The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that 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 and which elucidate difficult concepts. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu) or Mark A. Burns (e-mail: maburns@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

CHANGING VAPOR-LIQUID TRAFFIC IN A DISTILLATION COLUMN

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Changing vapor-liquid traffic in a distillation column is associated with the use of side-reboilers, side-condensers, and pump-arounds. Incorporating some of these features into a exercise tests the students' grasp of the McCabe-Thiele construction and gives an elementary insight into one aspect of heat integration.

Nowadays, most final designs for distillation columns are prepared using a simulation package, so it is easy to dismiss McCabe-Thiele construction as a routine piece of teaching. But for more complex columns, such as those incorporating a side-reboiler, for example, the ability to plan the design roughly on a McCabe-Thiele diagram is a great help in obtaining a swift convergence of the simulation program. Hence, this exercise is of value in making students consider the McCabe-Thiele construction as a flexible tool rather than a rigid routine.

Side-reboilers, side-condensers, and pump-arounds are typically, but not very accurately, illustrated as shown in Figure 1.[1,2] Side-condensers and pump-arounds are associated with column heat removal and are thus located above the feed. Heat removal condenses vapor and the operating line is of a shallower gradient above the point of heat removal than below. Correspondingly, side-reboilers are located below the feed and result in a steepening of the operating line gradient below the side-reboiler.

The justification for changing the vapor-liquid traffic in a distillation column is economic. Distillation columns are major energy users, and efforts to reduce plant utility costs can lead to energy integration requiring heat addition/removal at locations other than the main reboiler/condenser.[3] For example, lower temperatures found higher up the distillation column mean that a cooler, and hence cheaper, heating medium (often heat recovered from within the plant) can be used in the side-reboiler. To be set against this advantage is the tendency of side-reboilers to narrow the driving force between operating and equilibrium lines, resulting in the separation requiring more theoretical stages. Similarly, side-condensers and pump-arounds allow heat to be removed at a higher, and hence more useful or cheaper (if refrigerated), temperature level compared to the main condenser.

Side-reboilers and pump-arounds are the most commonly encountered. Pump-arounds are generally preferred over side-condensers because it is easier to engineer the liquid circuit of the pump-around than vapor withdrawal to a side-con-

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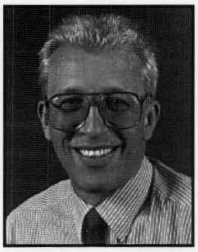

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denser. Further, side-reboilers and side-condensers are the easiest to analyze rigorously on the McCabe-Thiele construction. Therefore, a side-reboiler case has been chosen as the basis for the main example presented here. At the end, guidance is given on setting up a pump-around example, based on a simplifying assumption. The side-condenser case is a simple variation on the main example and is left to the reader.

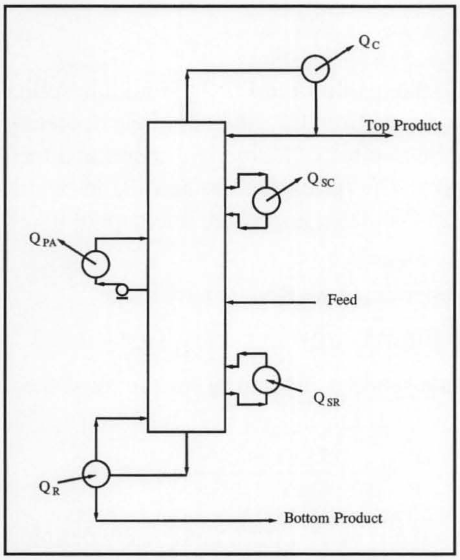

Figure 1. *Typical representation of distillation column with multiple heat additions/removals*

