Temperature-Heat Diagrams for Intercooled/Interheated Distillation Columns

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EDRC 06-57-89

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November 1988

Abstract

We show how to establish heating and cooling curves for distillation columns featuring interheating and intercooling. The approach is to construct a diagram that plots column pinch temperatures versus reboiler and condenser duties. No assumptions are needed on ideal behavior.

Introduction

A distillation column is conveniently thought of a device to degrade heat to produce separation work. Heat enters into the reboiler of a typical column, the hottest point in the column. It is removed from the condenser, the coldest point in the column. Often in industry one will see columns in which heat has been removed from or added to a column on an intermediate tray. To add heat one can remove liquid from the tray, take it to an outside heat exchanger where part or all of it is vaporized, and return the resulting stream back to the column. External condensing of vapor can be used to remove heat. Figure 1a illustrates. Such heat addition and removal is termed interheating and intercooling respectively.

The advantage obtained for using interheating or intercooling is that the heat is added or removed at a temperature which is between the temperatures of the reboiler and condenser for the column. Thus heat can be added at a lower temperature than the reboiler temperature or removed at a temperature higher than the condenser temperature, each of which is advantageous from a second law point of view.

Andrecovich and Westerberg (1985) presented a diagram to illustrate the flow of heat in a column on a temperature versus heat (T-Q) diagram. The axes for this diagram are the same as used in heat exchanger network synthesis calculations (Hohmann (1971), Linnhoff, et. al. (1982)), allowing this very useful "cascade" representation to be used on the same diagram as one would use to design heat exchanger networks. Figure 1b illustrates such a diagram for an interheated/intercooled column. The top of the area representing the column corresponds to heat entering the column at two temperatures: the hotter is the reboiler and the other is the interheater. Similarly heat is shown being removed at two temperatures: from the colder condenser temperature and from the intercooler.

Andrecovich and Westerberg argue that the amount of heat added to the reboiler of a conventional column is about equal to the heat removed from the condenser IF the column feed and top and bottom products are liquids at their respective bubble points. A heat balance around such a base case column gives:

$$h_F F \;-\; h_D D \;-\; h_B B \;+\; Q_R \;-\; Q_c \;-\; 0 \qquad (1)$$

The sensible heat terms are small compared to the reboiler and condenser heat terms. Thus they can be ignored to give

$$Q_R \;\text{"}\; Q_c \;{}^{m}\; \circ \qquad (2)$$

For the same base case of feed and products as bubble point liquids, the total of heat into a column through the reboiler and interheating will approximately equal the total of heat removed from the condenser and intercooling. Thus the notched box in Figure lb has the same width top and bottom and can be shown conveniently with lines connecting heat in and heat out to enclose an area.

If the column operates away from this base case, one can usually argue directly how to correct the construction of the T-Q diagram. For example, suppose the feed is added as a vapor (i.e., with a feed quality of <y=0). For this case one will discover that the condenser duty will exceed the reboiler duty by an amount of heat approximately equal to that required to preheat a bubble point liquid feed to form a dew point vapor feed. By mentally "bringing" the feed back to the base condition of a bubble point liquid, one readily sees this approximate relationship.

The main question to be answered in this paper is how does one construct this cascade diagram for a column in which there is interheating and intercooling taking place; i.e., how does one construct Figure lb given the column in Figure la?

Binary Columns

Ho and Keller (1987) present an analysis that allows one to construct this diagram for a binary column. We summarize their ideas here as these ideas motivate part of our development for columns which are separating more than two component feeds. We assume constant molar overflow for this analysis. When we look at the multicomponent case, we shall relax such assumptions.

Figure 2 is the top section of a distillation column where part of the heat is removed using a condenser and part using an intercooler. Two envelops, I and II, are illustrated which will be used to develop the operating lines for the section of the column above the intercooler (I) and the section just below (II).

Figure 3 shows the structure of a McCabe-Thiele Diagram for this column, as we shall now show. The operating lines, which come from a component material balance around the column, are as follows.

$$y = x\frac{L_I}{V_I} + x_D\frac{D}{V_I} \qquad (3)$$

$$y = x\frac{L_{II}}{V_{II}} + x_D\frac{D}{V_{II}} \qquad (4)$$

By substituting in $y = x$ into both of these equations, one discovers that both pass through $y = x = x_D$, as one should expect. By noting that

$$1 = \frac{L_I}{V_I} + \frac{D}{V_I}, \qquad (5)$$

a similar relationship for operating line II and that L_{II} is larger than L_I, one can argue that the slope for operating line II, L_{II}/V_{II}, must be larger than the slope for operating line I. Thus the general structure of the diagram in Figure 3 is consistent with these observations. What we find is that intercooling has changed only the slope of the operating line. To step off the number of trays for such a column, one steps down operating line I until the intercooler is encountered (which has to occur before this operating line hits the equilibrium line) and then switches to the other operating line as illustrated.

