ChE class and home problems

The object of this column is to enhance our readers' collection of interesting and novel problems in Chemical Engineering. Problems of the type than can be used to motivate the student by presenting a particular principle in class or in a new light or that can be assigned as a novel home problem are requested as well as those that are more traditional in nature that elucidate difficult concepts. Please submit them to Professor H. Scot Fogler, ChE epartment, University of Michigan, Ann Arbor, MI 48109.

SETTING THE PRESSURE AT WHICH TO CONDUCT A DISTILLATION

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This memorandum was issued to the students in chemical engineering stage operations, most of whom are sophomores and first semester juniors but none of whom have yet had any heat transfer courses. Thus the elementary explanation of heat exchangers may be unnecessary for more experienced students.

The subject of the memorandum is usually not covered at all in stage operation texts, or at most only lightly covered. In most of the problems on this subject for distillation the pressure is given but there is no statement as to how it is determined.

When the pressure is given, most students (and a few professors) will have no idea whether it is reasonable or even possible.

THE MINIMUM PRESSURE at which to conduct a distillation is set by the condenser. The temperature of condensation of the top product must be high enough to condense it with the cooling water available. We remove heat in the condenser with cooling water which rises in temperature as it removes heat, since its sensible heat rises with temperature. Also the condensing temperatures of the overhead product increase with increasing pressure.

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The maximum pressure for the separation is set by the reboiler. The boiling temperature of the bottom product must be low enough to be boiled by condensing the steam available. We must be able to add heat to the reboiler, by having the heat source at a higher temperature than the bubble point of the bottom product.

HEAT EXCHANGERS

Both the condenser and the reboiler are generic heat exchangers and all heat exchangers require that there be a temperature difference between the source of heat and the sink, *i.e.* the source must be hotter than the sink. The local temperature difference (Δt) between the two streams exchanging heat is often not a constant but it must be everywhere greater than zero. If the Δt is zero anywhere in the exchanger, the area required to transfer the heat becomes uneconomically large. It is useful to plot the temperature history in any heat exchanger to see what the Δt (driving force) is and how it varies throughout the device. For example, the overhead vapors (from a distillation column when heat is removed) will first begin to condense at their dew point. Further cooling will condense more until it is completely condensed at the bubble point.

THE CONDENSER

If the dew point of the overhead product at the column pressure is 140°F and the bubble point is 120°F—and if the inlet cooling water is

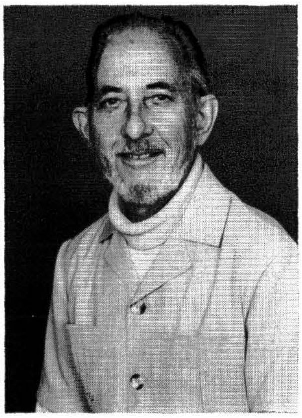
70°F and a 30°F rise may be taken—the temperature pattern in the condenser when the overhead is condensed completely but not subcooled is represented in Fig. 1.

The Δt driving heat transfer is thus between 40° and 50°F. This is quite adequate, but Δt's as low as 10 or 20°F are not uncommon.

Now if the pressure of operation were lowered then the dew and bubble point temperatures would be less than those shown and they might approach the cooling water temperature, thus decreasing the Δt which drives heat transfer and increasing the area required according to the design equation

$$A = \text{ft}^2 \text{ Area req'd.} = \frac{Q}{U\,\Delta t_{\text{mean}}}$$

where Q = the rate at which heat is to be transferred (Btu/hr.)
U = the overall heat transfer coefficient Btu/[(hr) (ft^2) (°F)]
Δt_{mean} = the mean driving force temperature difference in °F.



All during my undergraduate days (1936-1940) at the University of Washington in Seattle, the country was in the depths of the great depression and jobs were scarce. After obtaining my M.S. I was lucky to get one job offer with an oil refinery in California which I promptly accepted and started to work 24 November, 1941 just two weeks before Pearl Harbor.

The refinery work was very good chemical engineering experience for me. I worked there for over 7 years and remember wondering when I first arrived, why all de-butanizers operated at 50 to 60 psig and all depropanizers operated at 180 psig. When I later figured it out it was simple but I seldom come across any professors who have thought about it enough to have a well organized answer to my question of "How is the Pressure Set for a Distillation Column?" I have yet to see a thorough or even a sketchy treatment of this subject in any text on distillation. So I thought it would be appropriate to write this article for a class in Stage Operations and perhaps to publish it in **CEE**. The elementary discussion of heat exchangers was necessary because the students had not yet taken a course in heat transfer. **(Informal biographical sketch submitted by author.)**

The condenser thus sets the minimum pressure at which the column must operate. To find this minimum pressure, first find the bubble point pressure of the D product . . .

