Open-Ended Problems: A Future Chemical Engineering Education Approach. J. Patrick Abulencia and Louis Theodore.

11

Plant Design

This chapter is concerned with process plant design. As with all the chapters in Part II, there are several sections: overview, several technical topics, illustrative open-ended problems, and open-ended problems. The purpose of the first section is to introduce the reader to the subject of plant design. As one might suppose, a comprehensive treatment is not provided although several technical topics are also included. The next section contains three open-ended problems; the authors' solution (there may be other solutions) is also provided. The final section contains 35 problems; *no* solutions are provided here.

11.1 Overview

This overview section is concerned—as can be noted from the chapter's title—with plant design. As one might suppose, it was not possible to address all topics directly or indirectly related to plant design. However, additional details may be obtained from either the references provided at the end of this Overview section and/or at the end of the chapter.

Note: Those readers already familiar with the details associated with this subject may choose to bypass this Overview.

Current process and plant design practices can fall into the category of state of the art and pure empiricism. Past experience with similar applications is commonly used as the sole basis for the design procedure. The vendor (seller) maintains proprietary files on past installations, and these files are periodically revised and expanded as new installations are evaluated. In designing in a new unit, the files are consulted for similar applications and old designs are heavily relied upon [1].

By contrast, the engineering profession in general, and the chemical engineering profession in particular, has developed fairly well-defined procedures for the design, construction, and operating of many chemical plants. These techniques are routinely used by today's chemical engineers. These same procedures may also be used in the design of other facilities [1].

The purpose of this chapter is to introduce the reader to some of the process and plant design fundamentals. Such an introduction to design principles, however sketchy, can provide the reader with a better understanding of the major engineering aspects of new or modified facilities, including some of the operational, economic, controls, and instrumentation for safety and regulatory requirements, and environmental factors associated with the process [1].

The author [1] has simplified the design process by keying in five topics that are summarized via the acronym SCORE; i.e.,

Safety
Costs
Operability
Reliability
Environment

It should also be noted that process plant location and layout considerations are not reviewed. However, in a general sense, physical plant considerations should include process flow, construction, maintenance, operator access, site conditions, space limitations, future expansion, special piping requirements, structural supports, storage space, utility requirements, instruments and controls, and (if applicable) energy conservation. A more detailed presentation is provided in a later section. Finally the reader should note that no attempt is made in the sections that follow to provide extensive coverage of this topic; only general procedures and concepts are presented and discussed.

The remaining chapter contents include:

1. Preliminary Studies
2. Process Schematics
3. Material and Energy Balances
4. Equipment Design
5. Instrumentation and Controls
6. Design Approach
7. The Design Report.

The bulk of the material in this chapter has been drawn from:

1. Personal notes of Theodore [1],
2. T. Shen, Y. Choi and L. Theodore, *EPA Manual Hazardous Waste Incineration*, USEPA/APTI, RTP, NC, 1985 [2], and
3. L. Theodore, *Hazardous Waste Incineration*, Instructor's Guide, USEPA/APTI, RTP, NC, 1986 [3].

11.2 Preliminary Studies

A process chemical engineer is often involved in one of two principle activities: designing/building a plant or deciding whether to do so. The skills required in both cases are often similar, but the money, time, and details involved are not as great in the latter situation. The authors estimate that only one out of 15 proposed new processes ever reaches the construction stage.

In general engineering design practice, there are usually five levels of sophistication for evaluating projects and estimating costs. Each is discussed in the following list, with particular emphasis on cost.

1. The first level of analysis requires little more than identification of products, raw materials, and utilities. This what is known as an *order of magnitude estimate* and is often made by extrapolating or interpolating from data on similar existing processes.
2. The next level of sophistication is called a *study estimate* and requires a preliminary process flow sheet (to be discussed in the next section) and a first attempt at identification of equipment, utilities, materials of construction, and other processing units.

3. A *scope* or *budget authorization* is the next level of evaluation; it requires a more defined process definition, detailed process flow sheets, and pre-final equipment design (discussed in a later section).
4. If the evaluation is positive at this stage, a *project control estimate* is then prepared. Final flow sheets, site analyses, equipment specifications, and architectural and engineering sketches are employed to prepare this estimate.
5. The fifth and final (economic) analysis is called a *firm* or *contractor's estimate*. It is based on detailed specifications and actual equipment bids. It is employed by the contractor to establish a project cost and has the highest level of accuracy.

