Distillation with Intermediate Heat Pumps and Optimal Sidestream Return

The technique of distillation with intermediate heat pumps and optimal sidestream return—IHOSR distillation—is presented. IHOSR distillation allows heat to be moved between points in a distillation column with greater efficiency than several other methods of using heat pumps for distillation.

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SCOPE

Distillation is the most frequently used method of separation in the process industry. A practical means of decreasing distillation energy requirements could thus have considerable impact on existing processes that use distillation. In addition, reduced distillation energy requirements might make possible processes that are now impractical because of high separation costs. Examples of such processes are fermentative production of volatile compounds and recovery of industrial waste streams.

Distillation has been characterized as a highly inefficient process in terms of the ratio of separation work done to heat invested (Freshwater, 1951; Mix et al., 1978; Mah et al., 1977). Efficiency ratios that consider the work available from the heat rejected in the condenser give higher values and are also more realistic. However, the ability of the overhead vapor to do work is only relevant if there is a use for it, and heat integration between overhead vapor and a heat sink involves available work loss in itself (Fitzmorris and Mah, 1980; Bruzzi and Zanderighi, 1983a,b). The dramatic increase in the price of energy in the last decade has given rise to several approaches to reducing the energy requirement, and in particular the heat requirement, of distillation. These approaches can generally be grouped into schemes that involve:

1. Heat integration, or multieffect distillation.
2. Heat pumps in which heat is transferred from the overhead vapor to the reboiler.
3. Heat pumps in which heat is transferred between intermediate points in the column, notably distillation with secondary reflux and vaporization, or SRV distillation (Mah et al., 1977).

Overhead-to-reboiler heat pumps are relatively simple; however, they involve moving heat between the hottest and coldest points in the system and thus may not be as efficient as other applications of heat pumps. SRV distillation does not have this liability, however the complexity of the distillation apparatus is increased considerably due to the multiple sites of heat transfer between the rectifying and stripping sections.

In this paper, a new approach to using heat pumps in distillation is described: distillation with intermediate heat pumps and optimal sidestream return (IHOSR distillation). The change of the internal reflux ratio by heat or material flows is reviewed, the composition changes accompanying various strategies of moving heat within a distillation column are analyzed, and the constraints of these composition changes on the magnitude of heat flow are discussed. McCabe-Thiele operating lines are presented for the IHOSR method, specific examples are presented, and the IHOSR method is compared to conventional distillation and other methods for using heat pumps in distillation.

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CONCLUSIONS AND SIGNIFICANCE

Of several possible methods of moving heat between points in a distillation column, the preferred method appears to be removal of an internal stream, phase change of the removed stream, and return of the removed stream so as to minimize the free energy of mixing of the returned stream with the stream of like phase in the column. In particular, this technique allows more heat to be moved between a heat source and a heat sink at particular temperatures; alternatively, it allows heat sources and sinks with smaller temperature differences to be used for a given amount of heat moved. It is established that the amount of heat which may be moved between a particular heat source and sink is maximized when the liquid and vapor compositions at the point of sidestream return are in equilibrium.

The changes in the internal reflux ratio accompanying various configurations which move heat via the preferred method are examined with the aid of *X-Y* diagrams and the McCabe-Thiele method. The effect of applying the IHOSR method is shown to be a "custom tailoring" of the operating line to the equilibrium curve. In general, applications of the IHOSR technique involving a single heat pump appear to be of comparable complexity to a simple overhead-to-reboiler heat pump, while offering many of the advantages of SRV distillation and some unique advantages as well. A trade-off exists between the efficiency with which heat is moved and the amount of heat moved. The IHOSR strategy appears to be most attractive relative to an overhead-to-reboiler heat pump in cases with either a dilute feed or a large column temperature drop.

Introduction

The use of heat pumps in distillation is motivated by the possibility that a small amount of work may be invested to move or recycle a relatively large amount of heat within the distillation system. The term heat pump is used here in a general sense, meaning any application in which heat is moved between locations in a distillation column where the heat source has a lower temperature than the heat sink at the column pressure.