How does this situation differ from that for a conventional column in which all the heat is removed in the condenser? If operating line II represents the operating line for a conventional column, then adding the intercooler will require us to use a column with more stages to effect the same separation. These extra stages occur because operating line I is closer to the equilibrium line than operating line II. The total heat removed from the condenser and the intercooler will be exactly equal to the heat removed from the condenser of the conventional column. Thus we require the same total cooling, require more plates, BUT gain by being able to remove some of the heat at a higher temperature. Another way to state this is we come out even in terms of the first law (same amount of heat), lose on capital investment (more trays) but gain on the second law (can use cheaper cooling).

To motivate the algorithm to generate the diagram we are after, we note that the equilibrium line has a temperature implicitly associated with each point along it. Specifically the temperature is the dew point temperature for the vapor composition, y, for the point which equals the bubble point temperature for the liquid composition, x, for it. The temperature increases as we move down the equilibrium line.

The algorithm to construct our desired diagram is the following.

1. **Choose $\beta = 0$**
2. **Compute $L/V = \beta/(\beta+1)$**

3. Sketch the operating line with this slope which passes through x_D on the 45 degree line on the McCabe-Thiele Diagram. Find the point where it intersects with the equilibrium line. Let *T* be the temperature associated with this equilibrium point (i.e., T = dew point(y) = bubble point(x)).

4. Estimate the condenser duty associated with this operating line, for example, as equal to approximately the following:

$$Q_c \quad « \quad XD(J?+1) \tag{6}$$

   where *X* is the heat of vaporization per mole for the top product.

5. Plot *T* versus Q_c on a T-Q diagram.

6. Increase *R* by some small amount and repeat from Step 2. Keep repeating from Step 2 until *R* is as large as desired for operating the column (say 1.2 times the minimum reflux ratio predicted for the column).

The bottom curve in Figure 4a is such a plot for a suitable range of reflux ratios. The top half of Figure 4a is for doing a similar set of steps for putting heat into the reboiler, only here one would step through increasing reboil ratios *S^V̄IB*, from zero to the maximum desired for operating the column. It helps to remember that

$$V \; = \; \bar{V} \; + \; (l\text{-}q)F \tag{7}$$

which is readily converted into

$$D(/?+l) \; = \; SB \; + \; (l\text{-}q)F \tag{8}$$

to relate *R* to 5.

Given the plot in Figure 4a, we are now able to see how to construct the required notched T-Q cascade diagram for a binary column. Select a temperature at which it is desired to remove heat from the column using an intercooler, say 7*. Assume that the column operates with a total amount of heat removed, *Qc/nin>* corresponding to a conventional column with $R = k_{RiR_{min}}$ *Rmin** with $k_{RjR_{min}}$ in the range 1.1 to 2.0. At least the amount of heat labeled Min Q_c on Figure 4a must be removed in the condenser to allow the top operating line (operating line I in Figure 2) to get to the temperature 7* before it intersects with the equilibrium line. To move to operating line II in Figure 2, which has a total heat removal above it of Qc_yacv says that no more than Max *Qc* can t)e amoved from the intercooler. Thus Min Q_c is the minimum amount of heat to be removed from the condenser and Max $Q_c'_9$ the maximum removed from an intercooler operating at temperature 7*.

Fig. 4b shows a typical notched diagram then for a column for which intercooling is done at temperature 7* and interheating at temperature 7̄^

Multicomponent Columns

To extend the Keller and Ho analysis to multicomponent columns, we proceed as follows. By analogy with the binary case, we appreciate that we want to find points where the operating line intersects with the equilibrium surface in multidimensional space for increasing values of the reflux ratio, /?. The analysis here is not unlike that used by Underwood (1946,1948) to establish conditions for the minimum reflux conditions for a column. However, here we will not limit ourselves to the ideal assumptions that he used to derive his results.

Equilibrium between the vapor and liquid leaving a tray can be written as follows.

$$y_i = \frac{\alpha_i x_i}{\bar{\alpha}} \quad «$$

where

$$\bar{\alpha} = \sum_i \alpha_i x_i \quad \textbf{(10)}$$

is a mole fraction averaged relative volatility.

In contrast to the usual treatment, we do NOT have to assume that relative volatilities are constant. Indeed, they are in general a function of temperature, pressure and compositions. They tend to be much less strong functions of temperature than K-values.

The component material balance for vapor and liquid streams passing between two trays is given by

$$y_i V = x_i L + x_{Di} D \quad \textbf{(11)}$$

Note, we have not written the tray subscripts here to keep the notation as simple as possible.

The operating and equilibrium conditions intersect at a pinch point, as they did on the McCabe-Thiele plot above for a binary column, when y_i and x_t for one tray equals y_{-t} and x_i for the next for all *i*. An infinite number of trays results. Combining these relationships gives us our desired equations for analysis.

Figure 5 gives us an interesting insight into this calculation. It shows a conventional flash computation, Figure 5a, and this pinch calculation, Figure 5b. Note that they look very similar except for the direction of the feed flow and the vapor flow. These changes in flow direction introduce a minus sign in the

resulting equations and cause an enormous difference in the structure of the results, giving the multiple roots that one finds for the Underwood equations which do not occur for the flash calculation.

$$\frac{\alpha_i}{\bar{\alpha}} \quad \frac{R}{R+1} \quad = \frac{x_{Di}}{R+1} \tag{12}$$

or

$$x_i = \frac{\bar{\alpha} x_{Di}}{\alpha_i (R+1) - \bar{\alpha} R} \tag{13}$$

Summing over all components gives

$$\sum_i \frac{\alpha_i x_{Di}}{\alpha_i (R+1) - \bar{\alpha} R} = 1 \tag{14}$$

The algorithm to compute T versus Q is then as follows.