11.3 Process Schematics

To the practicing engineer and particularly the chemical engineer, the process flow sheet is the key instrument for defining, refining, and documenting a chemical process. The process flow diagram is the authorized process blueprint, the framework for specifications used in equipment designation and design; it is the single, authoritative document employed to define, construct, and operate the chemical process [4].

Beyond equipment symbols and process stream flow lines, there are several essential elements contributing to a detailed process flow sheet. These include equipment identification numbers and names, temperature and pressure designations, utility designations, mass, molar and volumetric flow rates for each process steam, and a material balance table pertaining to process flow rates. The process flow diagram may also contain additional information such as energy requirements, major instrumentation, environmental equipment (and concerns), and physical properties of the process streams. When properly assembled and employed, a process schematic provides a coherent picture of the overall process; it can pinpoint some deficiencies in the process that may have been overlooked earlier in the study, e.g., instrumentation overkill, by-products (undesirable or otherwise), and recycle needs. Basically, the flow sheet symbolically and pictorially represents the interrelation between the various flow streams and equipment, and permits easy calculations of material and energy balances. These two topics are considered in the next section. Controls and instrumentation must also be considered in the overall requirements of the system; these concerns are covered later in this chapter as well as in a previous chapter.

As one might expect, a process flow diagram for a chemical or petroleum plant is usually significantly more complex than that for a simple facility. For the latter case, the flow sequence and determinations thus approach a "railroad" or sequential type of calculation that does not require iterative calculations.

The degree of sophistication and details of a flow sheet usually vary with both the preparer and time. The flow sheet may initially consist of a simple free-hand block diagram with limited information that includes only the equipment. Later versions may include line drawings with pertinent process data such as the overall and componential flow rates, utility and energy requirements, environmental equipment, and instrumentation. During the latter stages of the design project, the flow sheet will consist of a highly detailed P&I (piping and instrumentation) diagram; this aspect of the design procedure is beyond the scope of this text; the reader is referred to literature [2,5] for information on P&I diagrams.

In a sense, flow sheets are the international language of the engineer, particularly the chemical engineer. Chemical engineers conceptually view a (chemical) plant as consisting of a series of interrelated building blocks that are defined as *units* or *unit operations*. The plant essentially ties together the various pieces of equipment that make up the process. Flow schematics follow the successive steps of a process by indicating where the pieces of equipment are located and the materials streams entering and leaving each unit [6–8].

11.4 Material and Energy Balances

Overall and componential material balances have already been described in some detail earlier in Chapter 4. As noted at that time, material balances may be based on mass, moles, or volume, usually on a rate (time rate of change) basis. Care should be exercised here since moles and volumes are *not* conserved, i.e., the quantities may change during the course of a reaction. Thus, the initial material balance calculation should be based on *mass*. Mole balances and molar information are important in not only stoichiometric calculations but also in chemical reaction and phase equilibria calculations. Volume rates play an important role in equipment sizing calculations.

Some present-day design calculations in the chemical industry include transient effects that can account for *process upsets*, *startups*, *shutdowns*, etc. The describing equations for these time-varying (unsteady-state) systems are generally *differential*. The equations usually take the form of a first-order derivative with respect to time, where time is the independent variable. However, design calculations for most facilities assume steady-state conditions, with the ultimate design based on maximum flow conditions. This greatly simplifies the calculations, since the describing equations provide an accounting or inventory of all mass entering and leaving one or more pieces of equipment, or the entire process.

The number of material balance equations can significantly depend on a host of factors, including the number of components in the system, process chemistry, and pieces of equipment. These are critical calculations since (as noted earlier) the size of the equipment is often linearly related to the quantity of material being processes. This can then significantly impact – often linearly or even exponentially – capital and operating costs. In addition, componential rates can impact on (other) equipment needs, energy considerations, material of construction, etc.

Once the material balance(s) is/are completed, one may then precede directly to energy calculations, some of which play a significant role in the design of a facility. As indicated earlier, energy calculations are also usually based on steady-state conditions. An extensive treatment of this subject has already been presented earlier in this text, and need not be repeated here. However, a thorough understanding of thermodynamic principles – particularly the enthalpy calculations – is required for most of the energy (balance) calculations.

