Intermediate Reboiler and Condenser Arrangement for Binary Distillation Columns

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The most thermodynamically efficient configuration for adding or removing heat from an intermediate location of an ideal binary distillation column distilling pure products is derived. The optimal policy requires that preconditioning of the feed be part of the overall decision-making process. The optimal configuration can be determined through the use of two parameters, α_{IR} and α_{IC}, that are solely functions of feed composition. Simple and readily usable heuristics using these parameters are developed that help instantly identify the most efficient selection among (1) totally vaporizing and returning a side-draw liquid stream from an intermediate location of the distillation column, (2) partially or totally vaporizing a portion of the given saturated liquid feed, (3) partially or totally condensing a portion of the given saturated vapor feed, and (4) totally condensing and returning a side-draw vapor stream from an intermediate location of the distillation column.

Introduction

The proper use of intermediate reboilers and condensers can often produce significant reductions in operating cost of a distillation system. Zodonik (1977) presented an example of an ethylene plant where the use of an intermediate reboiler near the middle of a deethanizer column led to energy savings with a payback period for the added equipment of much less than one year. Patterson and Wells (1977) presented another distillation example where the benefits of the intermediate reboiler were such that it took only half a year to recover the capital investment. In subambient distillations and distillations employing heat pumps, the use of intermediate reboilers and condensers to reduce energy consumption is well known (Kleinberg, 1987; Lynd and Grethlein, 1986). Recently Agrawal et al. (1996) have shown that, for a binary distillation, the use of a prefractionating column, in conjunction with an intermediate reboiler or condenser in the main distillation column, can reduce the total utility demand without changing the utility temperatures. In the accompanying article, an analysis is presented that leads to quick identification of the binary distillations for which an intermediate reboiler or condenser can lead to a substantial improvement in thermodynamic efficiency (Agrawal and Herron, 1998).

There seems to be some confusion regarding how heat should be added to, or removed from, an intermediate location of a distillation column. A few authors have suggested either preheating or precondensing the feed to a distillation column in lieu of an intermediate reboiler or condenser (Patterson and Wells, 1977). The use of two feeds that are of the same composition but with different enthalpies has been suggested for binary distillation (Wankat and Kessler, 1993). In this case, a portion of the liquid feed is vaporized outside the distillation column and is then fed a number of stages below the liquid feed. Lynd and Grethlein (1986) have suggested that for heat pumping applications, a liquid (vapor) stream be withdrawn from an intermediate location of the distillation column and, after total vaporization (condensation), be returned to a location where the composition of the returned vapor (liquid) matches with the vapor (liquid) in the column. These latter authors also reviewed three other methods for heat addition or removal from an intermediate location of a distillation column. In one of the methods, heat is directly added (removed) to a pool of liquid on a tray. In another method, all the liquid (vapor) is withdrawn from a stage, partially vaporized (condensed), then returned to the same location in the distillation column. Typically it is these two methods of adding or removing heat from an intermediate location of the distillation column that are discussed in the literature (Flower and Jackson, 1964; Terranova and Westerberg, 1989; Agrawal and Fidkowski, 1996).

As a further continuation of the work presented in the ac-

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companying article, thermodynamic efficiency analysis is used to answer some additional questions regarding the use of an intermediate reboiler or condenser in an ideal binary distillation column producing pure products. When is it thermodynamically more efficient to vaporize (condense) a portion of a given liquid (vapor) feed external to a distillation column and have two feeds to the distillation column as compared to locating an intermediate reboiler (condenser) at an internal location in the distillation column? Should a portion of the liquid (vapor) feed be totally or partially vaporized (condensed) prior to feeding it to a distillation column? Which is the more efficient arrangement of intermediate reboilers and condensers as compared to placing them directly inside a distillation column? A quick answer to these questions can provide valuable guidance when distillation flow sheets using intermediate reboilers and condensers are synthesized. More importantly, guidelines are developed that indicate what not to do when attempting to maximize the performance of a distillation column. Once thermodynamically efficient process schemes are identified, economic feasibility can be studied.

Answers to the preceding questions are developed using the procedure described in detail in the accompanying article, as well as in the earlier articles (Agrawal and Herron, 1997, 1998). For a large number of real binary mixtures with near-ideal thermodynamic properties, a good agreement was found between the thermodynamic efficiencies calculated from the simplified model and the ones calculated through the computer simulation using a detailed design software with actual thermodynamic properties (Agrawal and Herron, 1997). An ideal binary mixture AB is distilled to produce pure products A and B. The maximum thermodynamic efficiency of a pinched distillation column using either an intermediate reboiler or an intermediate condenser is then calculated. A number of simplifying assumptions were made that are listed in the accompanying article. Briefly, the most important assumptions are ideal vapor and liquid phases; equal latent heats for both components A and B; latent heat independent of temperature (over the operating temperature range of the distillation column); and the vapor pressure of a component as given by the Clausius–Clapeyron equation. In order to calculate the efficiency of the distillation column alone, exergy losses for only the streams entering and leaving the distillation column were considered. Both the bottom and intermediate reboiler and top and intermediate condenser, and any other heat exchanger, were excluded from the control volume under consideration. Subcooled liquid or superheated vapor feeds were not included in this study. The relevant equations are prescribed and discussed in the other two articles and will not be discussed here. The calculation results from these two papers will be used directly, followed by some interpretation and discussion.

