Teaching Chemical Engineering with Physical Plant Model at Cal Poly, Pomona

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A physical model is an exact replica of a real plant. Models are excellent teaching tools. During 1996-1997, I have taken the initiative to revitalize the physical model of ARCO's hydro-desulfurization plant, which was donated to the department many years ago, but was never used. Through my industrial contacts, I obtained the process flow diagram from ARCO and worked with several students cleaning and re-organizing the model. To gain a better understanding of the process, one student worked with me to simulate the process on the computer. In 1996, for the first time the model was used extensively as a teaching tool in the design class. The students can now identify the size and shape of equipment and have a feel for what it takes to build a plant.

During the spring quarter of 1997, I replaced the older ARCO plant model with three Chevron plant models. The models represent three of Chevron's newest plants for manufacturing cleaner fuels. I negotiated the delivery of the models at Chevron's cost and organized a student team to dismantle the old model and put together the new model.

During the summer of 1997, I studied the details of the Chevron plant models and developed two tiers of teaching materials, one for the seniors and one for the sophomores and started to use the materials in the fall. The physical models are valuable tools for introducing the sophomores to the essence of chemical engineering. By devising some design exercises around the model, I generated some excitement in the sophomore class. For the senior class, the models serve as excellent validation for the design concepts they have learned in class. I have also made arrangements for the senior class to visit the exact same plants represented by the models in the Chevron Refinery.

In order to encourage other faculty members to use the physical model approach, I have started preparing a teaching manual entitled "Teaching Chemical Engineering with Physical Models" which documents process descriptions, student assignments and solutions. It also contains suggestions on how the models can be integrated into other courses in the chemical engineering curriculum. The following summarizes the teaching materials that can be integrated into the four years of chemical engineering curriculum in Cal Poly, Pomona.

Freshmen Class

This year I have the opportunity of developing a new course for the freshmen class. Many students at age 18 come to the university and choose a major called chemical engineering without knowing what it is. Very often, they were disillusioned after two years in the major to find out that they really are interested in atoms and the magic of chemistry but not distillation or heat transfer. The objectives of this new course is to introduce to the students in their freshmen year what chemical engineering is through real-life experiments and demonstrations which they can see and touch. One colleague in the 1999 ASEE conference gave an inspiring talk on inductive teaching. He said that traditionally, we taught the students fundamentals of mathematics, science and transport phenomena for the first three years and asked them to be patient and promised them they would see applications either in the fourth year or when they worked in industry. "You know what," he said "the students do not trust us." It is my intent to adopt his inductive method of teaching applications first before differential equations, entropy or enthalpy. To teach chemical engineering applications to the freshmen, I needed something for them to see. What is better than pointing at a physical model which is an exact replica of a complete chemical plant and say that this is chemical engineering at work?

Figure (1) shows the photograph of the Chevron's TAME (tertiary amyl methyl ether) plant which was constructed in 1995 to produce high octane TAME for gasoline blending. On the photograph, you will see several students attempting to measure the size of the equipment.

Freshmen are given a simplified process flow diagram and a description of the process such as that shown in Figure (2). The description is short and easy for the freshmen to understand without any knowledge of chemical engineering terminology. The instructor "walks" them through the process showing where columns, pumps, exchangers and air coolers are. He also impresses them on the size of the equipment by having the students measure the model dimension and calculate the actual sizes. This is the first time students have an idea of what a chemical plant is and that this may be the type of plant they will design or work on after they graduate.

Sophomore Class

In the sophomore's stoichiometry class, the students are introduced to the onion diagram concept[(1)] depicting the hierarchy of process design and synthesis (Figure (3)).
The onion diagram shows that a process is constructed by building the innermost skin of an onion representing the reactor followed by the separator and the heat exchanger network (HEN). Finally, the outermost skin represents the utilities. While HEN provides heating and cooling requirements through process-to-process heat exchange, the utilities fill in the remaining energy requirement.

