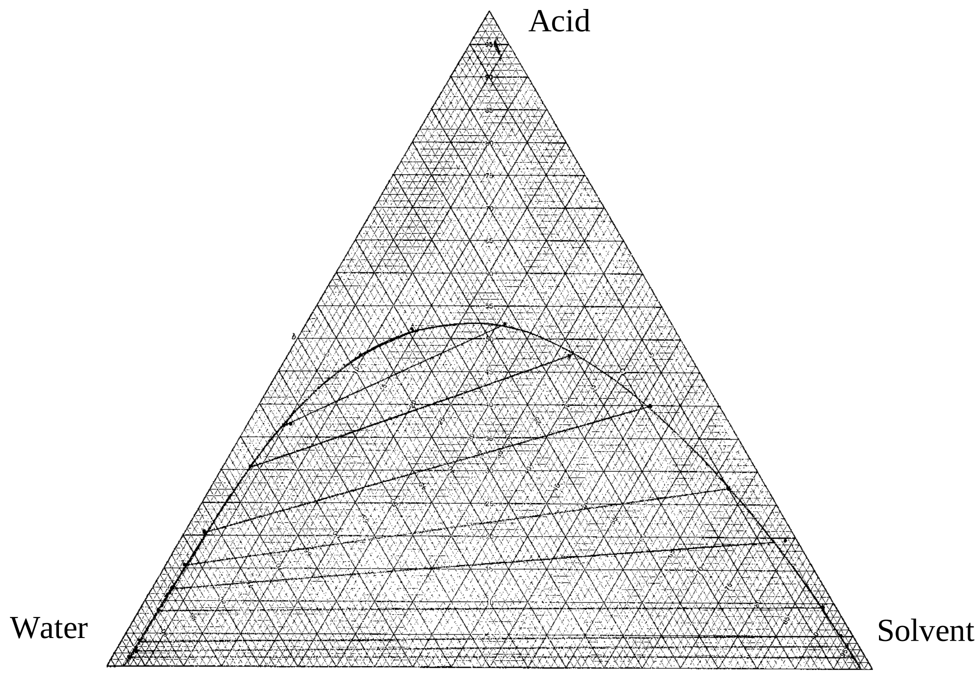

Figure 4. Acid/Solvent A/Water Ternary Phase Diagram

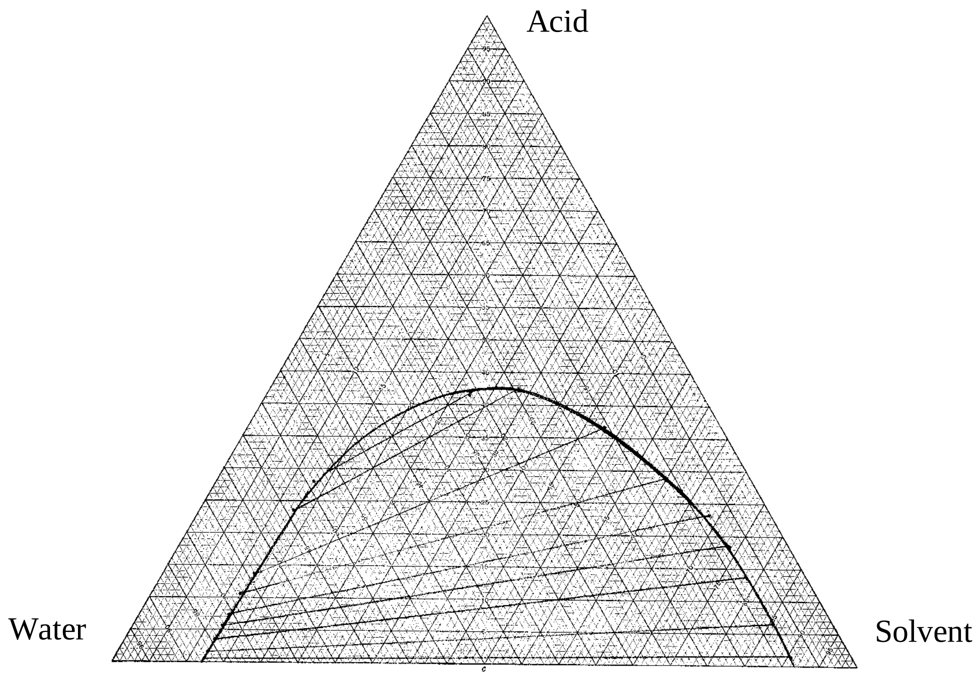

Figure 5. Acid/Solvent B/Water Ternary Phase Diagram

4.2.2 Development of Acrylic Acid Recovery System Layout

The purpose of the acrylic acid recovery system is to separate the acrylic and acetic acids from the solvent recovery column bottoms product (stream 18). The two product streams from the acrylic acid recovery system should be a 99.9 wt% pure acrylic acid stream and a 99 wt% pure acetic acid stream. Unlike the other sections of this design project, this section of the plant is completely unspecified. Therefore, before we can begin to specify the details of this section, we must arrive at a general design layout.

We would normally accomplish a simple binary separation like this one in a single distillation column with a partial reboiler and a total condenser. However, as was stated in the solvent recovery section, liquid solutions containing appreciable acrylic acid compositions polymerize if they are heated above 90°C. This affects our design in the following way. The hottest point in a distillation column is always the reboiler. If it is not possible to heat the solution in the column above 90°C, then we must set the reboiler at this temperature. This entails that the solution in the reboiler would have the pressure given by the following equations.

$$p^*_{HAc,90} = p_{Crit,HAc}\, exp\left(A_{HAc} - \frac{B_{HAc}}{90 + C_{HAc}} \right)$$
$$p^*_{AA,90} = p_{Crit,AA}\, exp\left(A_{AA} - \frac{B_{AA}}{90 + C_{AA}} \right)$$