One of the principal jobs of a chemical engineer involved in the design of a facility is to account for the energy that flows into and out of each process unit and to determine the overall energy requirements for the process. This is accomplished by performing the aforementioned energy balances on each process unit and on the overall process. These balances play as important a role as material balances in facility design. They find particular application in determining fuel requirements, in heat exchanger design, in heat recovery systems, in specifying materials of construction, and in calculating fan and pump power requirements.

11.5 Equipment Design

As noted previously, chemical engineers describe the operation of any piece of equipment on the basis of mass, energy, and/or momentum transfer as a *unit operation*. A combination of two or more of these operations is defined as a *unit process*. A whole chemical process can be described as a coordinated set of unit operations and unit processes. This subject matter has received much attention over the years and, as a result, is adequately covered in the literature. From details on these unit operations and processes, it is therefore possible to design new plants more efficiently by coordinating a series of *unit actions*, each of which operates according to certain laws of physics regardless of the other operations being performed along with it. The unit operation of combustion is used in many different types of industries; many of the critical design parameters for the combustion processes, however, are common to all combustion systems and independent of the particular industry.

For example, in a hazardous waste incineration plant, the major pieces of equipment that must be considered are all of the following: [9]

1. Storage and handling facilities (feed and residuals)
2. Incinerator (rotary kiln or liquid injection)
3. Waste heat boiler (primary quench system or energy recovery if economically practical)
4. Quench system
5. Wet scrubber – venturi scrubber (particulate removal scrubber)
6. Absorber (packed tower for acid-gas absorption)
7. Spray dryer (quench and acid gas absorption)
8. Baghouse or electrostatic precipitators (ESP)
9. Peripheral equipment (cyclone)
10. Fan(s) and blower(s)
11. Stack
12. Pumps (feed, recycle, and scrubber)

Since design calculations are generally based on the maximum throughput capacity for the proposed process or for each piece of equipment, these calculations are never completely accurate. It is usually necessary to apply reasonable *safety factors* when setting the final design. Safety factors vary widely and are a strong function of the accuracy of the data involved, calculation procedures, and past experience. A process engineer's attempt to quantify these is a difficult task.

Unlike some of the problems encountered and solved by the chemical engineer, there is absolutely no correct solution to a design problem; however, there is usually a *better* solution. Many alternative designs, when properly implemented, will function satisfactorily, but one alternative will usually prove to be economically more efficient and/or attractive than the others. This leads to the general subject of optimization, a topic briefly addressed earlier in Chapters 2 and 10.

11.6 Instrumentation and Controls

The control of a system or process requires careful consideration of all operational and regulatory requirements. The system is usually designed to process materials. Safety [10] should be a primary concern of all individuals involved with the handling, treatment, or movement of the materials. The safe operation of any unit requires that the controls keep the system operating within a safe operating envelope. (See also Chapters 14 and 15). The envelope is based on many of the design, process, and regulatory constraints. These are placed on the unit to ensure proper operation. Additional controls may be installed to operate additional equipment needed for energy recovery, neutralization, or other peripheral operations.

The control system should also be designed to vary one or more of the process variables to maintain the appropriate conditions with the unit. These variations are programmed into the system based on the past experience of the unit manufactured. The operational parameters that may vary include the temperatures, system pressure, etc.

The purpose of a control system is to ensure that the system is operating in a reliable and safe manner, and within the guidelines of the design. The control system is responsible for all of the variables that occur during operation of the system. The reader is referred to Chapter 9 for additional details on instrumentation and controls.

11.7 Design Approach

Although chemical engineers approach design problems somewhat differently, six major steps are generally required. These six steps are briefly discussed below and may also be applied to the design of most facilities:

1. The first step is to conceptualize and define the process. A designer must know the assumptions that apply, the plant capacity, and the process time allowed. Some of the answers to a host of questions pertaining to the process operation will be known from past experience.