The concept of using heat pumps in distillation has been known for a long time (Freshwater, 1951; Robinson and Gilliland, 1950). In its simplest application a heat pump may be used to move heat from the overhead vapor to the reboiler of an adiabatic column (Danzinger, 1979; Null, 1976). In addition to simple applications, the use of heat pumps with heat sources and/or sinks at temperatures intermediate between the temperature of the distillate and the bottoms has been proposed. Null et al. (1974) and Freshwater (1961) have proposed schemes involving single heat pumps that remove heat from between the feed location and the condenser and return heat between the feed location and the reboiler. When heat is thus recycled from the rectifying section to the stripping section, the duty of the condenser and reboiler is reduced. Null et al. and Freshwater have also proposed schemes using heat pumps to alleviate the "tangential pinch" which occurs in the concave region of the *X-Y* diagram for nonideal mixtures such as ethanol and water.

Flower and Jackson (1964) describe arrangements for reversible distillation involving an infinite number of heat pumps each moving an incremental quantity of heat from the rectifying section to the stripping section. In these arrangements, the internal reflux ratio is at its limiting value at every point in the column, implying reversible mass transfer. Systems with many features in common with the ideal systems proposed by Flower and Jackson have been described in patents by Haselden (1977) and Seader (1980), and have been studied extensively by Mah and co-workers (Fitzmorris and Mah, 1980; Mah, 1979; Mah et al., 1977). In all these systems, the rectifying section is maintained at a higher pressure than the stripping section by means of a single compressor, thus allowing heat transfer from the rectifying section to the stripping section to occur at as many points as desired with no further investment of work.

In addition to approaches that utilize heat pumps, the use of "pump-arounds" to move heat between points in a distillation column has been mentioned in the literature (Bannon and Marple, 1978; Henley and Seader, 1981; Rathore, 1982; Waggoner and Loud, 1977; Wang and Wang, 1981). Pump-arounds involve adding or removing heat from a sidestream withdrawn from a column, and returning the withdrawn stream, typically without a phase change, at a location different from the point of withdrawal. Utilization of pump-arounds in conjunction with heat pumps has not to our knowledge been investigated in any detail. Moreover, the significance of the point of sidestream return with regard to column composition changes, the constraints on the location and amounts of heat moved, and the implications of these phenomena on the efficiency of moving heat via heat pumps do not appear to have been recognized.

It is axiomatic that efficient use of heat pumps will occur when heat is moved across the smallest possible temperature difference. However, it will be shown that the amount of heat that may be moved within a distillation column is in general positively related to the temperature difference between the heat source and heat sink, and so is inversely related to heat pump efficiency. Thus, the application of heat pumps where the overhead vapor is compressed and condensed in the reboiler provides all of the heat required for the distillation, but does so by moving heat from the coldest to the hottest point in the system. An alternative strategy is to use a heat pump to provide a portion of the heat required for the distillation but to do so at greater efficiency by using heat sources and/or heat sinks with temperatures intermediate between the extreme temperatures in the column.

In this paper we investigate various methods of moving heat within a distillation column. Of the methods considered, open cycle heat pumps with internal column streams as the working fluid and with removed streams that have undergone a phase change returned at the optimal point of the column appear to be preferred on thermodynamic grounds; in addition, they involve relatively simple apparatus. In this technique, called distillation with intermediate heat pumps and optimal sidestream return, or IHOSR distillation, the optimal point of sidestream return is always different from the point of withdrawal, and thus mass as well as heat is moved. By contrast, all of the applications of heat pumps discussed above have the common feature that they focus soley on moving heat.

Change Of The Internal Reflux Ratio By Heat And Material Flows

The use of heat pumps with heat sources and/or sinks at intermediate column locations involves changing the internal reflux ratio at the points where heat is added or removed. The change in the internal reflux ratio brought about by addition of an amount of heat Q to a control volume such as shown in Figure 1 is described by Eq. 1:

$$\frac{L'}{V'} = \frac{L'' + Q\lambda}{V'' + Q\lambda} \tag{1}$$

Equation 1 shows that a specified heat flow, which may be + or −, implies a specific change in L/V. Conversely, a specified change in L/V implies a specific Q.