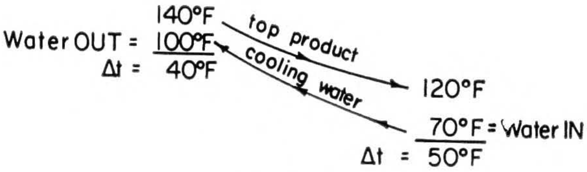


FIGURE 1.

The mean Δt is usually somewhere between the two terminal temperature differences (unless one of them is 0) and you will learn in Transport II how to calculate these mean Δt's.

The condenser thus sets the minimum pressure at which the column must operate. To find this minimum pressure, first find the bubble point pressure of the D product at a temperature of say 10° or 20°F higher than the inlet cooling water temperature. For a binary distillation this can be taken from the P-x-y diagram for that temperature, and for multicomponent mixtures one must use the relations for vapor-liquid equilibrium in multicomponent mixtures.

THE REBOILER

As the column pressure is increased, the Δt in the condenser will just get bigger and this is satisfactory; but the pressure also affects the operation of the reboiler in the opposite fashion. The material being boiled in the reboiler has the composition of the bottom product and the boiling temperature is the bubble point of W, the bottom product. It is fixed once its composition and the pressure are known. The heat source is usually condensing steam and the steam condensing temperature must thus be at least 10 or 20°F above the bubble point of the bottoms product. Since the latter temperature goes up with increasing pressure, this sets a maximum pressure at which the distillation may be conducted. The temperature pattern in the reboiler is simpler than that in the condenser since neither the steam nor the bottom product changes temperature as heat is transferred. If, for example, the bubble point of W is 300°F at the column pressure, and we have steam available at 300 psig, the condensing temperature for this steam (steam tables) is about 422°F. This temperature pattern is illustrated in Fig. 2.

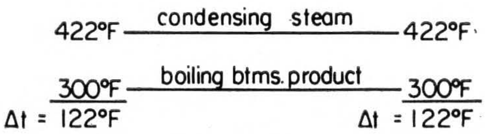


FIGURE 2.

The bubble point of the bottom product (which increases as P goes up) and the available steam pressure (and its condensing temperature) thus set a maximum pressure for the distillation. To find this pressure, estimate the bubble point pressure of the W product at a temperature of say 20°F (more or less) below the condensing steam temperature.

We now have both a maximum and minimum pressure at which the distillation can be carried out. Some pressure between these two would be used in the final design and its optimum value will be determined by an economic balance. The items to consider in such an economic balance are:

1. **The effect of P on the temperatures of condensation of the overhead and on the boiling temperature of the bottom product which affect the mean Δt in the condenser and reboiler and thus their areas. Each of these exchangers may be made smaller at the expense of the other one by adjusting the pressure up or down between the limits imposed. The higher the pressure, the smaller the condenser and the larger the reboiler, and vice versa. Pressure affects these two exchangers in opposite directions because we are removing heat from one and adding heat to the other.**
2. **The effect of the column design pressure on its wall thickness and thus cost.**
3. **The effect of pressure on the vapor-liquid equilibrium. This effect is likely small for nearly ideal liquid solutions since for these liquid mixtures the relative volatility is independent of pressure. For hydrocarbon systems for example, by changing the absolute pressure by a factor of 2, the relative volatility changes only about 5%. For non-ideal systems however pressure may have a more important effect especially when there are azeotropes since the composition of the azeotrope may change with pressure. It may even be possible to eliminate an azeotrope by suitably adjusting the pressure.**

A COMMON PROBLEM

It is entirely possible (especially when there is wide variation in the boiling points of the bottom and top product) that the minimum pressure set by the condenser is higher than the maximum pressure set by the reboiler. In this case there are three possible solutions. One is to use refrigeration to condense the top product, but this may be expensive. A second solution is to use a fired reboiler for the bottoms, i.e. send the liquid from the bottom tray to a furnace which may heat to temperatures much higher than condensing steam. The liquid is thus partially vaporized and sent to a flash drum to separate the vapor formed from the remaining liquid. The vapor off this drum is returned to the column below the bottom plate, and the liquid becomes the W product.

A third possible solution to the problem is to accept as a vapor that part of the overhead product which can not be condensed with the cooling medium, i.e. design a partial condenser. The part that is condensed is partly returned as reflux and the rest is liquid D product. The D products thus consist of two streams; one a vapor and one a liquid. This is usually the case for the first crude oil fractionation. The flow sheet is illustrated in Fig. 3.