2. After the problem has been defined, a method of solution must be sought. Although a method is seldom obvious, a good starting point is the construction of a process flow sheet. This effort usually produces variable results. For example, it may suggest to the designer ways of reducing the complexity of the problem; it can allow for easier execution of material and energy balances, which in turn can point out the most important process variables. It is an efficient way to become familiar with the process; and, information that is initially lacking often becomes evident.
3. The third step is the actual design of the process equipment that involves the numerous calculations needed to arrive at specifications of operating conditions, equipment geometry, size, materials of construction, controls, instrumentation, monitors, safety equipment (automatic feed cut-off), etc. Equipment costs must be established part of this step. Cost-estimating precision is dependent on the desired accuracy of the estimate. If the decision based on an estimate is positive, a detailed project control or contractor's estimate will follow.
4. An overall economic analysis must also be performed in order to determine the process feasibility. The main purpose of this step is to answer the question of whether a process will ultimately be profitable or not. To answer this, raw material, labor, equipment, and other processing costs are estimated to provide an accurate economic forecast for the proposed operation.
5. In a case where alternate design possibilities exist, economics and engineering optimization are necessary. Since this is often the case, optimization calculations are usually applied several times during most design projects.
6. The final step of this design scheme is the compiling of a design report. A design report may represent the only relevant product of months or even years of effort. This is discussed in the next, and final, section.

These six activities are prominent steps in the traditional development of all modern chemical processes. Today, safety and regulatory (if applicable) concerns have also been integrated into the approach [10].

As noted earlier, the safe operation of equipment requires that some of the operational parameter be constrained within specific bounds. Each system has parameters that must remain within the appropriate bounds to assure that the system is stable. Most systems will have safety equipment to prevent the system from being operated at a condition outside of the safe limits. Insurance companies such as Industrial Risk Insurers (IRI), Factory Mutual (FM), and national groups such as National Fire Protection Agency (NFPA) have recommended specific requirements, the most important being to assume that all personnel are properly trained on operation limitations of the equipment.

Any environmental regulation requires that each of the operational limits be monitored to assure that the system has not been operated when the parameters have been exceeded. However, any of the permit parameters often cannot be monitored on a continuous basis. The design of a system must include both standard and nonstandard operational conditions.

11.8 The Design Report

As pointed out in Step 6 in the previous Section, a comprehensive plant design project report is often required. This material should be written up in a clear and concise fashion. In addition, the project leader might be requested to make informal and/or formal presentations to management on the study. The report and presentation should explain what has been accomplished and how it has been carried out. There are many different formats for design reports; the format will vary with the organization and the project. One possible outline employed by the authors for a project report is given in the following list:

1. Title page
2. Table of contents
3. Executive summary (abstract)
4. Prefactory comments (optional)
5. Introduction
6. Discussion
7. Laboratory studies (if applicable)
8. Pilot plant studies (if applicable)
9. Comprehensive process design, process flow diagrams, including mass and energy balances, and annualized costs
10. Calculation limitations
11. Design limitations
12. Optimization studies

13. Recommendations
14. Acknowledgements
15. Appendix.

Great care should be exercised with the preparation of the *executive summary*. It is recommended that the executive summary be no longer than one single-spaced typewritten page. It should contain a short introduction, important results, and pertinent recommendations and conclusions. It should *not* refer to the body of the report. In many instances, the executive summary is the only portion of the report that upper-level management will initially review; *this one section is unquestionably the most important part of the report*.

A detailed and expanded treatment of plant design is available in the following three references:

1. R. Perry and D. Green (editors), *Perry's Chemical Engineers' Handbook*, 7th edition, McGraw-Hill, New York City, NY, 1997.
2. D. Kauffman, *Process Design*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APVI, RTP, NC 1992 [11].
3. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY, 2014 [12].

11.9 Illustrative Open-Ended Problems

This and the last section provide open-ended problems. However, solutions *are* provided for the three problems in this Section in order for the reader to hopefully obtain a better understanding of these problems which differ from the traditional problems/illustrative examples. The first problem is relatively straightforward while the third (and last problem) is somewhat more difficult and/or complex. Note that solutions are not provided for the 35 open-ended problems in the next section.

Problem 1: Discuss the role utility systems play in the design and operation of a chemical plant.

Solution: Utility systems provide the infrastructure in which chemical and petrochemical process plants operate. These systems can include such things as steam boilers and distribution lines, fuel distribution systems, cooling towers and cooling water distribution systems, compressed air systems, electrical distribution systems, inert gas distribution systems, lighting, communications, fire water, etc. No plant could operate without at least some of these utility systems, and many plants require all of them.