Two-Feed vs. Intermediate Reboiler or Condenser

In this section, the thermodynamic efficiency of a distillation column having a saturated liquid plus a saturated vapor feed, each of the same composition, is compared with distillation columns with only one feed but using an intermediate reboiler or condenser (Figures 1 and 2). In Figure 1, a given feed F is split into two feeds. For the case under consideration, the top feed (F_{TOP}) is saturated liquid and the bottom

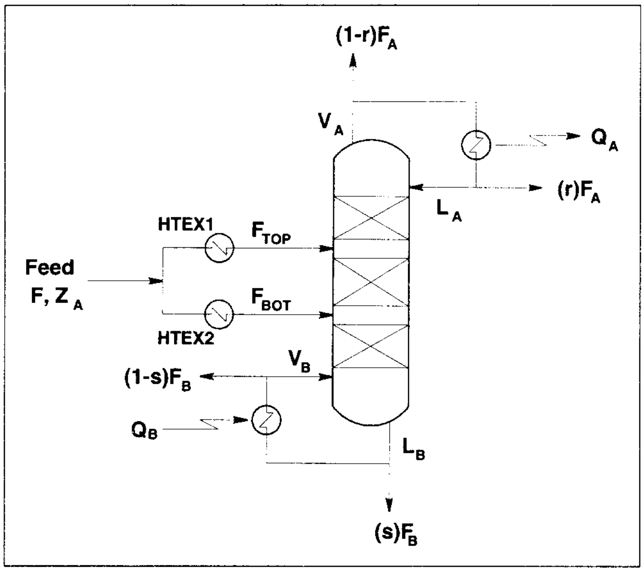

Figure 1. Distillation column with two feeds of same composition but different enthalpies: HTEX1 is a feed condenser, HTEX2 is a feed vaporizer.

feed (F_{BOT}) is saturated vapor. If the original feed F is saturated liquid, then duty in heat exchanger HTEX1 is zero and HTEX2 is a feed vaporizer. If feed F is saturated vapor, then HTEX1 is a feed condenser and the duty in heat exchanger HTEX2 is zero. In this figure, r and s are the fractions of total products A and B, which are withdrawn as liquid. Figure 2a shows only the stripping section of a full distillation column where a given feed is sent directly to the distillation column and an intermediate reboiler is used. Note that in this arrangement all the liquid, L_3, is withdrawn, partially vaporized, and returned to the same location in the distillation column. Figure 2b shows the rectifying section of a full distillation column with one feed and an intermediate condenser. Here all the vapor, V_2, is sent through the intermediate condenser, partially condensed, and returned to the same location in the distillation column. For thermodynamic efficiency calculations, the distillation columns are assumed to be pinched at the feed locations and at the intermediate reboiler or condenser locations.

Fidkowski and Agrawal (1995) analyzed this problem from the first-law perspective. If two feeds were used, a portion of the given saturated liquid feed was vaporized in a feed vaporizer, and fed a number of stages below the liquid feed (Figure 1). For the distillation with a single saturated liquid feed, the location of the intermediate reboiler was chosen such that the composition of the vapor phase exiting the intermediate reboiler, $y_{A,IR}$, was identical to the composition of the feed, Z_A (Figure 2a). It was found that for pinched columns, the heat input in the feed vaporizer was same as the heat input in the intermediate reboiler. Also, heat input to the bottom reboiler of both the columns was the same. Therefore, both cases performed the same from the first-law perspective. It will be now interesting to compare the performance of these two cases from the second-law perspective and gain some additional insight by comparing their thermodynamic efficiencies.

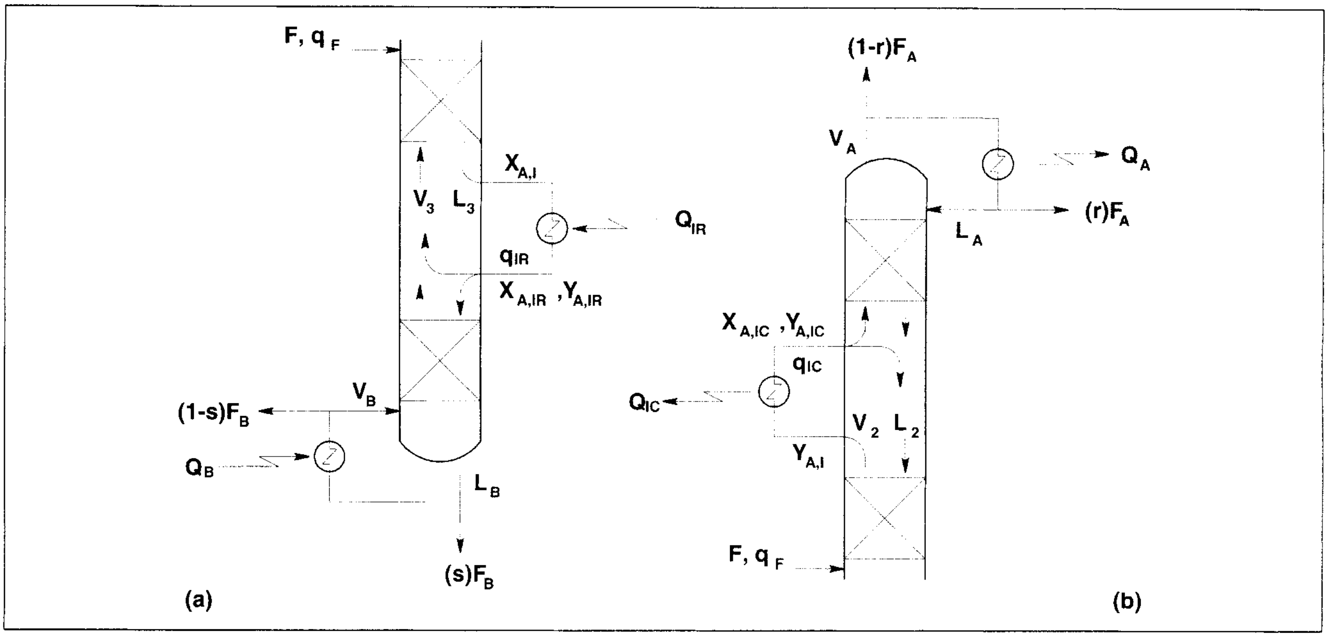

Figure 2. Configurations for side heat duties: (a) intermediate reboiler; (b) intermediate condenser.