The changes in the internal reflux ratio brought about by heat flow are important because the heat required by the reboiler from sources other than heat pumps, i.e., the external heat requirement, can be related to the internal reflux ratio. An enthalpy balance for a control volume including the reboiler and the portion of the distillation column below a cut at an arbitrary height is given in Eq. 2, derived with the assumption of constant molar enthalpies of liquid and vapor, respectively:

$$q_{reb} = \lambda \Sigma ((V_i/D)_{out} - (V_i/D)_{in}) - \frac{Q}{D} - w \tag{2}$$

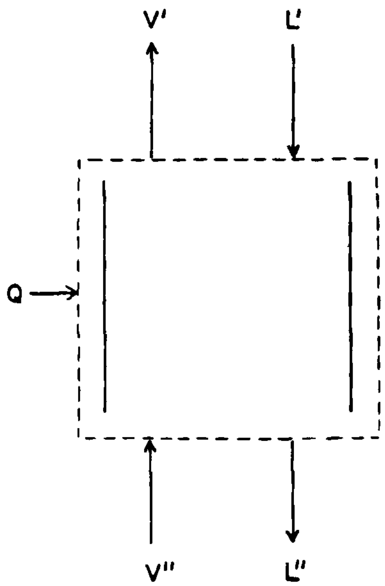

Figure 1. Change in the internal reflux ratio accompanying heat flow to or from a distillation column.

It is always possible to express V/D ratios, and therefore, q_{reb}, in terms of internal reflux ratios. For $Q = 0$, and L/V evaluated at a point in the stripping section with material balance

$$L_s = V_s + B \tag{3}$$

q_{reb} can be expressed in terms of the internal reflux ratio in the stripping section, $(L/V)_s$, by

$$q_{reb} = \lambda \frac{V_s}{B}\frac{B}{D} - w = \lambda \frac{1}{(L/V)_s - 1}\frac{X_d - Z_f}{Z_f - X_b} - w \tag{4}$$

A similar development for a point in the rectifying section where

$$V_r = L_r + D \tag{5}$$

gives q_{reb} in terms of the internal reflux ratio in the rectifying section, $(L/V)_r$

$$q_{reb} = \lambda\{(V/D) - (1 - q)(F/D)\} - w$$
$$= \lambda \frac{1}{(1 - (L/V)_r)} - (1 - q)\frac{X_d - X_b}{Z_f - X_b} - w \tag{6}$$

The expressions for (V_s/B), in Eq. 4, and (V_r/D), in Eq. 6, follow directly from the material balances in Eq. 3 and 5, respectively; the expressions for B/D and F/D are from material and component balances for the feed, bottoms, and distillate streams. The functional form of the dependence of q_{reb} on $(L/V)_s$ and $(L/V)_r$ shown by Eqs. 4 and 6 indicates that the direction the internal reflux ratio should be changed in order to minimize q_{reb}: $(L/V)_s$ should be made as large as possible, and $(L/V)_r$ as small as possible, given the constraint of the vapor-liquid equilibrium relationship.

It may be noted that the internal reflux ratio is changed by material flows as well as heat flows. Equation 7 describes the change in the internal reflux ratio brought about by addition of a stream with molar flow S and a molar fraction of liquid f, between 0 and 1, at a point in a distillation column with the same temperature and pressure as the introduced stream:

$$\frac{L'}{V'} = \frac{L'' - Sf}{V'' + S(1 - f)} \tag{7}$$

assuming constant molar enthalpies of liquid and vapor; S is negative for stream removal. An important difference between changing the internal reflux ratio by heat and material flows is that material flow causes a change in the material balance equation whereas heat flow does not. Thus, the McCabe-Thiele operating line segments above and below the point of mass addition or removal are continuous and have different points of intersection with the 45° line. By contrast, the operating line segments above and below the point of heat addition or removal must be discontinuous and have the same point of intersection with the 45° line. Failure to recognize this difference has resulted in inaccurate representations of heat flow within a distillation column in the papers of Freshwater (1961) and Null et al. (1974).

Composition Changes Associated With Various Methods Of Moving Heat

The constraint on the degree to which (L/V) can be changed at a particular point in a distillation column is the equilibrium relationship. Thus, the composition changes that accompany various methods for addition or removal of heat must be examined to answer questions such as how much heat may be moved between two points in a distillation column or what is the minimum ΔT for a particular amount of heat moved.

Three alternative methods of adding heat to, or removing heat from, a distillation column are presented in Figure 2. These methods are:

1. Heat addition (*a*) or removal (*b*) on a plate.
2. Heat addition (*c*) or removal (*d*) between plates.
3. Removal of a sidestream, heat flow to (*e*) or from (*f*) the sidestream, and return of the sidestream at the level of removal.

Method 1 has been suggested by Mah et al. (1977) and by Haselden (1977); heat removal according to method 2 has been suggested by Seader (1980).