Since plant utility systems are quite similar from one plant to the next, the chemical process engineers do not have to design them from scratch each time. It is customary to assume that the utility services will be available in whatever quantity is needed. They can be designed later. Or, in the case of installations at existing plants, they can be modified to supply the needs of a new process unit.

Problem 2: Discuss the difference between continuous and batch plant operation.

Solution: Most process plants can be categorized as either *continuous* or *batch* in nature. Continuous processes operate at steady state with respect to time; there is a continuous inflow of raw materials and a continuous outflow of products. Batch plants are characterized by process conditions that change with time; feeds are added at specific times, and products are removed at specific times.

Continuous plants have many distinct advantages. Once the plants are started up, all feed materials are processed in exactly the same way. Each step of the process takes place in a different piece of equipment, with the materials flowing continuously from one to the next. Uniform product quality can often be maintained easily. Storage requirements for feeds, products and intermediates are minimized. The quantity of material being actively processed at any one time is minimized. The task of the operators, once the plant is started up, is to maintain it in a single, steady operating mode. Small deviations from desired conditions can be easily detected and corrected. Continuous plants are most often used for production of large quantities of materials.

In batch plants, many distinct operations may take place in the same piece of equipment. Feeds are added at discrete times based on a “recipe” for the process. The operators must process each batch of material individually. Temperature and residence time control are more difficult than in continuous plants, but some difficult-to-control process features, such as extent of a polymerization reaction, can be followed and adjusted more closely. Batch plants are most often used when only small quantities of a product are needed or where many variations of a single basic product are needed, such as in the specialty chemical business. In addition, there are large-scale processes, such as manufacture of some plastic resins, for which continuous plants have proved impractical.

There are, of course, plants which are hybrid mixtures of continuous and batch processing. Many food processing plants fall in this category. “Cooking” operations are likely to be batch in nature; packaging operations are likely to be continuous.

Problem 3: A research chemical engineer has devised the processing scheme described below for the manufacture of a commodity chemical. The overall chemistry of the process can be represented by the equations:

$$A + 2B \rightarrow C + D$$

$$C + E \rightarrow F + G$$

A is an organic liquid. B is a gas. D is an unwanted gaseous byproduct which can be used as a fuel. E is an organic liquid. F is the desired product, an organic liquid. G is an unwanted organic byproduct which can be used as a fuel.

In the laboratory, the first reaction readily took place at 240°F and 150 psig, requiring about 30 minutes to go to completion. It was endothermic, with a heat of reaction of about 65 kcal/gmol of A reacted. The reactor used consisted of a one-liter stainless steel flask with the gases sparged in at the bottom. A reflux condenser was used to keep product C while venting D.

The second reaction takes place almost instantaneously upon addition of E to C at ambient conditions. It is exothermic, with a heat of reaction of about 25 kcal/gmol of C reacted. In the laboratory, this reaction was carried out by slowly adding E to the C, still contained in the stainless steel flask. Finally, F and G were separated by distillation in a lab column. F boils at about 240°F and G boils at 155°F at atmospheric pressure. Both remain liquid at ambient temperature.

Develop a preliminary flowsheet for a continuous plant to carry out the process.

Solution: One possible continuous plant for this process is sketched below in Figure 11.1.

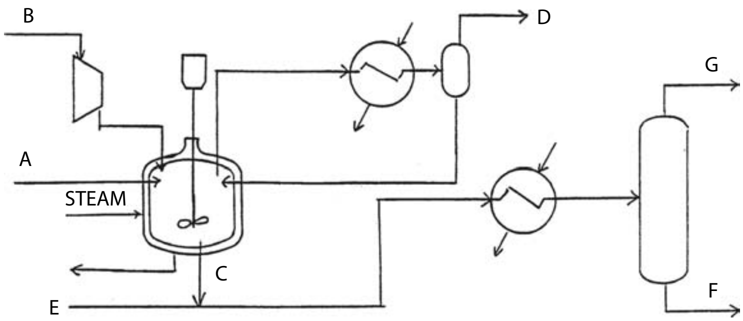

Figure 11.1 Preliminary flowsheet for Problem 2

The following 6 features of the system are described below.