$$P_B = x_{HAc,24}\, p^*_{HAc,90} + (1 - x_{HAc,24})\, p^*_{AA,90}$$

It is not economically feasible to operate industrial distillation columns at pressures below 50 mmHg. Therefore, the pressure at the top of our column cannot be any lower than this. This enables us to calculate the maximum number of stages in the distillation column we would like to design to separate AA and HAc. ΔP_{IDEAL} is the pressure drop for each ideal stage.

$$N_{IDEAL} \le \frac{P_B - 50}{\Delta P_{IDEAL}}$$

It is not possible to accomplish the AA/HAc separation in a distillation column that contains this many ideal stages without an absurdly high, and thus cost-prohibitive, reflux ratio. As a result, the design shown in Figure 6 has been proposed. The system is basically a single counter-current distillation cascade that has been divided into two separate columns. The temperature at the bottom of both columns is to be set at 90°C. In this way, it will be possible to allow for more than twice as many stages, and the separation can be accomplished with a reasonable reflux ratio. As shown in the diagram, the feed (stream 18) will enter at the top of the acrylic acid stripping column. The vapor leaving the top of this first column (stream 35) will be heated to 90°C and then enter the bottom of the acetic acid rectification column. The liquid from the bottom of this second column (stream 38) will enter the top of the first column. The entire system will have only one reboiler at the bottom of the acrylic acid stripping column and one condenser at the top of the acetic acid rectification column. It is important to note that this is not the only acceptable