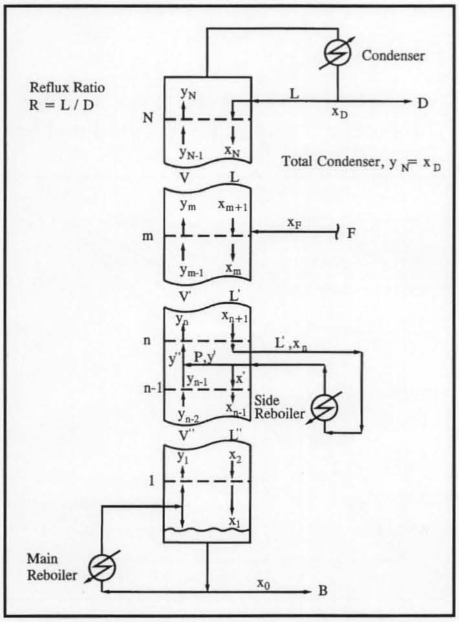

Figure 2. *Distillation column with side-reboiler*

PRACTICAL IMPLEMENTATION

A practical side-reboiler arrangement is shown schematically in Figure 2, where x and y denote the mole fraction of the more volatile component in the liquid and vapor phases. The design is based on total liquid trap-out to a once-through thermosyphon reboiler, where the stream is partially vaporized and the equilibrium two-phase mixture is returned to the column. The equilibrium vapor, P, combines with the ascending vapor, V'', and the equilibrium liquid, L'', descends to the main reboiler. Partial vaporization in the reboiler is important to reduce fouling and to maintain good heat transfer. A maximum vaporization of 20-25% of the feed to the reboiler is often used. Kister has presented an analysis based on partial liquid trap-out followed by total vaporization of the liquid.[4] This analysis would show a deep notch on the McCabe-Thiele construction, which effectively reverses some of the separation effected in the lower section of the column. Kayihan's McCabe-Thiele construction[1] shows the notch, but no analysis is presented.

PROBLEM STATEMENT

a. Sketch the operating lines for a binary distillation column incorporating a thermosyphon side-reboiler. Pay particular attention to the operating line end-points around the side-reboiler. You should make the usual simplifying assumptions and use the nomenclature in Figure 2. Figure 2 assumes a total condenser on the overheads and a recirculating thermosyphon as the main reboiler.

b. If the relative volatility of the two components in the binary mixture is denoted by α, show that x_n and x' are related by

$$x_n = \frac{x'}{L'}\left(\frac{P\alpha}{1+(\alpha-1)x'} + L''\right)$$

c. Saturated liquid comprising 50 mol % A and 50 mol % B is fed to a distillation column. The distillate is to contain 95 mol % A and the bottoms 95 mol % B. The relative volatility of A with respect to B is 2.5. Estimate the number of theoretical stages required for the separation, assuming:

- Reflux ratio is 1.4 times the minimum reflux ratio
- 25% of the liquid fed to the side-reboiler is vaporized
- Temperature level of the heat input to the side-reboiler is such that liquid containing a minimum of 35 mol % A can be vaporized

d. What proportion of the total heat input in (c) is made through the side-reboiler? Compare the number of theoretical stages and total heat input required for the side-reboiler case with that required for a simple distillation column operating with a reflux ratio of 1.4 times the minimum reflux ratio.

e. If you attempt to add the side-reboiler heat at successively lower temperature levels, what limitation do you reach? Illustrate your answer using the relevant information from (c).

f. For discussion: A preliminary design recommendation commonly quoted for higher energy cost regions is to use an operating reflux ratio 1.2 to 1.3 times the minimum reflux ratio. Why might it be appropriate to use a higher factor, say 1.4 to 1.5, when considering a side-reboiler?

SOLUTION

► a. The distillation column representation will incorporate three operating lines. The operating line applying above the feed will conform to the normal McCabe-

Thiele construction. Below the feed there will be two operating lines: line A applying below the side-reboiler (and down to the main reboiler), and the other (line B) applying above the side-reboiler (and up to the feed plate). The important point to note is that, although the two operating lines below the feed have different gradients (L'/V' and L''/V''), they pass through the same point, x_o on the 45° line, because no side-product is taken. Figure 3 illustrates the construction where a saturated liquid feed has been assumed.

The actual construction is straightforward for a given feed and required separation, and knowing x_D and selecting R permits construction of the top operating line. The intersection of the top operating line with the q-line gives one end of operating line B; the other end is x_o on the 45° line.

Operating line A can be added because we know it passes through x_o and has gradient L''/V''. Also, L'' and V'' are easily calculated from L' and V' by the equations

$$L'' = L' - P$$

$$V'' = V' - P$$

and L', V' are found in turn from L, V, F, and the feed condition.

The one outstanding problem concerns the transition from the operating line A to B. Point x', y_{n-1} is located at the end of operating line A. Point x', y' represents the equilibrium mixture returning from the side-reboiler. The vapor entering the section of column above the side-reboiler is a blend of compositions y' and y_{n-1}, so y'' must lie between these two values and the point x_n, y'' must lie at the lower end of operating line B.