1. Compressor for feed B: The compressor is needed to maintain the reactor at 150 psig. If the above supply of B is already at or above this pressure, the compressor would not be needed.
2. Reactor with steam heating jacket or coils: The reactor is designed to hold the liquid mixture for whatever reaction time is necessary to achieve sufficient conversion of A. It most likely will not be exactly the same as the 30 minutes used in the lab. Steam heating is provided by using steam coils in the reactor and/or a steam jacket surrounding the reactor.
3. Vent condenser: The vent condenser cools the gaseous by-product D and condenses out any residual A or C, retuning them to the reactor. D is sent for use as fuel elsewhere in the plant.
4. “Reactor” two: Where is it? There is no actual “reactor: for the second reaction. E is added directly to C and is mixed in the piping.
5. Intermediate cooler: This heat exchanger is designed to cool down the reaction products after the exothermic reaction between C and E. It will take more detailed analysis to determine whether or not it is actually required.
6. Distillation column: The column provides for separation of product F from by-product G.

In this process, undesired organic by-products are used as fuel elsewhere in the plant. A normal part of process design and analysis would be to see whether there were any higher-value uses for either of these by-products, or whether their formation could be eliminated by changing the overall process.

Note that this is but one possible scheme.

11.10 Open-Ended Problems

This last section of the chapter contains open-ended problems as they relate to plant design. No detailed and/or specific solution is provided; that task is left to the reader, noting that each problem has either a unique solution or a number of solutions or (in some cases) no solution at all. These are characteristics of open-ended problems described earlier.

There are comments associated with some, but not all, of the problems. The comments are included to assist the reader while attempting to solve the problems. However, it is recommended that the solution to each problem should initially be attempted *without* the assistance of the comments.

There are 35 open-ended problems in this section. As stated above, if difficulty is encountered in solving any particular problem, the reader should next refer to the comment, if any is provided with the problem. The reader should also note that the more difficult problems are generally located at or near the end of the section.

1. Describe plant design activities during the early years of the chemical engineering profession.
2. Discuss the recent advances in the design of plants.
3. Select a refereed, published article on plant design from the literature and provide a review.
4. Develop an original problem in plant design that would be suitable as an illustrative example in a book.
5. Prepare a list of the various books that have been written on plant design. Select the three best and justify your answer. Also select the three weakest books and justify your answer.
6. Describe the difference between plant design and project management. Also discuss how they are interrelated.
7. Explain why it is more difficult to design a plant/process than to predict performance.
8. Describe the difference between process synthesis for a known process as opposed to a new process.
9. Which equipment generally play the most important role in a plant design?
10. Describe the differences between informal and formal design reports.
11. "A generalization for equipment design is that *standard* equipment should be selected in the design of a plant". Comment on this statement.
12. Describe the differences between the following three classes of designs.
    - Preliminary designs
    - Detailed estimate designs
    - Firm process designs.
13. Describe in general terms the relationship between plant design and sales.

14. Describe the various procedures that are available in order to obtain the optimum design for a plant.
    Comment: Refer to Chapter 10, Economics and Finance.
15. Provide some general comments on flow diagrams.
16. Provide some general comments on process flow sheets.
17. There is much more variety in the selection and specification of equipment for handling solids than for liquids or gases, which are nearly always confined to pipes or ducts. Discuss the various methods of moving/conveying solids.
18. Describe how new processes impact the chemical engineer's approach to process and plant design.
19. Select a process of your choice and draw a flow diagram of the system.
    Comment: This will require the review of the literature.
20. Select a particular chemical process industry. Prepare a report using a tabulated format to describe the physical and chemical properties of the raw materials, intermediate products, by-products, and principal chemicals that will be encountered in the manufacturing process.
21. Refer to the previous problem. Prepare a material balance for individual units and the plant itself.
22. Refer to the previous problem. Prepare an energy balance for individual units and the plant itself.
23. Describe the advantages and disadvantages that pilot plant studies play in the design of a plant.
24. Suggest what steps can be taken to eliminate pilot plant studies in the design of a plant.
25. Discuss the general problems/associated with scale-up.
26. Discuss specific problems associated with scale-up as it applies to some of the major chemical process equipment, e.g., fluid bed systems, crystallizers, mixers, etc.
27. Describe the role the research department of a company plays in the design of a plant.
28. Describe the role the legal department of a company plays in the design of a plant.
29. Describe the differences between plant design drawings and construction and installation drawings.
30. Describe the logical evolution of a process (for a plant).
    Comment: Refer to F. Vilbrandt and C. Dryden's "Chemical Engineering Plant Design", McGraw-Hill, New York City, NY, 1934 [13].