1. Given D, given x_{Di} for all components *i.*
2. Compute by whatever means are available R_{min} for the column (for example, use existing simulation packages for this task).
3. Choose R - 0. Note, this is the value of R at the pinch point rather than at the condenser, i.e., it gives the value of the liquid flow down the column to the distillate product rate *at the pinch point.*
4. Estimate α_i for all components at the pinch point.
5. Use Equation 10 to compute S at the pinch point.
6. Use Equation 13 to compute x_i for all components i at the pinch point.
7. Compute the temperature corresponding to the bubble point for composition x_i all i. This computation can be a nonideal bubble point calculation which will result in a temperature and new relative volatility values, α_i.
8. Interate from Step 5 until the relative volatilities α_i do not change from one iteration to the next.
9. From a heat balance around the column (envelop I in Figure 2), determine the condenser duty. Since the value ofR and thus the liquid $(L = RD)$ and vapor flow $(V = (R+1)D)$ are at the pinch point, this computation is not approximate.
10. Plot T versus this heat duty, Q_c.
11. Increment R and repeat from Step 4. Keep repeating until R reaches the maximum value desired for operating the column (e.g., 1.2 times the minimum reflux ratio computed in Step 2 above).

Figure 6 is a typical plot that one might generate from this algorithm, showing a notch that corresponds to introducing an interheater into the column. It is for a column in which feed and products are bubble point liquids. It differs in form from the binary column in that the two curves (bottom for condenser and top for reboiler) do not generally intersect at the point where minimum reflux conditions occur. They will only intersect if all components appear in both products; then the two pinch points that will normally occur for the column will become one pinch point at the feed tray.

This diagram has been *extended* for feed conditions which are other than bubble point liquid. It can be *altered* easily to accommodate products which are not bubble point liquids.

To extend it for a feed with an arbitrary quality (q = 1 for bubble point liquid and q = 0 for dew point vapor), one must redo step 2 in the algorithm to find the minimum reboiler and condenser duties for whatever cases are of interest (e.g., for q - 0, 0.25,0.50,0.75 and 1.00). These points can be noted along the curves. Only for bubble point liquid feed will the condenser and reboiler duties be equal. For all others, there will be a difference in these duties which equals the amount of heat that is required to change the feed from bubble point liquid to the feed quality being considered. Figure 6 illustrates both these points.

Note for q = 0 (dew point vapor), the reboiler duty is reduced while the condenser duty is increased relative to q = 1. The same curves result irrespective of the thermal condition of the feed, so one has in fact proved that partially vaporizing the feed will always increase the condenser duty and decrease the reboiler duty relative to bubble point liquid feed. We show a "tie-line" which can be plotted on this figure to allow in-between values of q to be accommodated.

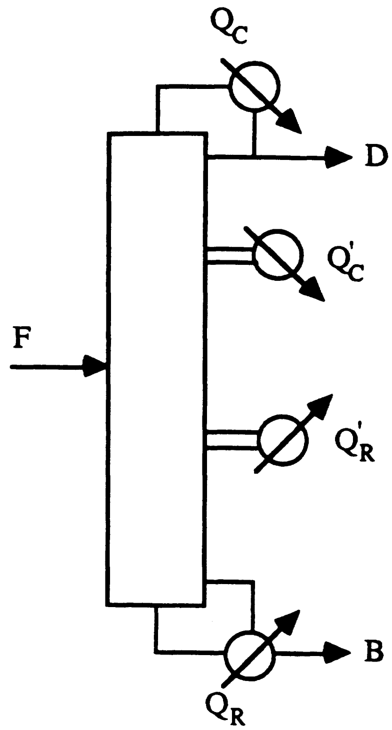
To change the thermal condition of the products requires that one alter the plot. The current plot is for a total condenser and has that the condenser duty must be at least enough to condense the top product for a zero reflux ratio. This amount of heat is labeled Q_D in Figure 6. If the top product is withdrawn as a dew point vapor, Q_D will become zero and the curve for the condenser duty will shift to the left everywhere by Q_D. Similarly, if one wishes to withdraw the bottom product as a dew point vapor, then the reboiler curve would have to shift to the right everywhere by the amount of heat needed to vaporize the bottom product. For a condenser from which both a vapor and liquid product is withdrawn, the value of Q_D can be appropriately adjusted. The curved segments of the plot are only shifted; their shapes are not altered.