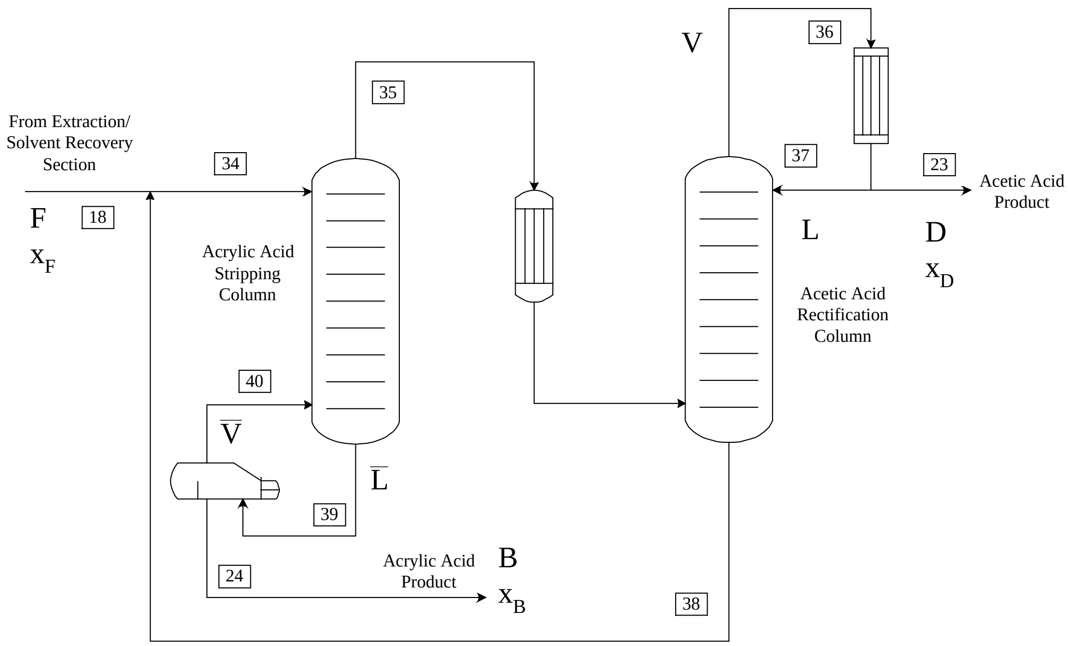

Figure 6. Acrylic Acid Recovery System

solution to the acrylic acid recovery system design problem, but it does seem to be an extremely economical one.

4.3 Vacuum Residue Heat Exchanger Design Problem Statement

Figure 2 shows the preliminary process flowsheet that has been proposed to perform the conversion of vacuum residue into MTBE. Your specific task is to design the heat exchanger system that is a part of the Rectisol plant.

The Rectisol plant is a turnkey facility that is used to remove all carbonyl sulfide, hydrogen sulfide, and carbon dioxide from the process stream leaving the product cooler. All sulfur compounds and carbon dioxide must be removed before the stream is passed into the methanol synthesis loop. The specific system of concern is shown in Figure 7. The individual component flowrates for Stream 1 are given below in Table 3.

Table 3. Stream 1 Flowrates.

Component	Stream 1 (kmol/h)
Carbon dioxide	180.20
Carbon monoxide	167.50
Carbonyl sulfide	0.60
Hydrogen	418.80
Hydrogen sulfide	8.50
Nitrogen	10.10

Stream 2A should be heated as much as possible (200°C or more, within reasonable design limits). The heat transfer coefficient for E101 is 2 Btu/h/ft^2/°F, and the heat transfer coefficient for E102 is 50 Btu/h/ft^2/°F.