The composition changes associated with methods 1, 2, and 3 for moving heat within a distillation column are presented in Figures 3a, 3b, and 3c, respectively. In these McCabe-Thiele diagrams heat flow occurs at a location in the stripping section with compositions Xs', Ys', or a location in the rectifying section with compositions Xr'', Yr''. In all three diagrams the operating lines labeled *a*, *b*, and *c* correspond to heat removal from the rectifying section; lines *d*, *e*, and *f* correspond to heat addition in the rectifying section; lines *g*, *h*, and *i* correspond to heat addition in the stripping section; and lines *j*, *k*, and *l* correspond to heat removal from the stripping section. Lines with like labels in different McCabe-Thiele diagrams represent like amounts of heat flow. The equations used to calculate the terminal points of the operating line segments shown are presented in the figure caption.

An important observation which can be made from the McCabe-Thiele diagrams in Figure 3 is that the limiting heat flows possible in methods 1 and 2 are accompanied by vertical discontinuities at constant liquid mole fraction for heat removal from the rectifying section, and horizontal discontinuities at constant vapor mole fraction for heat addition to the stripping section. In contrast to this, the limiting heat flows for method 3 are accompanied by horizontal discontinuities for heat removal from the rectifying section, and vertical discontinuities for heat addition to the stripping section. As a consequence of these relationships, some heat flows that are feasible by methods 1 and 2 are not feasible by method 3; for example, the heat flows corresponding to operating lines *a* and *g*, portions of which lie outside the equilibrium curve.

IHOSR Distillation

A fourth method of adding or removing heat from a distillation column is shown in Figure 4. For heat addition, liquid is removed, evaporated, and returned to the column below the point of liquid removal at a location where the composition of vapor in the column is the same as the composition of the returned vapor. For heat removal, vapor is removed, condensed,

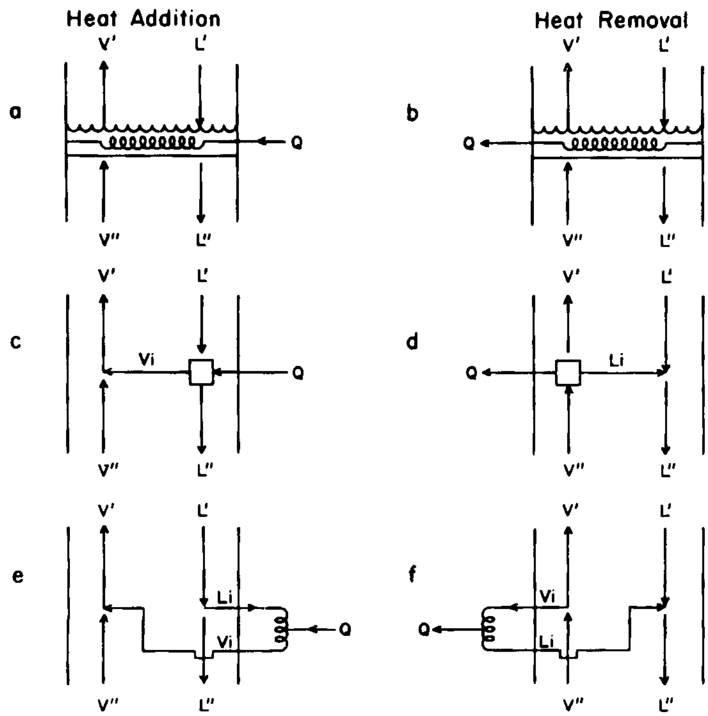

Figure 2. Alternative methods of adding or removing heat at an intermediate point in a distillation column.

a. Heat addition to an equilibrium plate
b. Heat removal from an equilibrium plate
c. Heat addition to liquid L' between stages, with generation of vapor V_i and mixing of V_i with vapor V'' at the level of heat addition
d. Heat removal from vapor V'' between stages, with generation of liquid L_i, which is mixed with liquid L' at the level of heat removal
e. Removal of liquid stream L_i, evaporation forming vapor V_i, and mixing of vapors V_i and V'' at the level of liquid withdrawal
f. Removal of vapor stream V_i, condensation forming liquid L_i, and mixing of liquids L_i and L' at the level of vapor withdrawal