Thermodynamic efficiency for the two-feed case with both feeds of the same composition, but one feed as saturated vapor and the other as saturated liquid, is described in detail by Agrawal and Herron (1997). These efficiency curves are reproduced in Figures 3 and 4 for three feed compositions of $Z_A = 25\%$, 50%, and 75%. For these two-feed cases, the fraction of the total feed fed as vapor is equal to Z_A. It can be proven that the maximum in thermodynamic efficiency for the two-feed case occurs for this split (Agrawal and Fidkowski, 1998). In Figure 3, the efficiency of the two-feed case is compared with the one saturated liquid feed plus intermediate reboiler case. This later case is decribed in detail in the accompanying article. The location of the intermediate reboiler is chosen to yield the maximum value of thermodynamic efficiency. It is interesting to note that for any given feed composition, there exist certain values of relative volatil-

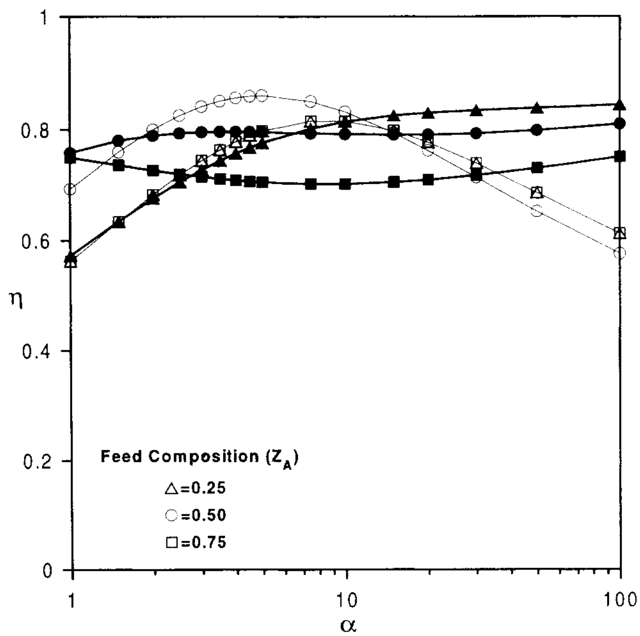

Figure 3. Thermodynamic efficiency of using two feeds (saturated liquid and vapor) (light lines, open symbols) vs. single saturated liquid feed using an intermediate reboiler (dark lines, filled symbols).

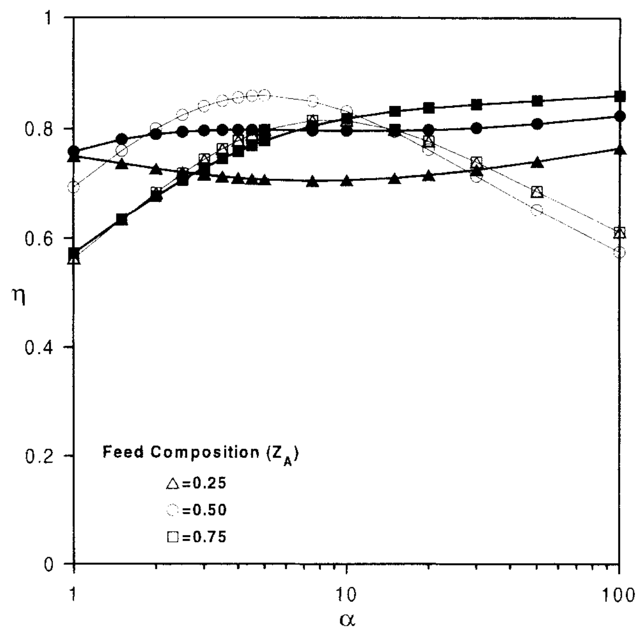

Figure 4. Thermodynamic efficiency of using two feeds (saturated liquid and vapor) (light lines, open symbols) vs. single saturated vapor feed using an intermediate condenser (dark lines, filled symbols).

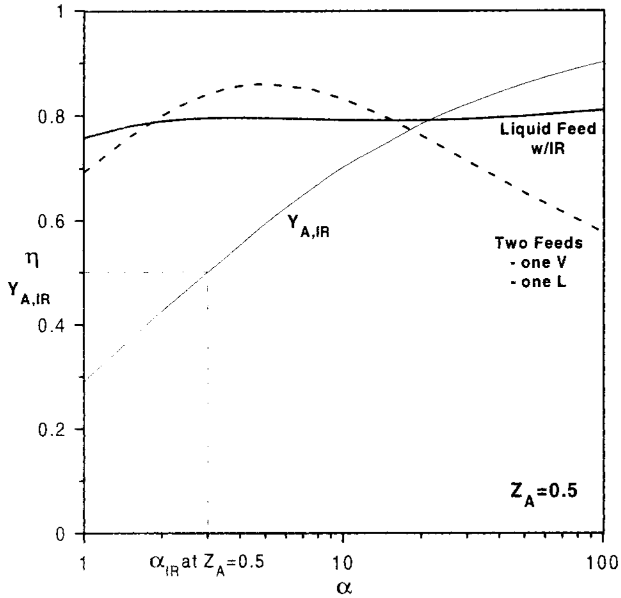

Figure 5. Thermodynamic efficiency of using two feeds (saturated liquid and vapor) (dashed lines) vs. single saturated liquid feed using an intermediate reboiler (dark, continuous line) at $Z_A = 0.5$.

The vapor composition $y_{A,IR}$ in the stream exiting the intermediate reboiler is also plotted.

ity, α, for which the two-feed case provides a higher efficiency than the one-feed plus intermediate reboiler case!

Close examination of the data reveals that for the results shown in Figure 3, the two-feed case is more efficient when the location of the intermediate reboiler is such that the vapor-phase composition, $y_{A,IR}$, of the two-phase stream exiting the intermediate reboiler is in close proximity to the feed composition. This information is shown in Figure 5 for a feed composition of 50% A and is found to hold for other feed compositions as well. In Figure 5 at $\alpha = 3$, the value of $y_{A,IR}$ is equal to the feed mole fraction of A ($Z_A = 0.5$). This means that for $\alpha = 3$, the optimum location of the intermediate reboiler is identical to the location where saturated vapor feed is fed for the two-feed case. From the work of Fidkowski and Agrawal (1995) it is known that in such a situation the heat input required to generate the saturated vapor feed in the feed vaporizer is identical to the heat input in the intermediate reboiler. This raises the question, if the heat input is the same for both these cases, then why is the two-feed case thermodynamically more efficient?