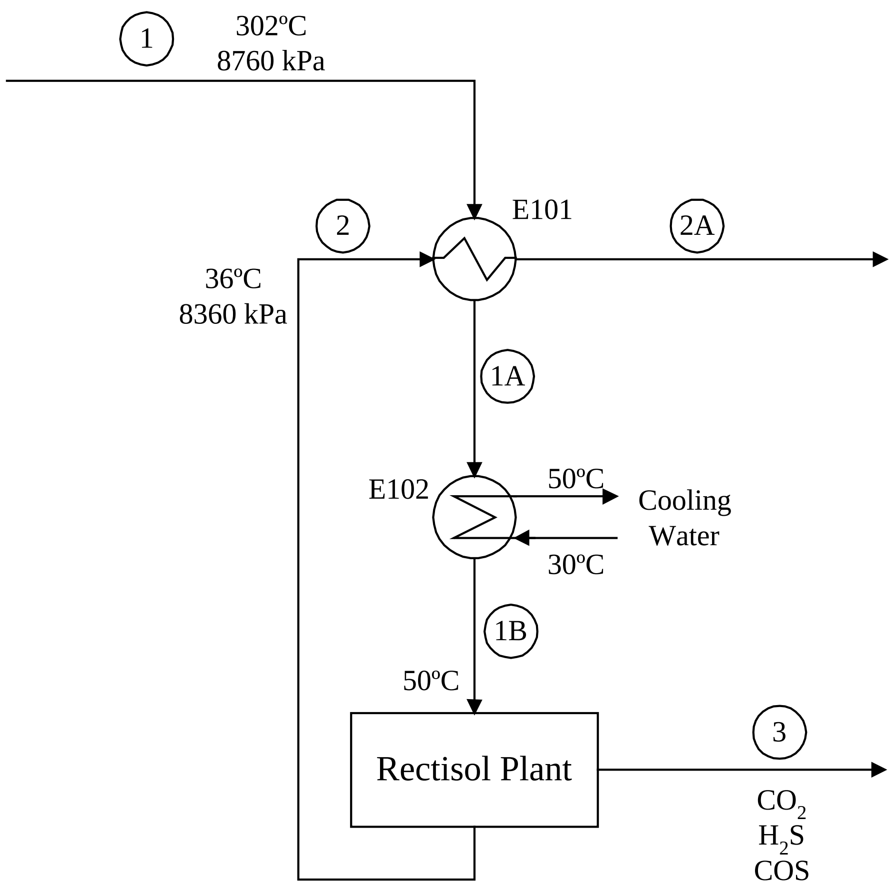

Figure 7. Rectisol Plant Heat Exchanger System

4.4 Vacuum Residue Methanol Synthesis Reactor Problem Statement

Your specific task is to design the methanol synthesis reactor for converting carbon monoxide and hydrogen to methanol. The required methanol production rate is 152 kmol/h. I spoke to Dr. Signs in Research and Development and obtained the information that I thought would be most important to you in designing this reactor. He has run the reaction on a pilot scale and determined that the optimum molar ratio of hydrogen to carbon monoxide in the fresh feed is 2.5:1 and that the maximum ratio in the total feed to the reactor should be 7.5:1. Unfortunately, approximately 0.4% by weight of the carbon monoxide in the feed will react with hydrogen to form dimethyl ether and water in a 1:1 molar ratio. Dr. Signs assures us that essentially all of the dimethyl ether formed in this reaction will dissolve in the condensed methanol and water. Also, the desired reaction (formation of methanol from carbon monoxide and hydrogen) will not reach thermodynamic equilibrium in any reasonable time and is therefore to be considered kinetically limited. The results of Dr. Signs' reaction kinetic experiments are as follows:

Table 4. Kinetic Data for Methanol Synthesis Reactor

Effective Methanol Reaction Rate (all values in table expressed as kmol/hr methanol produced per kg catalyst contacted)				
	Mole Percent Methanol in Mixture			
Temperature (C)	**0**	**2**	**4**	**6**
200	0.003	0.003	0.002	0.002
215	0.006	0.005	0.005	0.004
235	0.014	0.013	0.011	0.010
245	0.025	0.023	0.020	0.017
255	0.038	0.034	0.030	0.026
265	0.050	0.043	0.037	0.030

In addition to this reaction rate information, Dr. Signs' pilot team has also given us the following information derived from the research on their pilot reactors. The reactor should be a single-pass, shell-and-tube vertical vessel with a feed that has been preheated to 200°C. The tubes should be packed with a Cu/ZnO catalyst and should be cooled by shell-side saturated water maintained at 240°C. The steam generated on the shell side is used in the plant's powerhouse. The catalyst comes in extruded cylinders (6 mm diam. x 6 mm), can be operated between 200 and 265°C, and has a bulk density of 1120 kg/m^3. Each tube will have an inside diameter of 0.05m and a film heat transfer coefficient for the flow of heat from the reaction gas to the boiling water in the shell section of 125 $J/s/m^2/°C$. While it would be possible to design a custom reactor if you found it to be worthwhile, it would probably be more reasonable to use standard tube bundles, which are available in lengths of 3.05, 3.66, 4.88, and 6.10 m. A list of the number of tubes vs. vessel diameter follows.

Table 5. Standard Tube Bundles and Vessel Diameters

Shell Inside Diameter (m)	Number of Tubes
3.040	1150
3.650	1670
4.870	2960

In order to give you a better idea of the entire project scope and to clarify your particular task, I have attached an overall process flow diagram (Figure 2) and a close-up of the reactor you are to design (Figure 8). Please keep me informed of your progress, and do not hesitate to discuss with me any problems you encounter in the design process.