Example

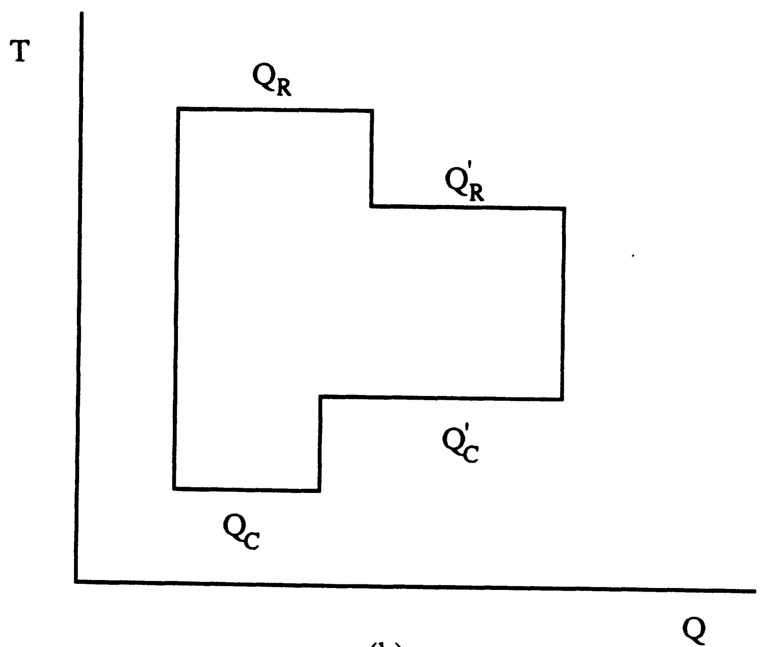
In Figure 7 we show the plot constructed for a column fed with 2.5 kg/s of equal *weight* fractions of five components: isobutane, n-butane, 2-methylbutane, n-pentane and n-hexane. The feed is bubble point liquid. The light key is isobutane; the heavy key is n-butane. 98% of the light key is recovered in the top product and 98% recovery of the heavy key in the bottom. The column operates at one atmosphere.

On this plot we also show the heating curve that indicates the temperature (K) at which heat has to be added to the feed to change it from being a bubble point liquid to a dew point vapor versus the amount of heat (kcal/s) to effect that change.

Figure 8 shows the *limiting* (in that no less heat can be put into the reboiler) heating and cooling curve for placing an interheater at 284 K into a column where the feed has been preheated from being a bubble point liquid to be 50% vapor (i.e., from ^7= 1.0 to <y=0.5). It was constructed entirely by using the information contained in Figure 7. We see here the folly of deliberately preheating the feed all the way to 50% vapor. First, part of that heat has to be put into the process at a temperature that exceeds the reboiler temperature of the column, and second, more heat passes through the process. For a multicomponent column where the heavy key is not the heaviest component, the *dew* point of the feed to a column can often exceed the *bubble* point of the bottoms product.



(a)



(b)

Figure 1: (a) Column with Interheater and Intercooler.
(b) T vs. Q Diagram for Interheated/Intercooled Column