The source of higher efficiency resides in the exergy needed to totally vaporize a fraction of the feed in the feed vaporizer vs. the exergy needed to partially vaporize a fraction of the stream through the intermediate reboiler (refer to Figure 6a). Since the vapor-phase compositions of the streams exiting both the heat exchangers are the same, their outlet temperatures are identical. However, the inlet temperature to the feed vaporizer is colder than the inlet temperature to the intermediate reboiler. Therefore, a portion of the feed vaporization takes place at temperatures lower than those in the intermediate reboiler. This means that at least in theory (and sometimes in practice), a lower temperature utility can be used to vaporize a portion of the feed in the feed vaporizer. Therefore, if the heat exchange were to be done reversibly in both the exchangers, the exergy need of the feed vaporizer would be less than that of the intermediate reboiler. For the case of a subambient distillation, this implies that addition of heat to boil the feed would generate more exergy. As a result, the two-feed case is thermodynamically more efficient. The efficiency difference is also reflected in the McCabe–Thiele diagram for the two cases shown in Figure 7. In the stripping section, operating line *abc* for the two-feed case is much closer to the equilibrium curve, while a section of the operat-

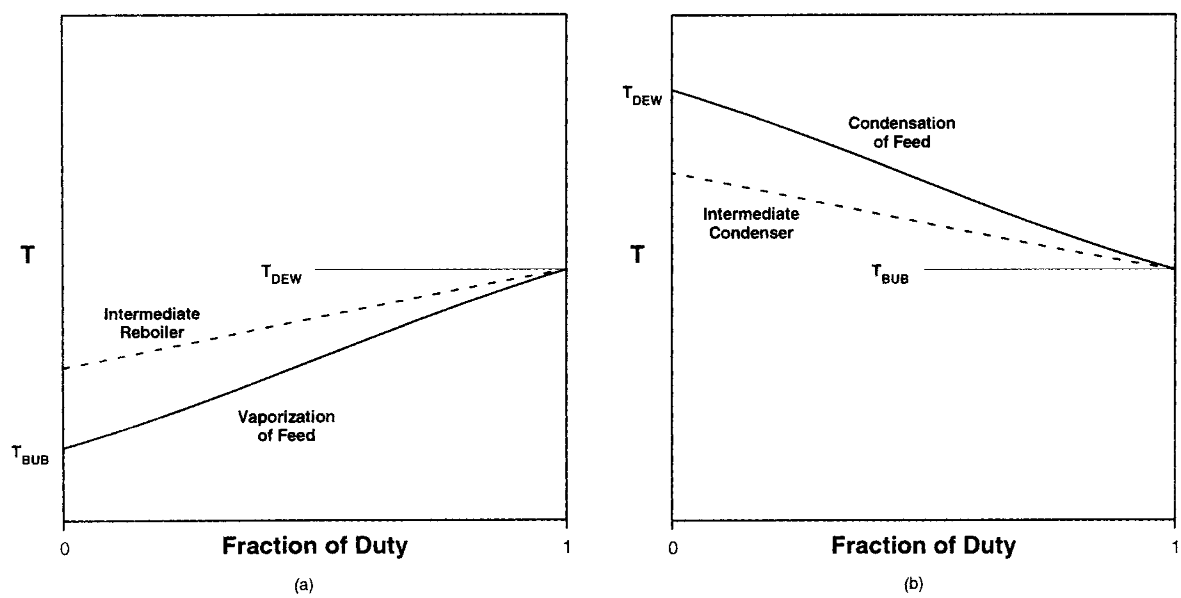

Figure 6. Temperature change of a stream as heat is added or removed.

T_{DEW} and T_{BUB} are the dew-point and bubble-point temperatures of the feed. (a) Total vaporization of feed vs. intermediate reboiler; (b) total condensation of the feed vs. intermediate condenser.

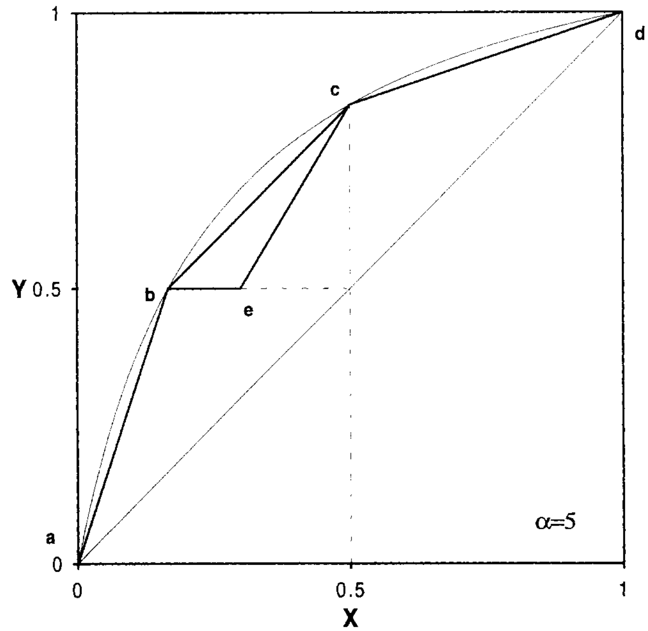

Figure 7. McCabe–Thiele diagram for a binary distillation.

The operating line for the two-feed case is *a-b-c-d*; the operating lines for the liquid feed plus intermediate reboiler are *a-b* and *e-c-d*.

ing line (ec) is further removed for the intermediate reboiler case. The increased amount of exergy input in the intermediate reboiler is wasted in the distillation column. This is also observed for cases with nonpinched columns that use the same amount of heat in corresponding reboilers; examples are available where nonpinched columns with an intermediate reboiler required fewer stages of separation than nonpinched columns with two-feeds (Fidkowski and Agrawal, 1995).

It is observed in Figure 5 that the optimum location of the intermediate reboiler (as seen by $y_{A,IR}$) moves up as the value of α increases. For α slightly greater than 1, the location of the intermediate reboiler is such that $y_{A,IR}$ is considerably less than Z_A, that is, the temperature at which heat is added in the intermediate reboiler is higher than the dew-point temperature of the feed. For such cases, the efficiency of a liquid feed with an intermediate reboiler is generally greater than for the two-feed case. As α increases further, the optimum location of the intermediate reboiler is such that $y_{A,IR}$ is close to Z_A, and the two-feed case provides higher efficiency. At even higher values of α, the optimum location of the intermediate reboiler moves further up and the temperature of the stream exiting the intermediate reboiler is significantly below the dew-point temperature and close to the bubble-point temperature of the feed ($y_{A,IR}$ is much greater than Z_A). At this point the efficiency of the saturated liquid feed with intermediate reboiler is again greater than the two-feed case.