Note the above design avoids the deep notch previously mentioned. But care is needed when drawing the theoretical stages. Stages can be drawn in the normal manner, commencing at x_D on the 45° line and terminating at x_n, y''. A discontinuity occurs between x_n, y'' and x', y_{n-1}, and the stages will be recommenced at the latter point, terminating at x_o. We cannot simply draw steps over the transition region, as suggested by Petterson and Wells.[3]

▶ b. The equation, which is useful for specifying the transition between operating lines A and B, is easily derived using a componential mass balance on the side-reboiler

$$L'x_n = Py' + L''x'$$

where y' is eliminated using the equilibrium relationship

$$y' = \frac{\alpha x'}{1 + (\alpha - 1)x'}$$

to give

$$x_n = \frac{x'}{L'}\left(\frac{P\alpha}{1 + (\alpha - 1)x'} + L''\right)$$

▶ c. After drawing the equilibrium line, a minimum reflux ratio of 1.1 is easily found from the gradient of the operating line giving an infinite number of theoretical stages at a feed composition, $x_F = 0.5$. The reflux ratio to be used in operation is 1.4 x 1.1 = 1.54, and this implies an intercept of 0.677 on the q-line.

Below the feed, operating line B must have slope

$$L'/V' = (0.677 - 0.05)/(0.5 - 0.05) = 1.393$$

while below the side-reboiler, operating line A must have slope

$$\frac{L''}{V''} = \frac{L' - P}{V' - P} = \frac{0.75 \times 1.393 \times V'}{V' - (0.25 \times 1.393 \times V')} = 1.603$$

This implies $y_{n-1} = 0.531$ at $x' = 0.35$, completely defining operating line A. All that remains is to establish x_n on operating line B, and this is achieved using the equation derived in (b)

$$x_n = \frac{0.35}{L'}\left(\frac{0.25 \times L' \times 2.5}{1 + (1.5 \times 0.35)} + (L' - 0.25\,L')\right) = 0.406$$

The completed construction is shown in Figure 4. Above the side-reboiler, 7.7 theoretical stages are required and be-

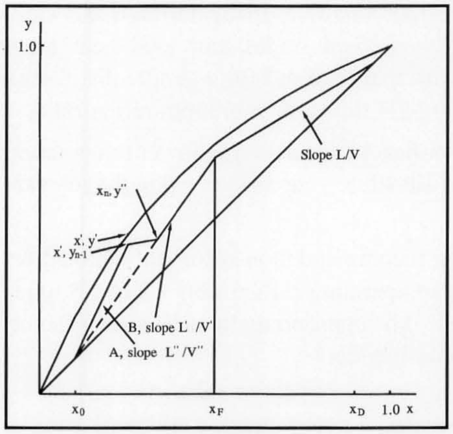

Figure 3. *Operating line construction for distillation column with side-reboiler*

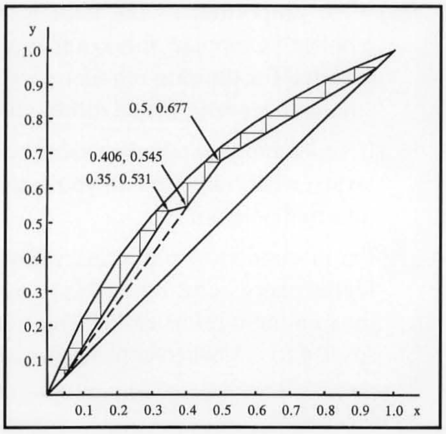

Figure 4. *McCabe-Thiele construction for the problem.*

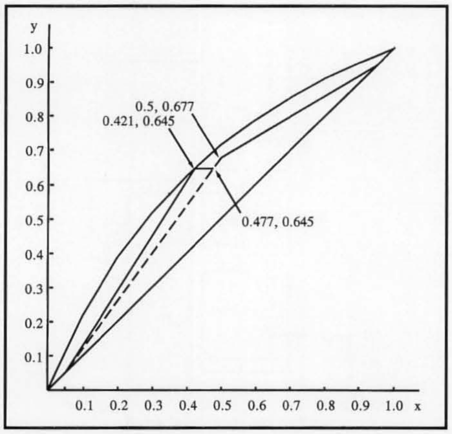

Figure 5. *Introduction of a pinch by a side-reboiler.*

low 6.5 are needed, but this includes a recirculating thermosyphon reboiler which is *not* one theoretical stage[5] but may be taken as roughly 0.5 of a stage. Hence, the total number of theoretical stages is 13.7.

► d. The usual simplifying assumptions for McCabe-Thiele construction require the components to have equal latent heats of vaporization. Hence, to compare heat inputs, we simply need to compare vapor flows.