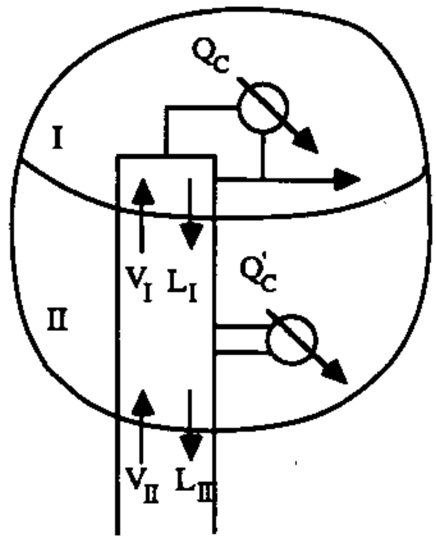


Figure 2: Material and Heat Balance Envelops for Deriving Effect of Intercooling

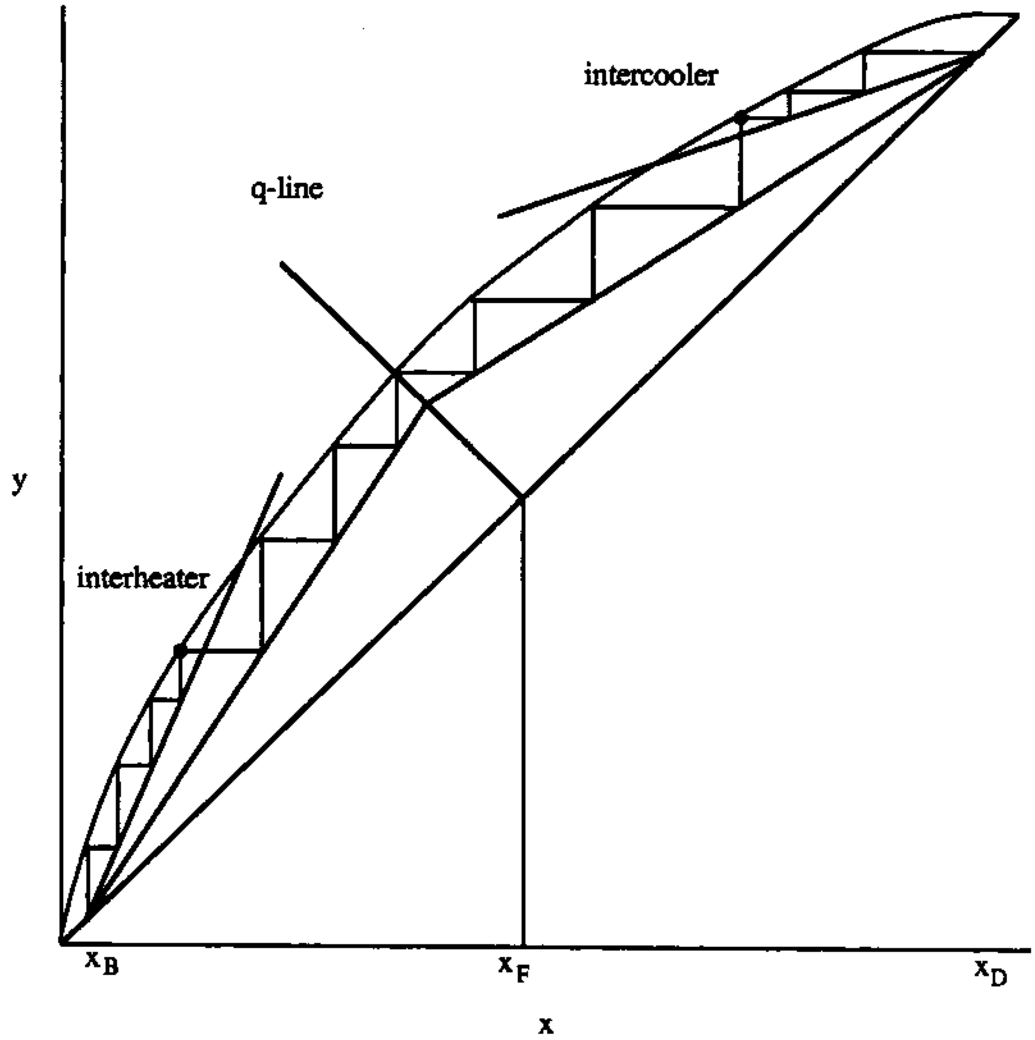
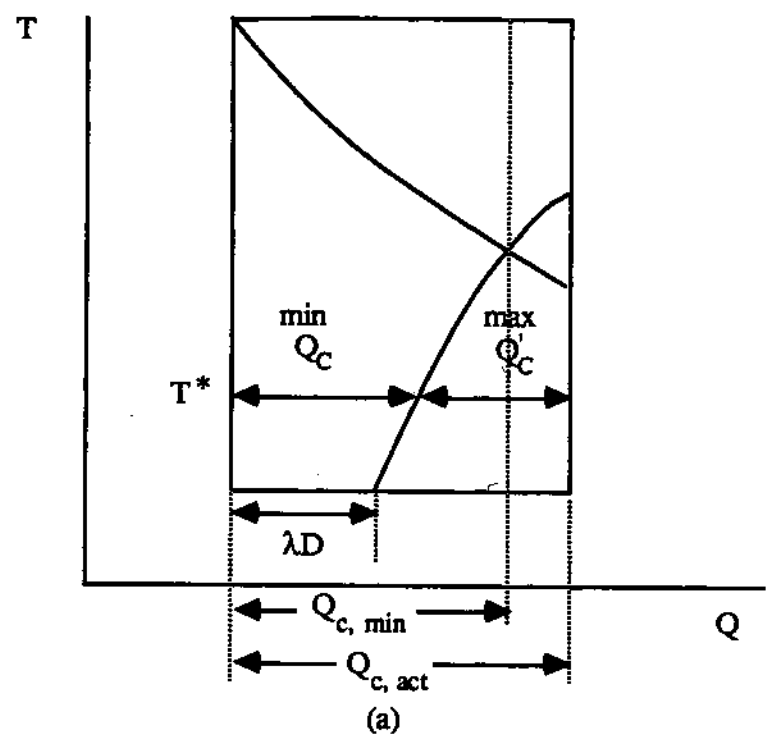