An equivalent situation exists when the given feed is saturated vapor and the use of a feed condenser or an intermediate condenser is compared (Figure 4). In the two-feed case, a fraction (equal to $1-Z_A$) of the feed is totally condensed in a feed condenser and fed as a separate feed to the distillation column. As long as the optimum location of the intermediate condenser is such that the liquid composition in the two-phase stream exiting the condenser ($x_{A,IC}$) is in the neighborhood of the feed composition, the two-feed case gives higher efficiency. Once again, this can be easily explained by reference to Figure 6b. The vapor stream, V_2, going to the intermediate condenser is colder than the dew-point temperature of the vapor feed, that is, a portion of the heat can be removed at higher temperatures from the feed condenser. For above ambient distillations this means that less exergy is recovered from the intermediate condenser and for subambient distillations it means that more exergy would be needed to pump heat from the intermediate condenser to the bottom reboiler or to the reference ambient temperature. For the intermediate condenser case, at low values of α the optimum location is high up in the column ($x_{A,IC} > Z_A$), and as α increases, this optimum location moves closer to the saturated vapor feed point.

The observation that, for certain values of α, the two-feed cases can give higher efficiencies raises the question: If heat is to be added or removed from an intermediate location of a distillation column, then what is the most efficient configuration to accomplish the task?

Efficient Configuration of Intermediate Reboiler or Condenser

From the preceding discussion it is clear that an efficient distillation configuration using intermediate heat addition or removal has to allow for the possibility of preconditioning a portion of the feed to generate a second feed for the distillation column. In order to create the most efficient configuration, assume that the heat exchange at an intermediate location is totally reversible, that is, the exchanger's exergy loss is zero. Then, for a given location of the intermediate reboiler ($y_{A,IR}$ fixed), it is desirable that the saturated liquid feed to this reboiler be chosen such that its temperature be at the lowest possible level. Similarly, for a given location of the intermediate condenser ($x_{A,IC}$ fixed), it is preferred that the saturated vapor feed to this condenser be chosen such that its temperature be the highest possible. This suggests, for the intermediate reboiler case when $y_{A,IR}$ is less than Z_A, and for the intermediate condenser case when $x_{A,IC}$, is greater than Z_A, that the optimal side stream return policy suggested by Lynd and Grethlein (1986) be used. Based on these observations, efficient configurations for a saturated liquid feed plus an intermediate reboiler, and a saturated vapor feed plus an intermediate condenser are shown in Figure 8a and 9a.

Figure 8 shows the proposed configuration for a saturated liquid feed with intermediate heat input. This figure illustrates that the preferred mode of operation of an intermediate reboiler depends on its location. When the optimum location for the intermediate heat addition is below the saturated vapor feed location ($y_{A,IR} < Z_A$), then it is better to side draw a portion of the descending liquid from a number of stages below the feed to the distillation column, totally vaporize it, and return it at the desired location; intermediate reboiler IR3 shows such a possibility (Figure 8a). When the optimum location is at or above the saturated vapor-feed location ($y_{A,IR} \geq Z_A$), then rather than using side liquid draw and its total vaporization and return policy it is better to precondition a portion of the feed with intermediate heat, as shown in

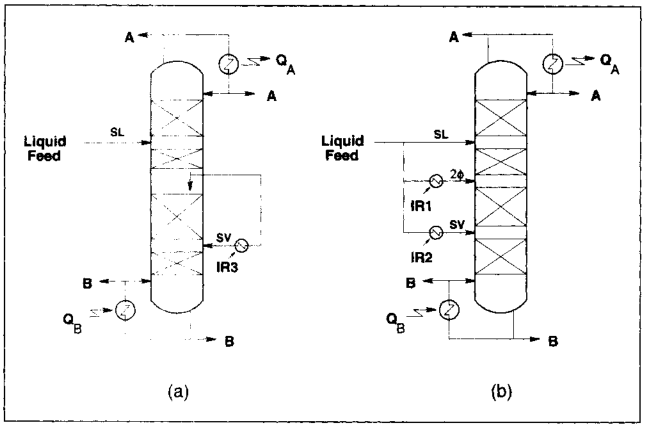

Figure 8. Saturated liquid feed and intermediate heat addition.

(a) Optimal side-stream return policy for $\alpha < \alpha_{IR}$; (b) feed preconditioning options for $\alpha \geq \alpha_{IR}$. SL = saturated liquid; SV = saturated vapor; 2ϕ = two-phase.

Figure 8b. When the optimum location of an intermediate reboiler coincides with the saturated vapor-feed location ($y_{A,IR} = Z_A$), then a fraction Z_A of the feed should be totally vaporized in feed vaporizer IR2 and fed to the distillation column as shown. When the optimum location is above the saturated vapor-feed location ($y_{A,IR} > Z_A$), then a portion of the feed should be partially boiled and fed at the desired location, as shown by partial feed vaporizer IR1.

It turns out that for a given liquid-feed composition and α, a calculation can be done for the arrangement in Figure 2a to quickly determine whether the optimum location for the intermediate heat input is at, below, or above the location where the saturated vapor composition is the same as the feed composition ($y_{A,IR} = Z_A$). This comes from an observation that for a given feed composition in Figure 2a, there exists a value of relative volatility α_{IR} at which the optimum location of the intermediate reboiler is such that $y_{A,IR} = Z_A$. Furthermore, at this location the fraction of the total vapor flow in the stripping section that is generated in the intermediate reboiler is equal to Z_A. It is also known from Fidkowski and Agrawal's (1995) analysis that the total vapor generated in the intermediate reboiler is identical to the two-feed case with the vaporized fraction of feed equal to Z_A. Therefore, for such a value of α_{IR}, the total vapor flow in the distillation is equal to the total feed flow rate. On the basis of a total feed flow rate of one, the total vapor flow V_3 is given by (Agrawal and Herron, 1998):

$$V_3 = \frac{(1 - Z_A) + \alpha_{IR} Z_A}{\alpha_{IR} - 1} = 1.$$

This gives

$$\alpha_{IR} = \frac{1 + Z_B}{Z_B}. \tag{1}$$

A mathematical proof that an extremum in the value of the thermodynamic efficiency for a given feed composition Z_A and $y_{A,IR} = Z_A$ indeed occurs at the value of α_{IR} is given in the Appendix.