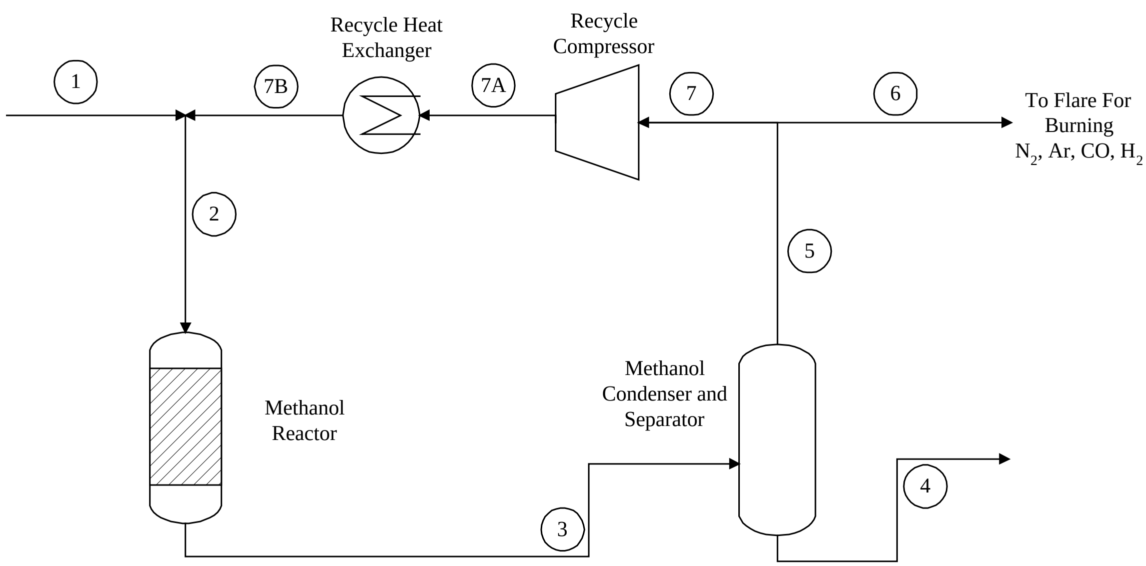

Figure 8. Methanol Synthesis Reactor Loop

5 Project Evaluation

An important step in changing any curriculum is understanding the impact that it has on the students and how to measure this impact. This section will suggest some ways to measure the quality of education, and discuss data that has been recently collected.

5.1 Student Interviews

Working as teaching assistants over the last several years has given us the opportunity to talk with a number of students about the chemical engineering program at Penn State. We were mostly interested in how well students were prepared for ChE 464 (Plant Design) and what changes they believed might be useful in order to better prepare them for the course. The students unanimously agreed that ChE 464 was an incredible amount of work and was overwhelming at times. In relation to design, several students were frustrated by their previous lack of exposure to design in their coursework. Many had never generated design specifications for any unit operations at all, and being asked to specify an entire plant seemed like an insurmountable task. Some students wished they had gained some exposure to the simulation programs before starting the design course, so that they would not have been forced to simultaneously learn plant design and a new computer program.

Based on our discussions with these students, we concluded that they generally felt under-prepared for the design course, and that prior exposure to design would have been helpful. One good way to determine what would be helpful to students is to simply ask the students themselves.

5.2 Student Surveys

Two groups of students were surveyed: students who were taking plant design in Spring 1997, and students who were not. A large portion of chemical engineering students was surveyed during class time in ChE 301, 302, 303, 304, 413 and 414. The survey was designed to quickly assess a student's estimation of their own personal understanding of a subject matter related to theory and applied design of a particular subject. A similar survey was presented to ChE 464 students during the interview sessions that were a required part of the course. Students completing this survey had more time to look at it, and so a slightly more detailed survey was used.

In both surveys, students were asked to rate their overall understanding of a particular theoretical topic from each core course. Students were also asked to rate their understanding of how to design particular unit operations that they might see in their plant design course. The goal of the survey is somewhat obvious: to compare a theoretical understanding versus the application of this theory for designing unit operations. In addition students were also asked about any co-op or internship experience. The point of this question was to see if experience in industry had any significant impact on either theoretical or applied understanding of a topic.

From a preliminary analysis, students that did have case study projects in their courses tend to rate their understanding of both theory and practice higher than students that did not. Unfortunately, with such limited data, it is nearly impossible to tell if higher ratings are due to the quality of the instructor or the use of the case study projects.

The number of "core" students varies for each course because students not yet taking the course were eliminated from each individual average. A total of 190 "core" students and 79 ChE 464 students were surveyed. It should be noted that the sum of the all the "core" students will be greater than the number actually surveyed. This is due to the fact that almost every student takes more than one chemical engineering course in any given semester.

Table 6. Number of Students Surveyed for Each Course

Course	Number of students surveyed
ChE 301	191
ChE 302	157
ChE 303	174
ChE 304	87
ChE 413	81
ChE 414	42
ChE 464	79

Each theoretical topic is shown with its associated course in Table 7.