Figure 3: McCabe-Thiele Diagram for Interheated/Intercooled Binary Column



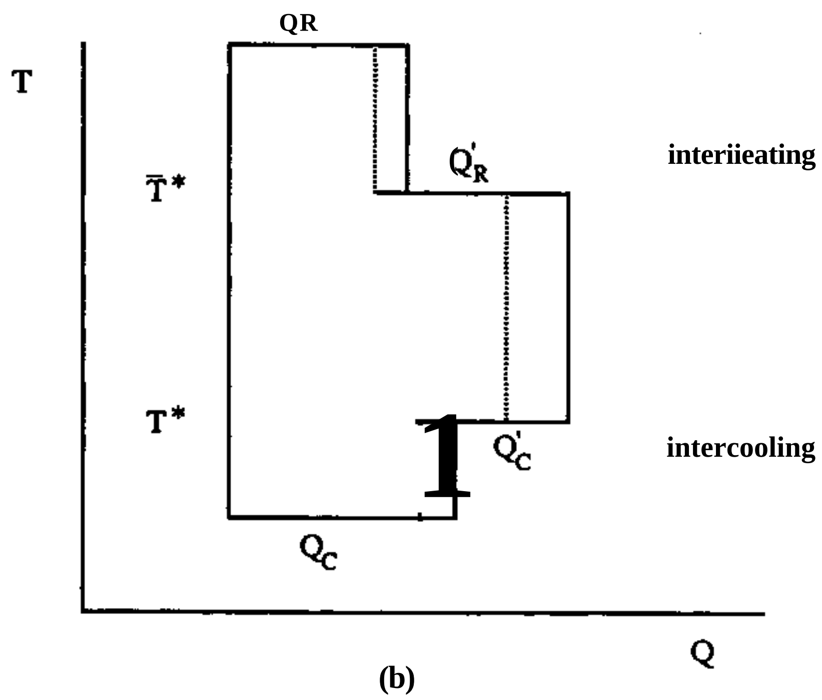
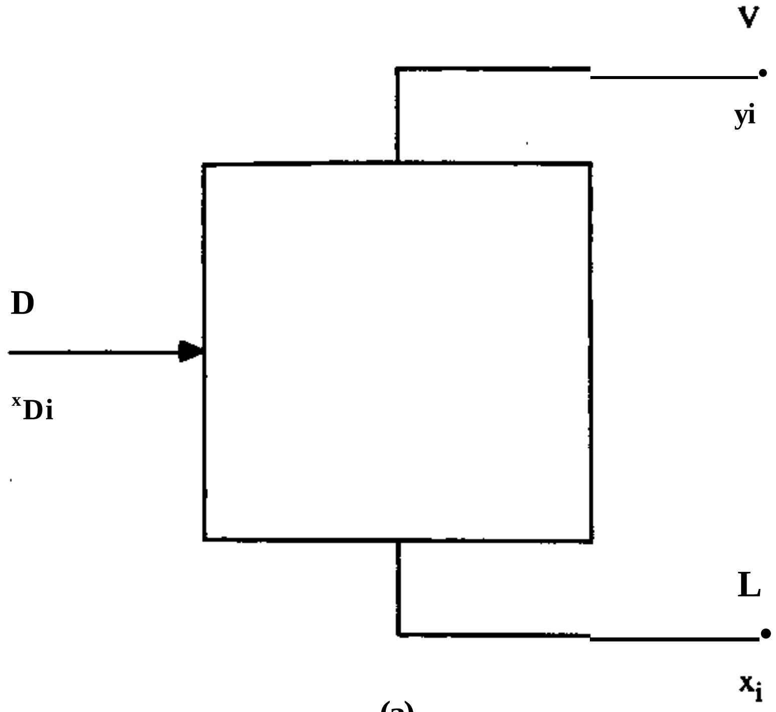
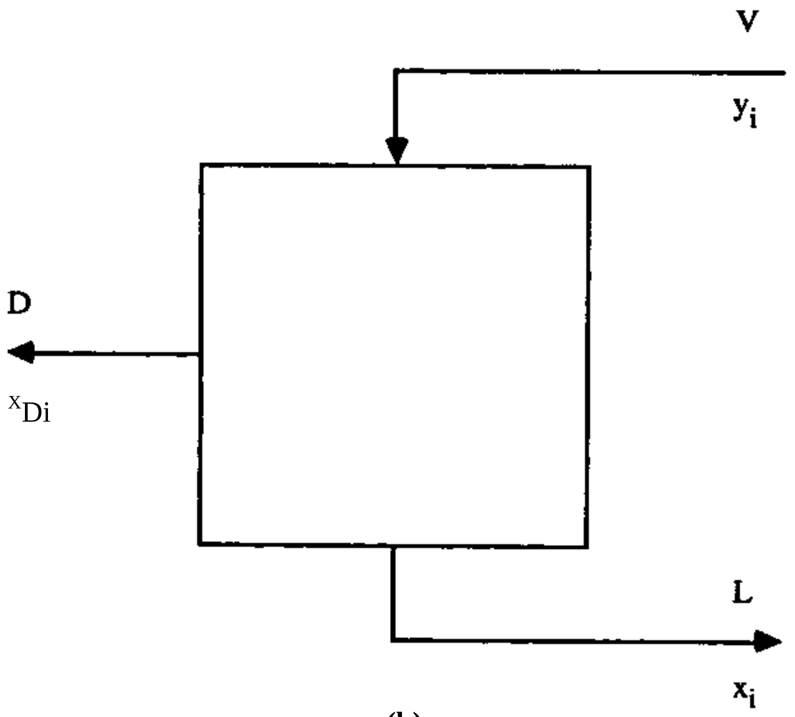


Figure 4: (a) Interheating/Cooling Diagram for Binary Column, (b) T vs. Q Diagram for Interheated/cooled Column Constructed from Information in Fig 4a.