Since side liquid draw and its total vaporization and return (Figure 8a) yields higher efficiencies than the intermediate reboiler configuration of Figure 2a, an unanswered question remains. For the configuration in Figure 8a, is α_{IR} still the relative volatility at which intermediate heat addition location coincides with the location where the saturated vapor composition is the same as the feed composition? For this purpose, equations using the earlier stated simplifying assumptions were developed for the configurations in Figure 8. Thermodynamic efficiency calculations for pinched distillation columns were done for several values of relative volatilities at different liquid-feed compositions. An example result that is representative of other results is shown in Figure 10.

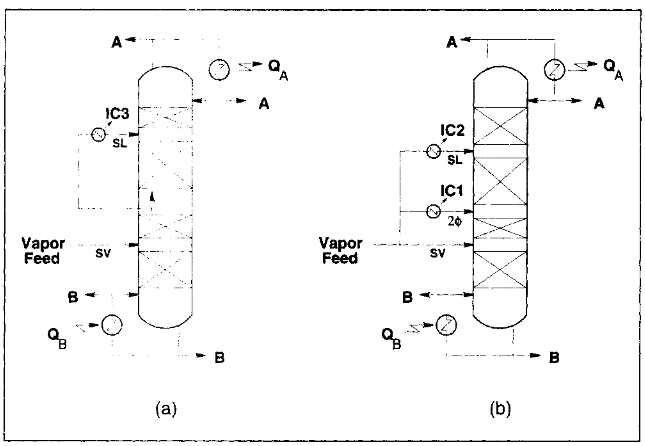

Figure 9. Saturated vapor feed and intermediate heat removal.

(a) Optimal side-stream return policy for a $\alpha < \alpha_{IC}$; (b) feed preconditioning options for $\alpha \geq \alpha_{IC}$. SL = saturated liquid; SV = saturated vapor; 2ϕ = two phase.

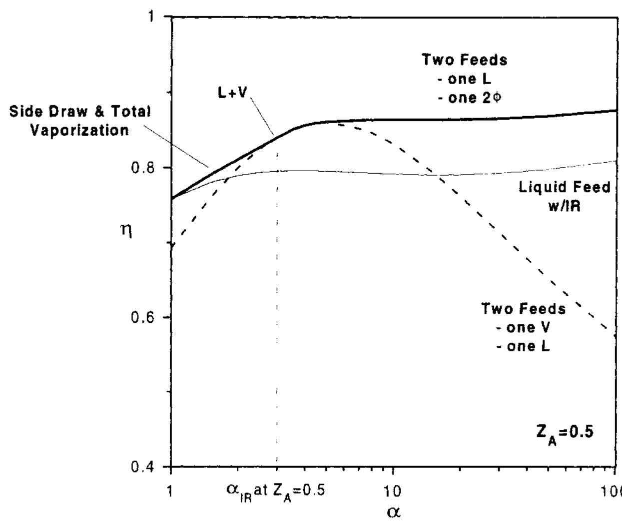

Figure 10. Thermodynamic efficiency for different methods of intermediate heat addition at $Z_A = 0.5$.

Dotted line is for saturated liquid plus saturated vapor feed. Light continuous line corresponds to the intermediate reboiler configuration of Figures 2a. Dark line is for optimal return policy configurations of Figure 8.

The feed composition is 50% of light component A. From all the numerical calculations, it is found that α_{IR} is still the relative volatility for which the composition of the side-draw liquid coincides with the given feed composition! Thus for a given feed composition, when relative volatility is less than α_{IR}, the highest thermodynamic efficiency is achieved by using the side liquid draw and its total vaporization and return policy from Figure 8a. As the value of relative volatility is increased, the location of the side liquid draw moves up the stripping section of the column. At $\alpha = \alpha_{IR}$, a Z_A portion of the feed is to be totally vaporized and fed to the column (reboiler IR2 in Figure 8b). It is natural to expect that as α increases beyond α_{IR}, the location of the intermediate heat addition will further move up the distillation column and the portion of the feed to be vaporized will be two-phase exiting the feed reboiler (IR1 in Figure 8b). However, in our calculations we have found that as relative volatility is increased beyond α_{IR}, the optimum quality of the stream exiting the feed reboiler remains virtually vapor up to values of α that are sufficiently larger than α_{IR}. For example, in the calculations for Figure 10, within the significant digits of calculations used, we found that the optimum condition of the stream exiting the feed reboiler starts as total vapor at the relative volatility of 3 (the value of α_{IR}) and remains the same up to relative volatilities of about 5. Similar behavior was observed for all the feed compositions for which calculations were done. Thus, as the value of relative volatility increases beyond α_{IR}, the transition of the stream exiting the feed reboiler from total vapor to significantly two phase is found to be quite slow. For a liquid feed, these results are summarized in Table 1.

It is clear from Figure 10 that the intermediate heat addition scheme shown in Figure 8 provides the highest thermodynamic efficiency. The difference in thermodynamic efficiencies calculated from Figures 8 and 2a can be quite large at higher values of the relative volatilities, especially when α is in the neighborhood of or higher than α_{IR}. An interesting observation from the calculation results is that for a given feed composition when $\alpha < \alpha_{IR}$, the location for the return of the totally vaporized stream in Figure 8a coincides closely with the corresponding composition $y_{A,IR}$ in Figure 2a.

It may be attractive to implement the cases where a portion of the feed is vaporized and fed to the distillation column to achieve high efficiencies (for $\alpha \geq \alpha_{IR}$). This avoids the need to have an additional section break in the distillation column for the liquid side draw and its total vaporization in an intermediate reboiler. In cases where optimal side-stream return policy is not used, and an intermediate reboiler arrangement of the type shown in Figure 2a is used, total vaporization of a portion of the feed still gives higher efficiency for values of α that are less than but in the neighborhood of α_{IR} (Figure 5). From inspection of the calculated results, we find that a rough rule of thumb for such cases is to use total vaporization of a portion of the feed as long as $\alpha > 0.5\alpha_{IR}$.