Figure (3) shows a model-related assignment that the sophomore class does. In this assignment, students identify major pieces of equipment marked by their ID's and state whether they are columns, vessels, exchangers, or air-cooler, etc. and categorize each piece of equipment according to the hierarchy in the onion diagram. For exchangers, students can determine whether they are HEN or utility exchangers by observing the color codes of the pipes. Students also measure the dimensions of the equipment and calculate its sizes. The objectives of the exercise are manifold: (1) students learn what an exchanger, a pump or a column looks like (2) students appreciate the size of the equipment, (for example, a column could be 10 feet in diameter and 180 feet high, an exchanger is 30 inches in diameter and 20 feet long), (3) students learn that almost all major equipment in a plant fits into any one category of the onion diagram.

A subsequent exercise in this class is to have students synthesize an ammonia plant using the onion diagram concept. Besides installing reactors and separators, the students now appreciate the concept of heat integration in creating a HEN for process heat recovery.

In one exercise, students complete the material balance of the entire TAME plant.

Junior Class

My favorite assignment for the students is to ask students in the Fluids Class to size several pipes for both liquid and vapor and several pumps in the TAME plant. Figure (4) shows the assignment in which the students have to size pipes based on common velocity and pressure requirements. Students can check their answers against actual measurements from the model. They now appreciate that the vapor lines are significantly larger in diameter than those of liquid lines. From the model, they can easily identify whether the line is for vapor or liquid just by observing the relative sizes. For example, they can readily identify the liquid and vapor lines and the steam and condensate lines in a reboiler by observing the size of the nozzle. Figure (5) shows a picture of a reboiler. The green line on the top is the steam line which is much bigger than the green line at the bottom, the condensate line. The returning vapor line is also large and sits on top of the reboiler.

Students also size pumps for delivering liquid from the reflux accumulator to the top of a 180-ft high column by applying the Bernoulli equation. They can also identify that in this case the potential energy term is dominant.

In the heat transfer class, the model offers many examples of heat transfer equipment. Figure (6) shows an exercise on classifications of heat exchangers. Students discuss the sizes and shapes, advantages and disadvantages, capital and operating costs of the different types of exchangers.

Senior class

The senior curriculum at Cal Poly, Pomona is dominated by a series of process design and synthesis courses. To be exact, there are six courses, two in each quarter. For the entire academic year, students meet formally for six hours a week, three hours for lectures and three hours for design laboratory. The model is used extensively to show how a plant is designed and constructed, from process engineering, detailed equipment design, piping, civil electrical and instrumentation and finally to construction.

They now appreciate how complex the piping network is or how and why such a plot plan is put together. Students also have an opportunity to visit the actual plant in Chevron's El Segundo Refinery. It is such a treat to the students to finally see the real plant, exactly the same as the model which they have studied for several years. They climbed to the platform to see the large air-coolers and their exposed finned tubes. They marveled at the height of the depropanizer.

The design sequence follows a well-planned syllabus in which the first quarter discusses general concepts of plant design and synthesis. The onion diagram hierarchy of design is emphasized and extensively demonstrated using the TAME plant model. Heat integration by process-to-process heat transfer is common place in this plant. Students appreciate the importance of HEN in a plant as a mean of minimizing energy usage. They look for places where they can take advantage of process-to-process heat transfer for further heat integration.

The second quarter is devoted to equipment design. There are many examples students can draw from the model. Students design shell-and-tube exchangers in the form condensers, kettle reboilers, and thermosiphon reboilers and validate their designs with those in the plant model. Students also design the methanol recovery extraction and distillation columns found in the model with the aid of PROVISION, a computer process simulator. They determine the diameter and height of the columns and compare with those from the model. They design air-coolers which are common in many industries today, especially refineries.

Students observe that the overhead condenser and the reflux accumulator are actually at ground level and not near the top of the column as the instructor draw their sketches many times in their unit operation class. And the condenser could be an air-cooler in this case instead of a shell-and-tube exchanger. Students also observe that the columns usually have long skirts, 20-30 feet above the ground to allow for foundation, convenient maintenance, or extra hydraulic head for product pumps.

In the last quarter, the students perform the design of a complete plant. An ammonia plant was chosen for its many energy integration opportunities. Figure (7) shows a model of a primary reforming furnace in which natural gas reacts catalytically with steam in a high temperature environment. Students have an opportunity to design an intricate HEN to recover heat from the hot flue gas. The model was donated to Cal Poly by Brown & Root Inc.