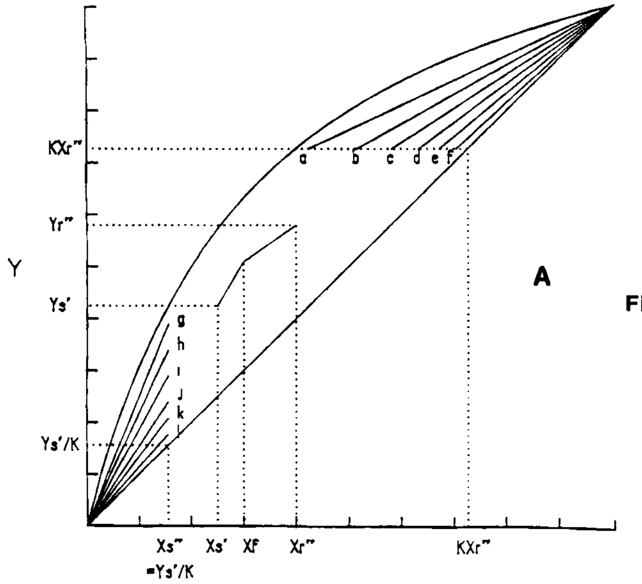

Figure 3. Composition changes accompanying alternative methods of adding or removing heat.

Line segments labeled with like letters have the same slopes and corresponding heat flows for Figure 3A, B, and C.

a–c, *j–l* = heat removal; *a*, *l* = greatest amounts removed

d–i = heat addition; *f*, *g* = greatest amounts added

Terminal points of operating line segments are calculated as follows (presented only for rectifying section, but analysis for stripping section follows similar lines):

Fig. 3A. $Y' = KX''$ because of the ideal plate assumption. Substituting KX'' for Y' and $(L'' + (Q/\lambda))/[V'' + (Q/\lambda)]$ for L'/V' into the operating line equation gives X' in terms of Q and quantities below the point of heat flow, namely:

$$X' = X_d - \{[V'' + (Q/\lambda)]/[L'' + (Q/\lambda)]\}(X_d - KX'')$$

Y' can be found from X' using the operating line equation, with L'/V' as given by Eq. 1.

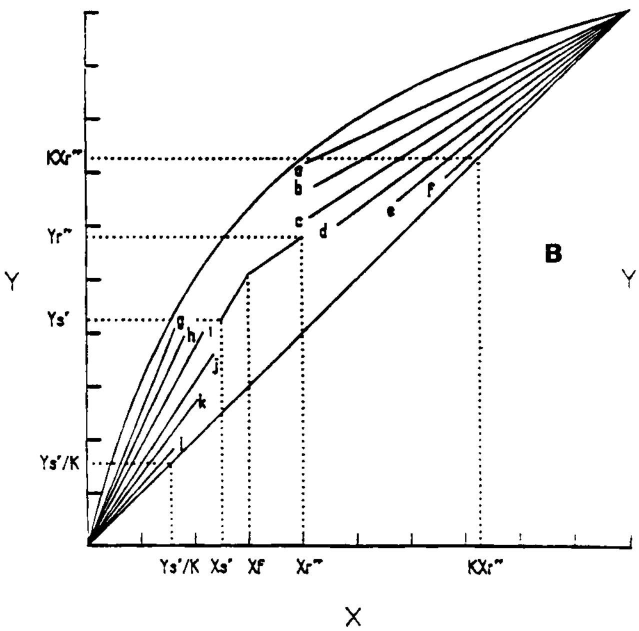

Fig. 3B. It is assumed that the mole fractions of V_i and L'', and V' and L_i in Figures 2c and 2d, respectively, are in equilibrium. Then, mass component and enthalpy balances at the point of heat flow give:

$$X' = X''[1 + (Q/\lambda L')(K - 1)] \text{ for heat addition, and}$$

$$Y' = Y''/\{1 + (Q/\lambda V'')[1 - (1/K)]\} \text{ for heat removal.}$$

These equations apply in both the stripping rectifying sections. The unknown mole fraction, X' or Y', can be found using the operating line equation.