(a)



(b)

Figure 5: (a) Material Flow Diagram for Flash Unit,
(b) Material Flow Diagram for Pinched Top Part of Distillation Column

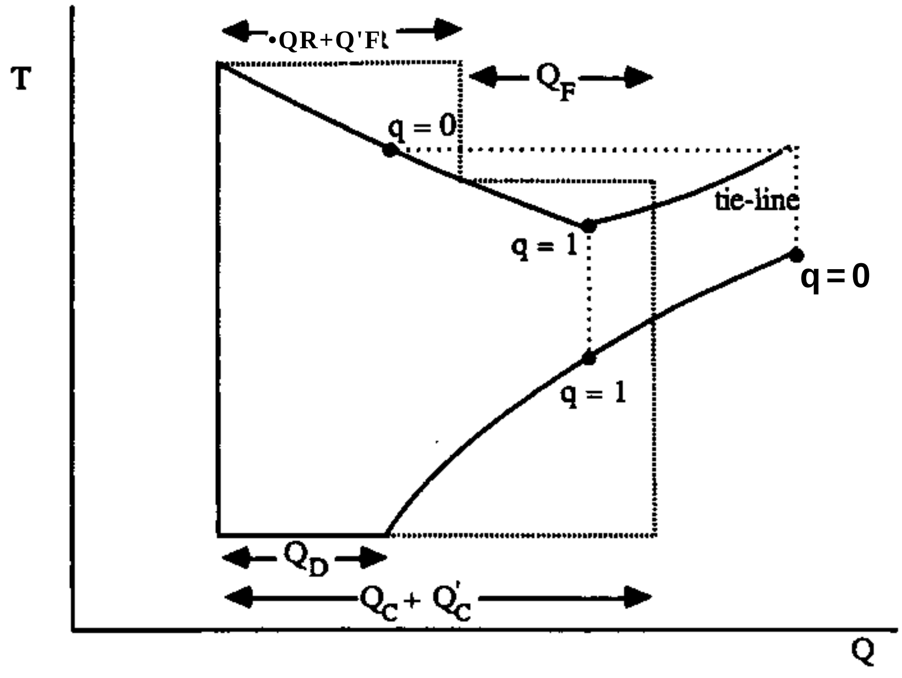


Figure 6: Interheating/Cooling Diagram for Multicomponent Distillation Column. Lower cooling line extends past q= 1 point which is partially vaporized. Tie line locates points with same feed quality on heating and cooling curves, as illustrated for $q = 0$ points.

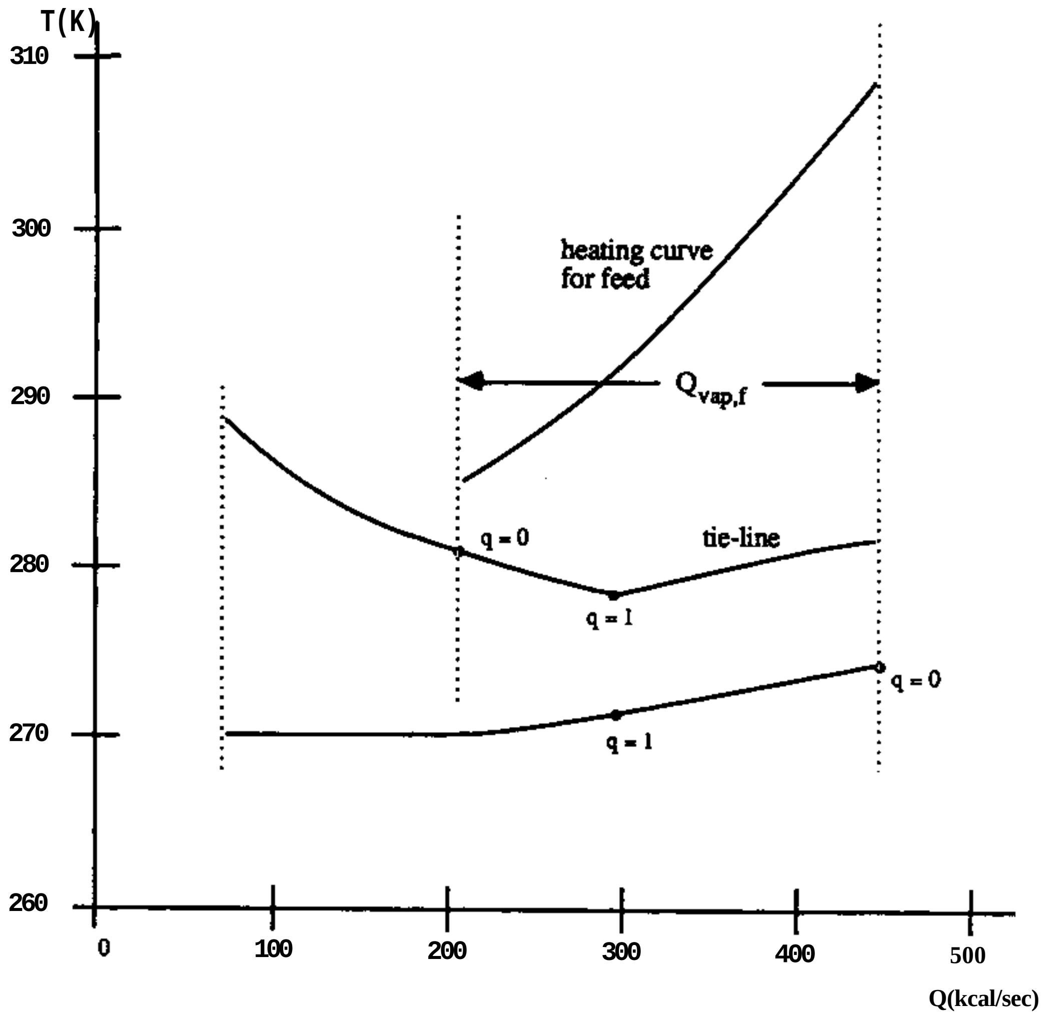


Figure 7: Interheating/Cooling Diagram for Example Problem.
Heating Curve for Preheating Feed from Bubble Point Liquid to Dew Point Vapor Shown