The models offer many opportunities for senior projects. A complete model of the Chevron's Alkylation plant which started up in 1995 was donated to Cal Poly, Pomona. Several students used Provision to simulate the plant and to perform process studies. Figure (8) shows a complete model of the plant. You will notice one of the columns, the de-isobutanizer which is 7 feet tall (205 feet actual dimension) can not be fitted in the low ceiling model room. The top section had to be taken off (Figure 9). This plant offers many systems of HEN, large contactor-reactors of intricate design and settling drums (Figure 10). This plant has a refrigeration section which provides the students with an opportunity to design and validate such a system.

This model has not yet been fully integrated into our curriculum. As you know, MTBE, TAME and other ethers will be banned in United States in two years as additives to gasoline. We expect Chevron to shut down the TAME plant in the near future. At that time the TAME model will be replaced by the Alkylation model as our main teaching tool.

In conclusion, the physical models offer the students an opportunity to touch and feel a plant and to apply engineering concepts to the design of equipment. From the model, students will get a sense of the working environment they will be in when they graduate. The models are excellent teaching tools for the instructors, as they "walk" the students through the "plant" pointing out along the way the concepts of engineering. In my first lecture of Process Design, I adopted the method that Robin Williams used in his movie "The Dead Poet's Society". I asked the students to stand on their chairs to look from above at the TAME model located at the back of the classroom. I asked them to tell me what they see. I told them not to be overwhelmed by the complexity of a plant. It is simply a collection of equipment by pipes in an orderly manner.

1. Smith Robin, Chemical Process Design, P1-14, (1995), McGraw Hill Inc.

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Figure(1) Physical Model of Chevron's TAME Plant

Figure (2) Process Description of Chevron's TAME PLANT

The TAME plant which Started up in 1995 is One of Chevron's clean fuel project. The plant Combines amylene(isopentene) with methanol to make tertiary amyl methy ether(TAME)which is a critical component for gasoline because of its high octane and low vapor pressure. TAME as an ether also contains oxygen which enhances complete combustion of gasoline to carbon dioxide instead of carbon monoxide.

The TAME plant is one of the few plants in an oil refinery where operating temperatures and pressures are moderately low(about 200^{o}F and 50 psia. It is not uncommon for other plants in the refinery to have temperatures and pressure exceeding 600^{o}F and 800 psia.

In the TAME process, the feed containing amylene and other heavier hydrocarbons is first passed through the depentanizer where amylene is separated from the heavy components. Amylene then reacts with methanol in the primary reactor. The product from the reactoris pumped to the catalytic distillation column where further reactions and separation of TAME from unreacted components takes place. The unreacted methanol and amylene are separated in a mthanol recovery liquid-liquid extraction and distillation columns The recovered methanol is returned to the primary reactor. The amylene which now contains other by products is sent to another plant in the refinery.

The TAME plant is exclusively air-cooled except for minor water cooling necessary to control the product temperature for storage. There is also an intricate system of heat exchanger net for heat recovery.

This model is an exact replica of the Chevron's TAME plant. The scale is 1 inch in the model to 2.5 ft in the actual plant. Equipment includes:
40-foot high, 10-foot diameter primary reactor
180-foot high, 10-foot diameter depentanizer
180-foot high, 10-foot diameter catalytic distillation column
135-foot high, 9-foot diameter methanol recovery column air-cooler (10 feet by 30 feet rectangular block with circular rings on top)

Figure (3) Sophomore Class Assignment

From the physical model in room 13-214, perform the following tasks.

(1) Identify items marked 1- 30 by their equipment IDs.

(2) State whether they are column, exchangers, vessels, pumps, or reactors. Categorize each piece of equipment according to the hierarchy in the onion diagram.

(3) Using a scale of 1 inch to 2 ft 6inches, estimate the size of each equipment in terms of its diameter, length/height.