Table 1. Efficient Choices for Intermediate Heat Addition or Removal from a Distillation Column

Saturated liquid feed and intermediate heat addition	
$\alpha < \alpha_{IR}$	Optimal liquid side draw, its total vaporization and return policy with mole fraction of A in the vaporizing stream less than Z_A
$\alpha = \alpha_{IR}$	Totally vaporize Z_A fraction of feed
$\alpha > \alpha_{IR}$	Partially vaporize a portion of feed in a partial vaporizer
Saturated Vapor Feed and Intermediate Heat Removal	
$\alpha < \alpha_{IC}$	Optimal vapor side draw, its total condensation and return policy with mole fraction of A in the condensing stream greater than Z_A
$\alpha = \alpha_{IC}$	Totally condense $1 - Z_A$ fraction of feed
$\alpha > \alpha_{IC}$	Partially condense a portion of feed in a partial condenser

An equivalent situation exists when the given feed is saturated vapor and an intermediate condenser is to be used. The preferred arrangements for such a case are shown in Figure 9. For a given feed composition, Z_A, there exists a value of relative volatility, α_{IC}, at which optimal location of the intermediate condenser coincides with the saturated liquid feed location of the two-feed case ($x_{A,IC} = Z_A$). The equation for α_{IC} is derived to be

$$\alpha_{IC} = \frac{1 + Z_A}{Z_A}. \qquad (2)$$

For a given feed composition, the value of α_{IC} is readily calculated and compared with the given value of α. When $\alpha = \alpha_{IC}$, a fraction ($= 1 - Z_A$) of the feed is totally condensed in the total feed condenser IC2 and fed a number of stages above the saturated vapor feed location (Figure 9b). If $\alpha < \alpha_{IC}$, then a portion of a vapor stream is drawn from a location in the rectifying section of the distillation column, totally condensed and returned a number of stages above in the distillation column ($x_{A,IC} > Z_A$). Intermediate condenser IC3 in Figure 9a is such an example. For $\alpha > \alpha_{IC}$, a fraction of the saturated vapor feed is partially condensed in feed condenser IC1 and fed slightly above the saturated vapor feed ($x_{A,IC} < Z_A$). These results are summarized in Table 1. If the optimal arrangement of Figure 9 is not used, and instead the arrangement shown in Figure 2b is used, then it is found that it can be thermodynamically more attractive to totally condense a portion of the feed even for those values of α that are less than but in the neighborhood of α_{IC}. Again, it is found that a rough rule of thumb for such cases is to use total condensation of a portion of the feed down to values of α in the neighborhood of $0.5\alpha_{IC}$.

It follows from the preceding discussion that for a saturated vapor feed, when an intermediate reboiler configuration of Figure 2a is justified, the side liquid draw and its total vaporization and return policy will give higher thermodynamic efficiency. Similarly for a saturated liquid feed, when an intermediate condenser configuration of Figure 2b is justified, the side vapor draw and its total condensation and return policy will give higher thermodynamic efficiency.

It is worth pointing out that while the distillation columns in Figures 8 and 9 are more efficient than the distillation columns in Figure 2, the efficiency advantage can be easily lost in the heat exchangers used to provide intermediate heating or cooling duty. If a constant-temperature heat source or cold source was to be used, the intermediate heat exchangers of Figures 8 and 9 would have larger average temperature differences than the corresponding heat exchangers in Figure 2. This would lead to smaller surface area for the intermediate heat exchangers in Figures 8 and 9; however, the distillation columns require a larger number of stages than the distillation columns in Figure 2. In such a case, the overall thermodynamic efficiency of distillation column plus the intermediate heat exchanger would be the same for both the methods. Even in such situations, when the optimum solution is to preheat or precool a portion of the feed, the configuration in Figures 8 and 9 could be more attractive due to operational simplicity.

Conclusions

The most thermodynamically efficient position to add heat to or remove heat from an intermediate location of an ideal binary distillation column distilling pure products is analyzed. From analysis of the computer-simulation results, two parameters α_{IR} and α_{IC} are identified. These parameters are functions of feed composition only. For a given saturated vapor feed, the magnitude of the relative volatility α with respect to α_{IC} provides clues for efficient location of the intermediate heat-removal heat exchanger. Similarly, for a given saturated liquid feed, the magnitude of relative volatility α can be compared with α_{IR} to determine the optimal intermediate location for heat input. These results are summarized in Table 1.

It is found that the optimal policy requires that when the value of α is sufficiently large ($\alpha \geq \alpha_{IC}$ or $\alpha \geq \alpha_{IR}$), preconditioning of the feed should be part of the overall strategy. In such situations, it is better to totally or partially vaporize (condense) a portion of the saturated liquid (vapor) feed rather than to place the vaporizer (condenser) at an intermediate location of the distillation column. This result is fortunate because preconditioning a portion of the feed may be easier than placing a condenser or a reboiler at an intermediate location of the distillation column. Quite often the feed to a distillation column originates from another unit operation in the plant, and it may be possible to precondition the feed at the point of origin without much additional capital cost. This is particularly true when distillation sequencing with multiple distillation columns is used for multicomponent separation. For low values of relative volatility ($\alpha < \alpha_{IC}$ or $\alpha < \alpha_{IR}$), however, the efficient strategy is to side draw a liquid (vapor) stream, and after its total vaporization (condensation) return it back to the distillation column at an optimal location.

This study provides guidelines for selecting a thermodynamically efficient configuration for adding or removing heat from an intermediate location of a distillation column. This information is useful when flow sheets with distillation columns using an intermediate reboiler or condenser are to be synthesized. Once thermodynamically efficient process schemes are identified, then economic feasibility can be studied.