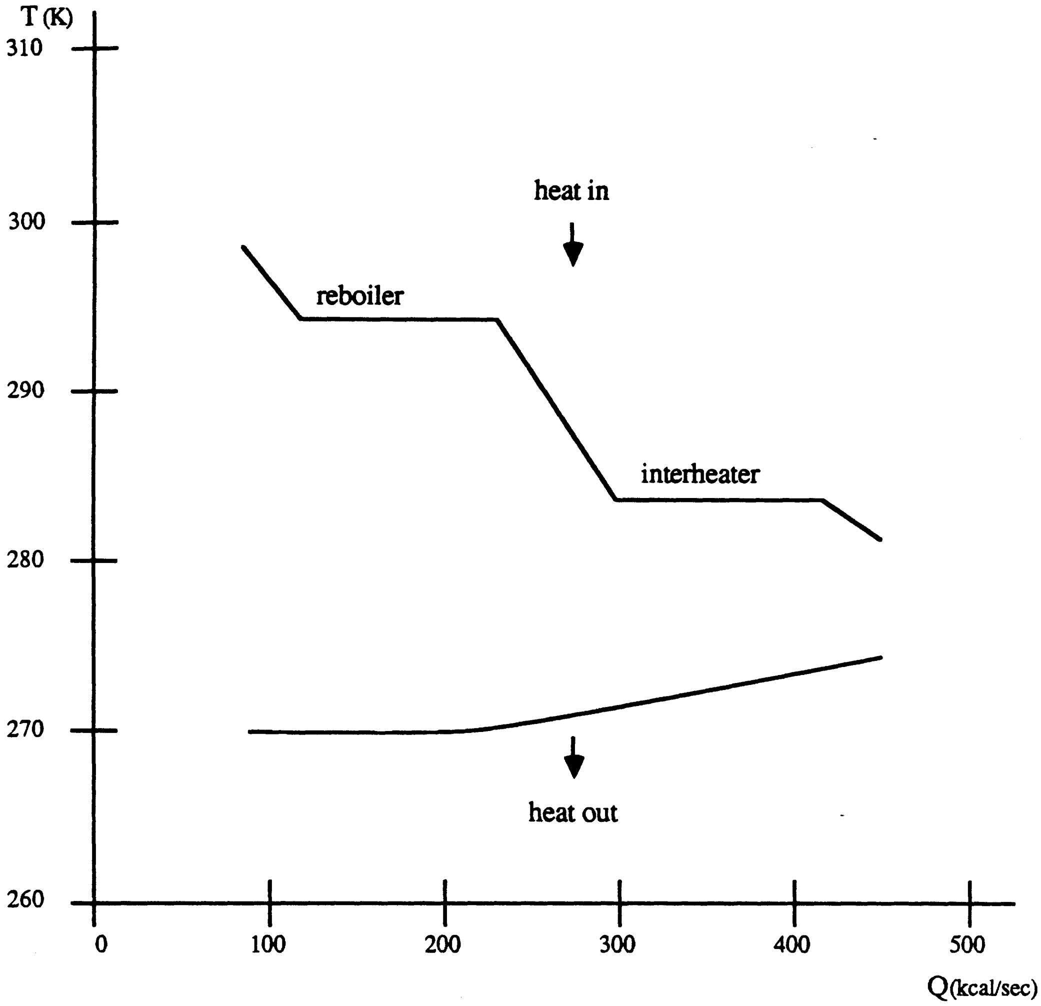


Figure 8: Heating (upper) Curve and Cooling (lower) Curve for Example Problem When Feed is Preheated to 50% Vapor. Sloped portions of top curve are heating curve for preheating feed.

References

Andrecovich, M.J.; Westerberg, A.W. A Simple Synthesis Method Based on Utility Bounding for Heat-Integrated Distillation Sequences. *AIChE Journal,* **1985,***31 (3),* 363.

Hohmann, E.C. *Optimum Networks for Heat Exchange.* PhD Thesis, University of Southern California, **1971.**

Ho, F.G.; Keller, G.E. Process Integration. *Recent Developments in Chemical Process and Plant Design.* Liu, Y.A.; McGee, H.A.; Epperly, W.G., eds. John Wiley, **1987,** 101-126.

Linnhoff, B.; et. al. A User Guide on Process Integration for the Efficient Use of Energy. *Technical Report, The Institution of Chemical Engineers,* **1982.**

Underwood, AJ.V. Fractional Distillation of Multicomponent Mixtures - Calculation of Minimum Reflux Ratio. / *Inst Petrol,* **1946,***32,* 614.

Underwood, AJ.V. Fractional Distillation of Multicomponent Mixtures. *Chem Eng Progress,* **1948,** *44,* 603.