Figure (4) Fluids Assignment for Junior Class

(1) Design the size of the pipe for the vapor line leaving E5747 and the intake line of the pump P5740 by calculating the velocity of the vapor and the pressure drop per 100 feet of the pipe for several pipe sizes. Choose the size of the pipe which meets the following design criteria:

Design liquid velocity should be between 3 ft/sec and 10 ft/sec
Design vapor velocity should be between 30 ft/sec and 80 ft/sec
Design pressure drop per 100 ft of pipe should be less than 0.1 lb_f / in^2

The design procedure is as follow:
(a) Pick three nominal pipe sizes. Get an approximate size from the model. Use Standard Steel Pipe Tables to get inside diameter (Fluid Mechanics For Chemical Engineers by Noel de Nevers p509 or Perry's Handbook 5th edition 6.64). Assume Schedule 40 pipes
(b) Calculate velocity and pressure drops per 100 ft of pipe and choose the smallest pipe size which meet the design criteria.

(2) Design the horsepower of the pump P5740 which should be sufficient to pump the liquid from the accumulator V5740 to the top of the column C5740.

Figure (5) Model of A Reboiler

Figure (6) Heat Exchanger Assignment for Junior Class

(1) There are four type of heat exchangers in this plant, air coolers (finned fan exchangers), kettle reboiler, thermal siphon reboiler, shell-and-tube. Provide an example of each type of exchanger by its ID and its function. Use diagrams and a short descriptive to show their differences. Show where the fans are located in the air coolers and state whether the air coolers are induced draft or forced draft. Compare the physical size, the capital and operating costs of the following pairs of exchangers:
the shell-and-tube heat exchanger and the air cooler; the thermal siphon reboiler and kettle reboiler.

(2) For units 21, 22 and 23, use diagrams to show the direction of flow in the tube shell and the shell side to indicate whether they are connected in parallel or in series. State which one is a utility exchanger and which one is a process-to-process exchanger.

Figure(7) Model of a Primary Reforming Furnace

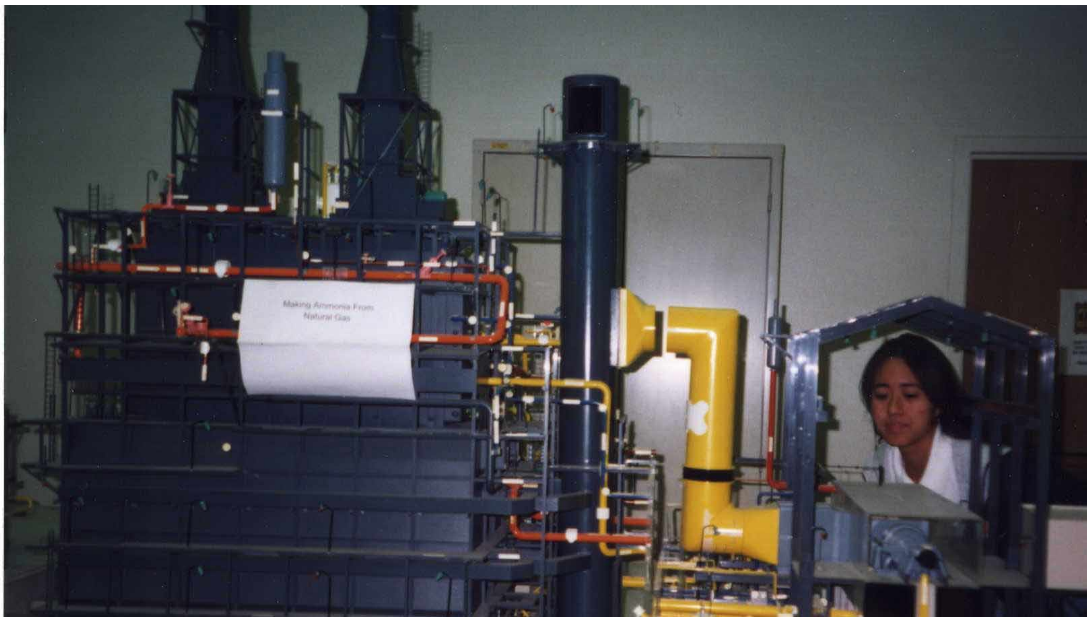

Figure (8) Model of Chevron's Alkylation Plant

Figure (9) Model of De-isobutanizer in Chevron's Alkylation Plant

Figure(10) Model of Contactor-Reactor and Settling Tank