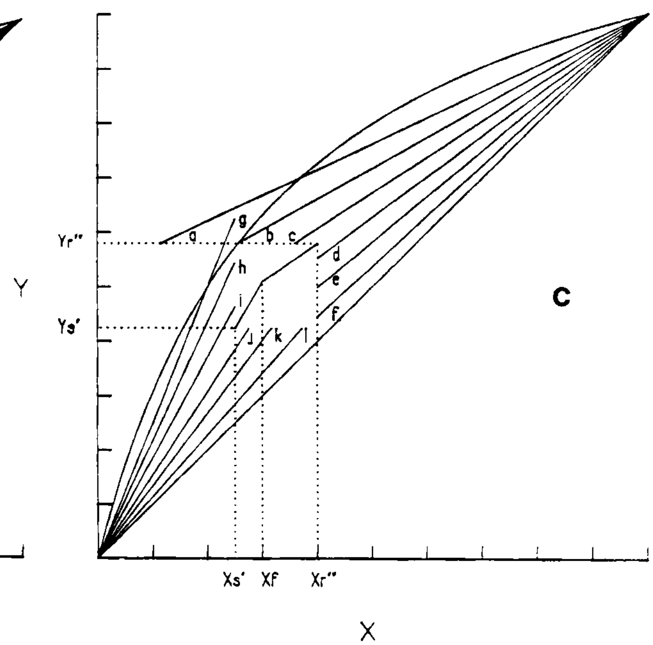

Fig. 3C. To find in any column section:

Heat addition: $X' = X'' = Y_i$

Heat removal: $Y' = Y'' = X_i$

Y' (heat addition) and X' (heat removal) can be found by using the appropriate operating line equations.

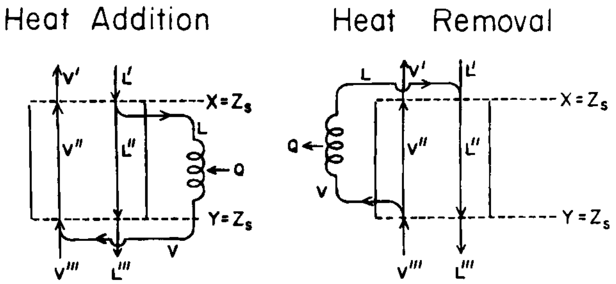

Figure 4. Heat addition and removal by stream removal, phase change, and optimal sidestream return in a distillation column.

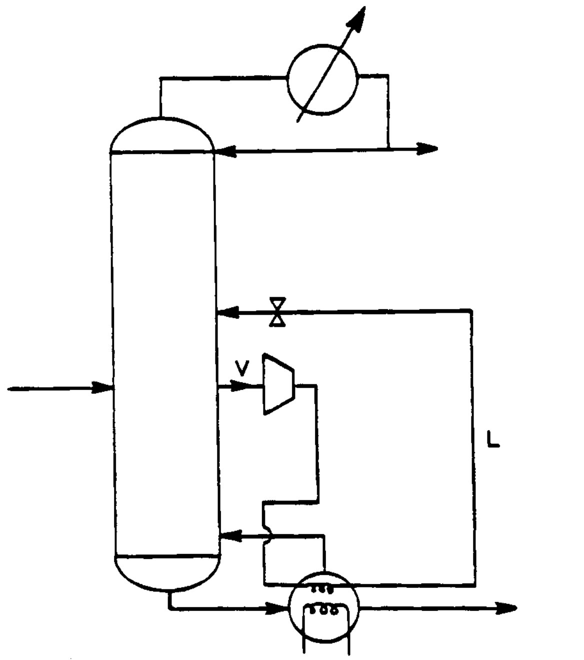

Figure 5. Distillation column with heat moved from a point in the column to the reboiler, with optimal sidestream return of withdrawn vapor after it is condensed.

and returned to the column above the point of vapor removal, at a location where the composition of the liquid in the column is the same as the composition of the returned liquid. This method of adding and removing heat is the basis for what we call distillation with intermediate heat pumps and optimal sidestream return or IHOSR distillation. It should be noted that the intermediate column section between the point of sidestream withdrawal has a distinct operating line from the sections above and below these points because the material balance is not of the same form.

An example of distillation using a heat pump according to the IHOSR method is shown in Figure 5. In this example heat is moved from the rectifying section to the reboiler. Vapor is withdrawn from the distillation column, compressed, condensed in the reboiler, and returned at a level above the point of withdrawal. Operating lines for this IHOSR strategy are presented in Figure 6. Figure 6A shows operating lines corresponding to varying sidestream flow, with lines *1* through *5* having progressively higher flow rates through the sidestream loop. The maximum sidestream flow, and therefore the maximum amount of heat moved, occurs when the column becomes pinched at the point of sidestream return. Figure 6B shows operating lines for a variety of points of vapor withdrawal, with vapor removed at the feed plate for line *1*, at progressively higher locations above the feed plate for lines *2* through *5*, and below the feed plate for line *6*. Since greater changes in the internal reflux ratio accompany greater heat flows (Eq. 1), the operating line slopes above the point of sidestream return in Figure 6B demonstrate that more heat can be moved when vapor is withdrawn at higher levels above the feed plate. However, moving heat from locations with higher mole fractions of the more volatile component to the reboiler implies a larger temperature difference between the heat source (the withdrawn vapor) and the heat sink (the reboiler).