Table 7. Theoretical Topics and Associated Courses

Topic	Course
Material Balances	ChE 301
Fluid Flow	ChE 302
Heat Transfer	ChE 302
Thermodynamics	ChE 303
Phase Equilibrium	ChE 304
Mass Transfer	ChE 413
Reaction Kinetics	ChE 414

The average student rankings of their personal knowledge is given below for both groups of students. (1 = do not understand at all, 7 = understand completely). Each theoretical topic is grouped with its corresponding unit operations.

Table 8. Comparison of Theoretical Versus Application Knowledge

Subject	Core Students	ChE 464 Students	Unit Operation	Core Students	ChE 464 Students
Material Balances	6.01	6.44			
Fluid Flow	4.75	4.81	Pumps	3.17	3.09
Heat Transfer	4.85	4.95	Heat Exchangers	4.16	4.35
Thermodynamics	5.41	5.29	Air Compressors	2.42	2.56
Phase Equilibrium	5.05	4.99	Flash Drums	3.66	3.75
Mass Transfer	5.26	4.77	Distillation Columns	5.49	4.49
			Absorbers/Strippers	4.75	3.39
			Liq.-Liq. Extractors	5.04	3.67
Reaction Kinetics	5.05	5.03	Reactors	4.93	4.39

In general, both core students and ChE 464 students gave similar ratings for their understanding of a particular topic. The one noticeable difference is mass transfer, but this is due to instructor differences, and so resolving this disparity will not be addressed within this paper. In general, students rank their design knowledge lower than their understanding of theoretical principles. This is particularly noticeable in ChE 303 and ChE 304 regarding the design of air compressors and flash drums.

ChE 464 students were asked a few additional questions regarding how well prepared they were for the course, the importance of learning unit operations design prior to 464, and what items helped them learn chemical engineering principles the best. The table below shows the rankings for various learning tools (1 = not helpful at all, 7 = very helpful).

Table 9. Student Rankings of Learning Tools

Learning Tool	Score
Case Study Projects	5.75
Homework	5.65
Lectures	4.69
Textbooks	4.68
Exams	4.29

The above table tells us that case study projects and homework are an integral part of teaching students about chemical engineering. The result reaffirms that using case studies and homework assignments to teach students about design can be effective. No significant correlation was found between co-op/internship experience and any of the other variables within the survey, although this could be due to some inherent flaws with the method of surveying students.

The most significant problem with the survey is that students judge themselves based on some internal measure. As students gain more exposure to a topic and learn more about it, they realize how little they understand in relation to the overall picture. Since everyone evaluates themselves, there is no absolute standard but instead an internal standard which means something different for each person. This can be problematic since two people with entirely different understandings of a topic can give the same score. This problem should not be ignored, but the survey still serves a purpose for identifying how students feel about their understanding of a topic. Extensive statistical analysis will not resolve this internal bias within each person, which simply means that the numbers are useful as indicators, but not as absolute measures of how much a student understands. The individual ratings of understanding are better described as students' confidence in their abilities in a particular topic.

There are always improvements that can be made to these surveys. The learning tools can be expanded slightly to include some other topics identified by students: student/teacher interaction, student/teaching assistant interaction, and student/student interaction.

6 Conclusion

The vertical design of chemical engineering involves exposing undergraduate students to design principles throughout their coursework. The purpose of this project was to develop a series of design projects and case studies that can be integrated into the existing core courses during the sophomore and junior year. By using the 1986 and 1989 AIChE Student Contest Problems as a starting point, several projects were developed for each of the six core courses in Chemical Engineering at Penn State University. In addition, a CD-ROM containing these case study projects and solutions in electronic form has been assembled and made available to the faculty at Penn State. These projects will help to prepare students for their senior capstone design course by exposing them to design principles as they learn theory in each course.

The work on implementing the program is far from over. These projects will never add value to the program unless they are actually used by faculty members within the department. It is also necessary to put a system in place which evaluates the progress of engineering students relative to their understanding of design principles. Understanding the program's effectiveness will direct what should be done in the future and what changes should be implemented to improve how students learn chemical engineering principles.

In conclusion, these projects should greatly enhance any student's classroom experience by showing them how to apply what they have learned. Even if students never actually design unit operations in their professional careers, the enhanced understanding and application of what they have learned will help better prepare them for the problems they will see in industry. The next step is to continue implementation, and to begin evaluating and understanding the effects of vertically integrating design into chemical engineering.

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