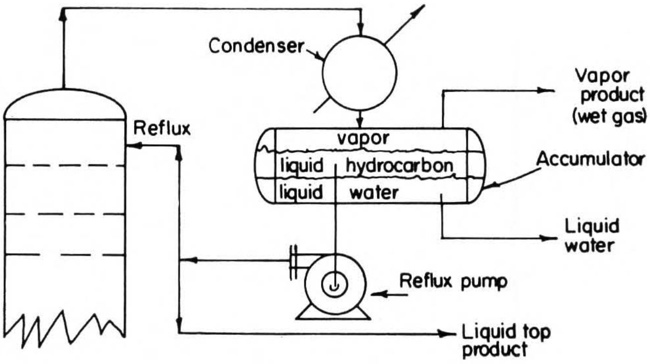


FIGURE 3.

The vapor product contains methane, and ethane which can't be condensed easily. The vapor product is called "wet gas" not because it contains water (which it does), but because it contains some condensible hydrocarbons. It is sent to compressors and thence to an absorption column where the ethane and heavier are removed as ethane and L.P.G. (Liquified Petroleum Gasses) which consist mostly of C_3's and C_4's. The methane containing very little ethane and heavier is called dry gas and is about the same as natural gas. The ethane is usually cracked at high temperature to yield ethylene which is the source of many of our petrochemicals.

The liquid water product comes from open steam used to assist in the first crude oil fractionation instead of having a reboiler.

GENERAL FRACTIONATION NOTES

(a) The optimum reflux ratio is said by Treybal to fall in the range of 1.2 to 1.5 times the minimum reflux ratio. This rule was formulated when heat was cheap, say $0.50 to $1.00 per million Btu. With currently expensive heat, say $5.00 to $8.00 per million Btu the optimum reflux ratio comes much nearer to the minimum and may lie in the range (1.05 to 1.2) (R_{min}).

(b) In desert areas when water is scarce and expensive, air cooling is often used to condense the overhead vapors but in this case the overall heat transfer coefficients are much lower than with water cooling and the optimum approach temperature differences for condensing may be much larger than the 10° to 20°F quoted above. Also the design air inlet temperatures may have to be 90° to 110°F or even 120°F in order to get a design which will work most of the time. □

DESIGN COURSE

Continued from page 29.

projects with gross profit, tax and depreciation schedules are described. Finally, cash flow diagrams are introduced for comparing investments on the basis of simple rate of return, present worth of cash flows, or discounted cash flows.

Given profitability measures, questions of optimality arise. The optimization problem is defined in general terms to begin coverage of this comprehensive subject. The objective is to introduce optimization methods, suggesting the need for further study. Single variable, unconstrained methods known as sequential search methods (e.g., the Golden-Section method) are covered using the excellent descriptions in Chap. 10 of *Digital Computers and Numerical Methods* [2] with two example problems from Chap. 10 of Peters and Timmerhaus (optimal insulation thickness and optimal batch time). Then, multivariable, unconstrained methods are covered including lattice search, repeated uni-directional search, and optimal steepest descent [2].

Next, the students optimize the design of a distillation tower with a condenser, reboiler, and reflux pump. Throughout the course they have solved problems involving these components, so for this problem they are given the FORTRAN function DISTIL which computes the rate of return on investment as a function of the product purity, the reflux ratio, and the fractional recovery of the most volatile species in the distillate. The use of DISTIL to (1) carry out material balances, (2) count trays, (3) calculate the tower diameter, heat exchanger areas, and pump horsepower, and (4) calculate costs, cash flows and discounted cash flow rate of return is reviewed. Then, the students write a program to calculate the maximum rate of return on investment. Incidentally, DISTIL was written by Prof. D. Brutvan [1] and has been modified slightly for use in our course. Prof. Brutvan prepared an excellent problem-statement, typical of a large company, with design specifications, sources of physical property data, cost data, and explanations of the algorithm. This has also been modified for use in our course.

After the introduction to process synthesis, the course concentrates on analysis with the configuration of the process flowsheet given. The design variables are adjusted to locate an optimal design for a given configuration. However, in process synthesis, the emphasis is placed upon finding the best configuration. This approach is well-suited to teach methods of increasing the thermodynamic efficiency by heat integration. The monograph, *Availability (Exergy) Analysis* [13] and the paper "Heat Recovery Networks" [11] provide excellent introductions to the analysis of thermodynamic efficiency and the pinch method for minimizing utilities. Synthesis of separation processes is also covered, but briefly in just two hours. The key considerations are introduced, time being unavailable to solve a meaningful problem.

The course concludes with a final exam and the course grade is based upon two mid-semester exams and the homework. Approximately 15 problem sets are assigned, with two problems using FLOWTRAN and one problem in which the rate of return for a distillation tower(using the DISTIL function) is maximized.

SPRING COURSE: PLANT DESIGN PROJECT

Penn's strength in process design can be attributed in part to the large concentration of chemical industry along the Delaware River and to our close interactions with several industrial