31. Discuss the potential role the stock market plays in the design of a plant.
32. The analysis of chemical reactors is a basic feature of most chemical and petrochemical plant designs. It is the ability to operate large-scale chemical reactors that has made possible the efficient production of many chemicals employed in the world today. Chemical reactors in process plants can have many different shapes and sizes. Describe these units. Comment: Refer to the literature [14] for additional details and to Chapter 8.
33. Cooling towers operate by contacting warm water with ambient air. The air is heated and becomes saturated with water vapor at its exit temperature. The evaporation of a small portion of the warm water passing into the air cools the rest of the water as pictured in Figure 11.2 [11].

    A cooling tower at sea level is fed 10,000 gpm (5,000,000 lb/h) of water at 115°F and cools it to 90°F. On a particular day, the ambient air temperature is 70°F and the relative humidity is 50%. How much air flow is needed for the cooling tower and how much water is evaporated? [11] Finally, design the cooling tower. Specifically state the assumptions in your design.
34. Atmospheric pressure tanks are used to store most liquids in process plants. The vapor in an atmospheric pressure tank is connected to the atmosphere through a vent line so that there will not be any net pressure difference between the inside and outside of the tank roof. Vapor recovery systems are often put on the vent line to reduce either air pollution or material losses, or both [11].

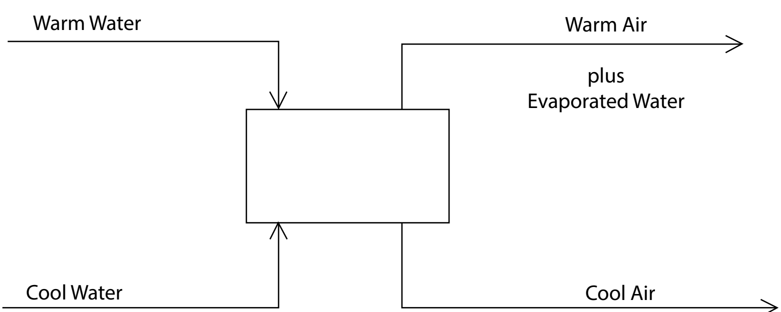

Figure 11-02 Cooling Tower Schematic

A 40,000-bbl atmospheric pressure tank is used to store kerosene. The tank is 30 ft tall and 98 ft in diameter. What is the maximum pressure that could be exerted by the kerosene on the tank wall? How much kerosene vapor would be vented to the atmosphere in day/night "tank breathing" if the tank has no vapor recovery system? [11] Discuss the validity and limitations of your calculations.

35. The basic goal of most chemical and petrochemical processing is to convert less valuable raw materials into more valuable products. A simple example is found in many refineries – the conversion of toluene, the most abundant aromatic compound in crude oil, to more valuable benzene and xylene products. The process is referred to by some as "toluene disproportionation." The overall chemical reaction involved is:

$$2C_6H_5CH_3 = C_6H_6 + C_6H_4(CH_3)_2$$

This reaction is usually carried out in the vapor phase at moderately high temperatures and moderate pressures. There are three isomers of xylene (para-xylene, meta-xylene, and ortho-xylene), and all three are formed in the reaction, which proceeds rapidly to chemical equilibrium [11]. The equilibrium mixture from the reactor, which consists of benzene, toluene and all three xylene isomers, is separated. The toluene is recycled to the front end of the process; therefore, the only end products are benzene and the xylenes.

Prepare a line flow diagram for this example. Also prepare a material balance in bbl/day for a toluene disproportionation unit which has a fresh feed rate of 1000 bbl/day. The reactor operates at 50 psia and 400°F. Under these conditions, one can assume an equilibrium chemical product mixture of 26.2 mol% benzene, 47.6 mol% toluene, 6.4 mol% para-xylene, 14.4 mol% meta-xylene and 5.4 mol% ortho-xylene.

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