A second IHOSR distillation strategy, this time involving heat moved from the overhead vapor to the rectifying section, is shown in Figure 7. Liquid is removed, vaporized, and returned to the column as a vapor below the point of sidestream withdrawal. Operating lines for this IHOSR strategy corresponding to different locations of liquid withdrawal are presented in Figure 8. Liquid is removed at the feed plate for line *1*, at progressively lower locations below the feed plate for lines *2* through *5*, and above the feed plate for line *6*. The greater changes in the slopes of the operating lines below the points of vapor return establish that more heat can be moved as liquid is withdrawn from successively lower locations, with correspondingly greater

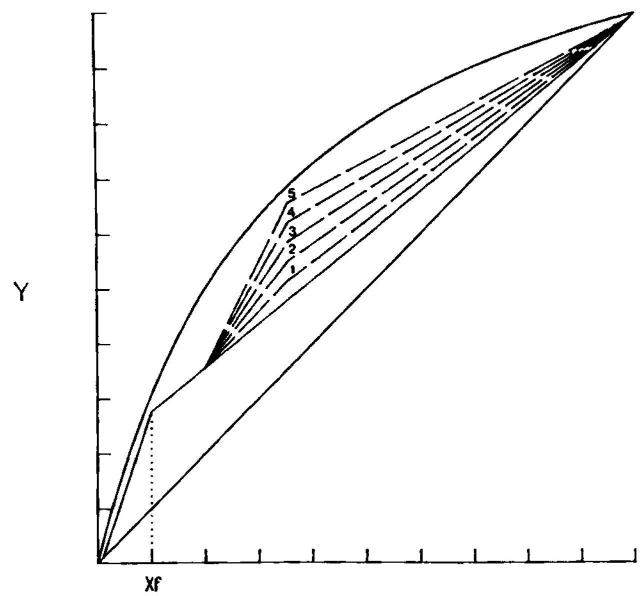

Figure 6a. Influence of sidestream flow rate for a column with vapor removed above feed plate, condensed in reboiler, and returned optimally.

——Conventional adiabatic column
— —Deviation from conventional for V removed at a point above feed.

Lines *1–5* have progressively higher flow rates through the sidestream loop, with correspondingly greater amounts of heat moved from rectifying section to reboiler.

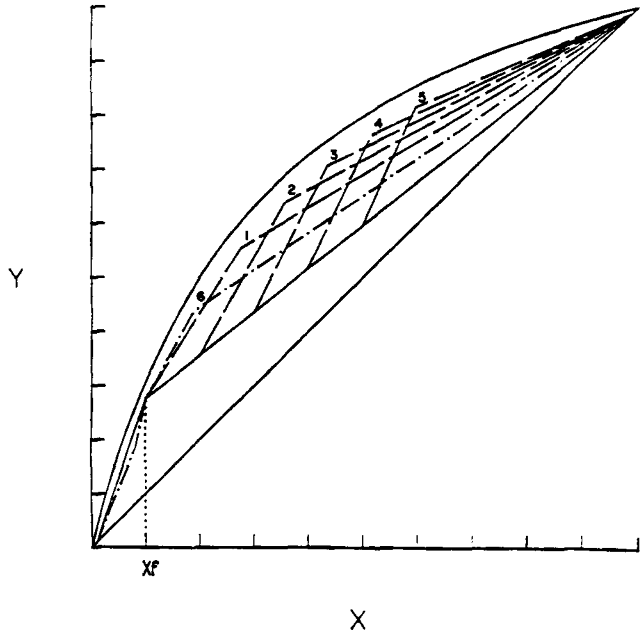

Figure 6b. Influence of point of vapor removal for a column with vapor removed, condensed in reboiler, and returned optimally.
——Conventional adiabatic column
— —Deviation from conventional for V removed at or above feed
— · —Deviation from conventional for V removed below feed
Line *1*: vapor removed at feed plate; *2–5*: vapor removed at progressively higher locations above feed plate; *6*: vapor removed below feed plate. Flow rate through the sidestream loop is not the same for the various lines shown.