Notation

L = molar liquid flow rate
q = mole fraction of liquid in a stream
q_{IR} = fraction of liquid in the stream exiting intermediate reboiler
x_A = mole fraction of A in the liquid phase
$x_{A,I}$ = mole fraction of A in the liquid to the intermediate reboiler

Literature Cited

Agrawal, R., and Z. T. Fidkowski, "Improved Direct and Indirect System of Columns for Ternary Distillation," *AIChE J.*, **44**, 823 (1998).

Agrawal, R., and Z. T. Fidkowski, "On the Use of Intermediate Reboilers in the Rectifying Section and Condensers in the Stripping Section of a Distillation Column," *Ind. Eng. Chem. Res.*, **35**, 2801 (1996).

Agrawal, R., Z. T. Fidkowski, and J. Xu, "Prefractionation to Reduce Energy Consumption in Distillation Without Changing Utility Temperatures," *AIChE J.*, **42**, 2118 (1996).

Agrawal, R., and D. M. Herron, "Optimal Thermodynamic Feed Conditions for Distillation of Ideal Binary Mixtures," *AIChE J.*, **43**, 2984 (1997).

Agrawal, R., and D. M. Herron, "Efficient Use of an Intermediate Reboiler or Condenser in a Binary Distillation," *AIChE J.*, **44**, (5), 1303 (May 1998).

Fidkowski, Z. T., and R. Agrawal, "Utilization of Waste Heat Stream in Distillation," *Ind. Eng. Chem. Res.*, **34**, 1287 (1995).

Flower, J. R., and R. Jackson, "Energy Requirements in the Separation of Mixtures by Distillation," *Trans. Inst. Chem. Eng.*, **42**, T249 (1964).

Kleinberg, W. T., "Dual Air Pressure Cycle to Produce Low Purity Oxygen," U.S. Patent No. 4,702,757 (1987).

Lynd, L. R., and L. R. Grethlein, "Distillation with Intermediate Heat Pumps and Optimal Sidestream Return," *AIChE J.*, **32**, 1347 (1986).

Patterson, W. C., and T. A. Wells, "Energy-Saving Schemes in Distillation," *Chem. Eng.*, **84**, 78 (1977).

Terranova, B. E., and A. W. Westerberg, "Temperature-Heat Diagrams for Complex Columns: 1. Intercooled/Interheated Distillation Columns," *Ind. Eng. Chem. Res.*, **28**, 1374 (1989).

Wankat, P. C., and D. P. Kessler, "Two-Feed Distillations: Same-Composition Feeds with Different Enthalpies," *Ind. Eng. Chem. Res.*, **32**, 3061 (1993).

Zodonik, S. B., "Balancing Energy Costs Against Equipment Costs," *Chem. Eng.*, **84**, 99 (1977).

Appendix

The objective of this Appendix is to show that for a given value of Z_A and the intermediate heat-addition arrangement of Figure 2a, when $\alpha = \alpha_{IR}$ the thermodynamic efficiency function $\eta_{l,IR}$ indeed has an extrema at $y_{A,IR} = Z_A$. All the pertinent equations for parameters V_3, L_3, q_{IR}, and $\eta_{l,IR}$ in Figure 2a are given in the accompanying article (Agrawal and Herron, 1998). For a given feed composition, the extremum in $\eta_{l,IR}$ occurs when the denominator in Eq. 15 of the cited reference is at its extremum value. This implies that the following function Φ be equal to zero:

$$\Phi = \ln \alpha \frac{\partial V_B}{\partial x_{A,I}} - L_3 \frac{\partial}{\partial x_{A,I}} \int_{q_{IR}}^{1} \ln\left[\frac{x_A(\alpha-1)+1}{\alpha}\right] dq = 0. \quad \text{(A1)}$$

Rather than substituting $y_{A,IR} = Z_A$ in the preceding equation and then solving the resulting equation to obtain an expression for α_{IR}, we adopted a different procedure. The value of $y_{A,IR} = Z_A$, along with α_{IR} from Eq. 1, was substituted in Eq. A1 to obtain an equation as a function of Z_A, and then the value of the resulting equation was numerically checked to be zero for arbitrary chosen values of Z_A. Thus:

$$\frac{\partial V_B}{\partial x_{A,I}} = \left[\frac{\alpha}{\alpha-1}\right] \frac{\partial q_{IR}}{\partial x_{A,I}} \quad \text{(A2)}$$

$$\alpha_{IR} = \frac{2 - Z_A}{1 - Z_A} \tag{A3}$$

$$\alpha_{IR} - 1 = \frac{1}{1 - Z_A} \tag{A4}$$

$$q_{IR}|_{\alpha = \alpha_{IR}} = \frac{2(1 - Z_A)}{2 - Z_A} \tag{A5}$$

$$\left.\frac{\partial q_{IR}}{\partial x_{A,I}}\right|_{\alpha = \alpha_{IR}} = 1 \tag{A6}$$

$$x_A|_{q = q_{IR},\ \alpha = \alpha_{IR}} = \frac{Z_A}{2} \tag{A7}$$

$$x_{A,I}|_{\alpha = \alpha_{IR}} = \frac{Z_A}{2 - Z_A}. \tag{A8}$$

Equations A2–A8 are substituted in Eq. A1 to obtain function, Φ_1, which needs to be checked for its values at different values of Z_A:

$$\Phi_1 \equiv \ln\left[\frac{2 - Z_A}{2(1 - Z_A)}\right] - \int_{q_{IR}}^{1}\left[\frac{1 - \alpha_{IR}}{2q(1 - \alpha_{IR})x_A + (\alpha_{IR} - 1)\left(q + x_{A,I}|_{\alpha = \alpha_{IR}}\right) - \alpha_{IR}}\right]dq \tag{A9}$$

The integral in the preceding equation is calculated by using the following relation:

$$x_{A,I}|_{\alpha = \alpha_{IR}} = qx_A + (1 - q)\frac{\alpha_{IR}x_A}{1 + x_A(\alpha_{IR} - 1)}. \tag{A10}$$

The two terms on the righthand side of Eq. A9 were numerically calculated for several values of Z_A, and the absolute value of the relative difference between the two terms was found to be zero (arbitrary small) for all values of Z_A tested. This proved that $\eta_{I,IR}$ has an extremum value for a given Z_A and $\alpha = \alpha_{IR}$ when $y_{A,IR} = Z_A$.

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