Above the side-reboiler, the vapor flow is directly related to the total heat input and we know $V' = L'/1.393 = 0.718\,L'$. In the side-reboiler, vaporization $P = 0.25\,L'$, and hence percentage heat input through the side-reboiler = (0.25 x 100)/0.718 = 34.8%.

In the case of the simple distillation column, operating line B (from the side-reboiler case) now applies at all points below the feed. This immediately tells us the total heat input must be the same for the two cases. To complete the comparison, we need the number of theoretical stages for the simple distillation column, and this is easily obtained by stepping off along operating line B and its extension to give 12.2 stages, after allowance for the reboiler. (This construction is not shown in Figure 4.) Hence, we have a trade-off in which 34.8% of the heat is saved at the highest level in return for installation of an extra 1.5 theoretical stages plus side reboiler.

► e. Successively lower temperature levels for heat addition means that the increasing amounts of more volatile component A must remain in the unvaporized side-reboiler return liquid. This is equivalent to lengthening operating line A and correspondingly shortening B. Ultimately, an alternative pinch would be generated at 0.421, 0.645 on the equilibrium line (illustrated in Figure 5). Note that the transition has become horizontal, as can be expected.

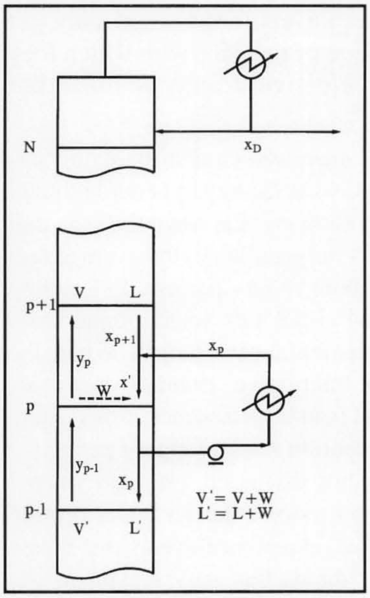

Figure 6. *Distillation column with a pump-around*

► f. Optimum reflux ratio is a balance between operating costs and capital investment. Use of a lower-cost heating medium for part of the heating effectively reduces the average heating-medium cost and this changes the balance, moving the optimum in a direction that reduces capital investment and permits slightly more energy consumption, *e.g.*, increasing the factor from 1.2 - 1.3 to 1.4 - 1.5, say.

PUMP-AROUND

In theory, a pump-around can be viewed as operating over one theoretical stage, as shown in Figure 6. Part of the liquid exiting stage p is withdrawn and circulated through a cooler before returning to the same stage. The circulation rate and extent of cooling can be adjusted to control heat removal. For analysis, we represent the heat removal as equivalent to the latent heat released by "flow" W changing phase from vapor to liquid.

Stage p+1 and above is represented as operating line C, while stage p-1 and below is represented by operating line D. Operating line C is of a shallower slope than D, and noting y_p and x_p are in equilibrium (a consequence of the theoretical stage assumption), then the relationship between the end points of operating lines C and D adjacent to the pump-around is as shown in Figure 7.

In summary, we have succeeded in representing the pump-around as a theoretical stage "jumping" between operating lines. Operating line C can be drawn based on column reflux ratio, and D can be added by adjusting for quantity changing phase, W.

Strictly, this representation is optimistic because cold liquid returned to the column will not be heated to its bubble point on one real tray; generally a few trays are needed. But if the extra trays are added, then, by way of compensation, the mass transfer will be better than indicated in Figure 7, *e.g.*, x_p and y_p will no longer correspond to a point on the equilibrium line. Provided these considerations are borne in mind, this pump-around analysis makes a thought-provoking exercise, leading to a clearer understanding of the topic.

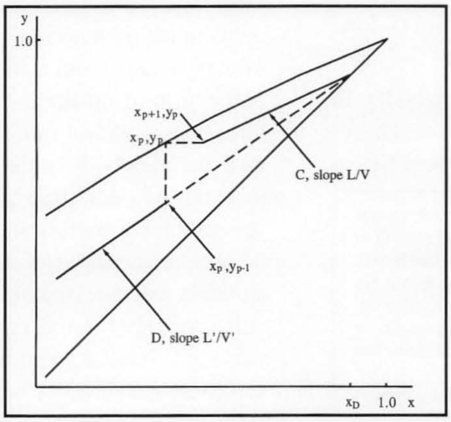

Figure 7. *Operating line construction for distillation column with pump-around.*

ACKNOWLEDGMENT

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