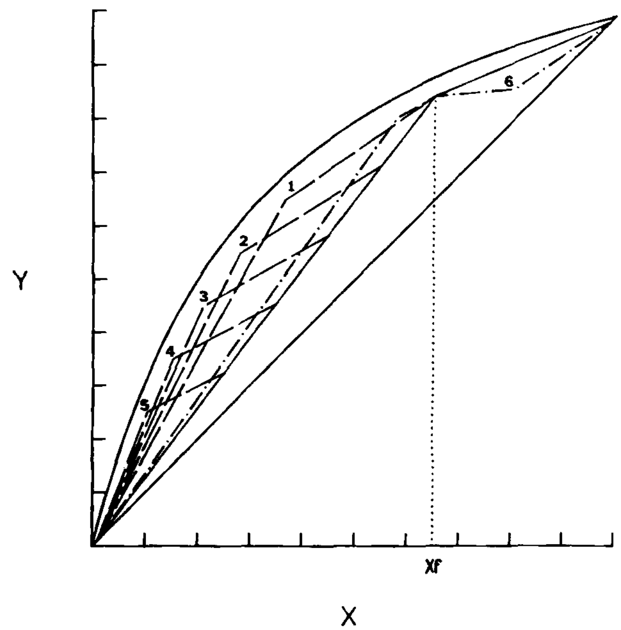

Figure 8. Influence of point of liquid removal for a column with liquid removed, vaporized at the expense of compressed overhead vapor, and returned optimally.
——Conventional adiabatic column
— —Deviation from conventional for L removed at or below feed
— · —Deviation from conventional for L removed above feed.
Line *1*: liquid removed at feed plate; *2–5*: liquid removed at progressively lower locations below feed plate; *6*: liquid removed above feed plate.

temperature differences between the heat source (the overhead vapor) and the heat sink (the withdrawn liquid).

These two IHOSR strategies involve either vapor or liquid removal from intermediate column locations. It is also possible to remove both vapor and liquid from intermediate column sections and return them according to the IHOSR method. This third strategy is presented in Figure 9. Figure 10 shows representative operating lines for this strategy, with liquid and vapor removed either at the feed plate, or below and above the feed plate, respectively.

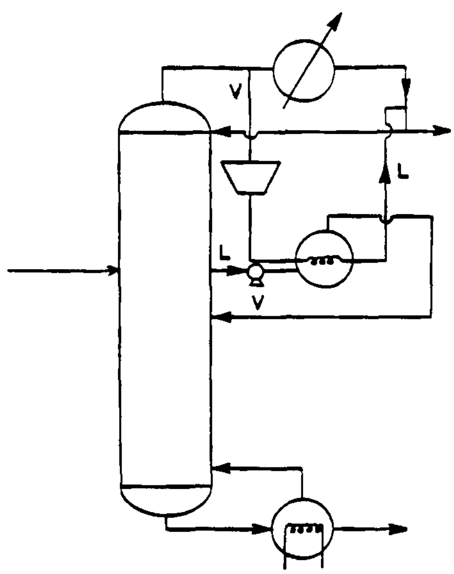

Figure 7. Distillation column with heat moved from the overhead vapor to a point in the column, with optimal sidestream return of withdrawn liquid.

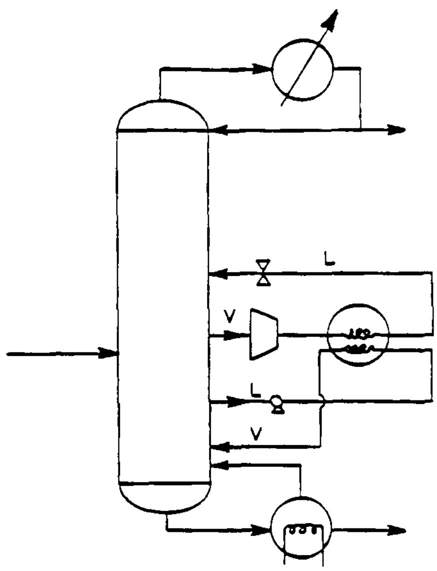

Figure 9. Distillation column with heat moved between two points in the column via withdrawn liquid and vapor streams, with optimal sidestream return of both streams.

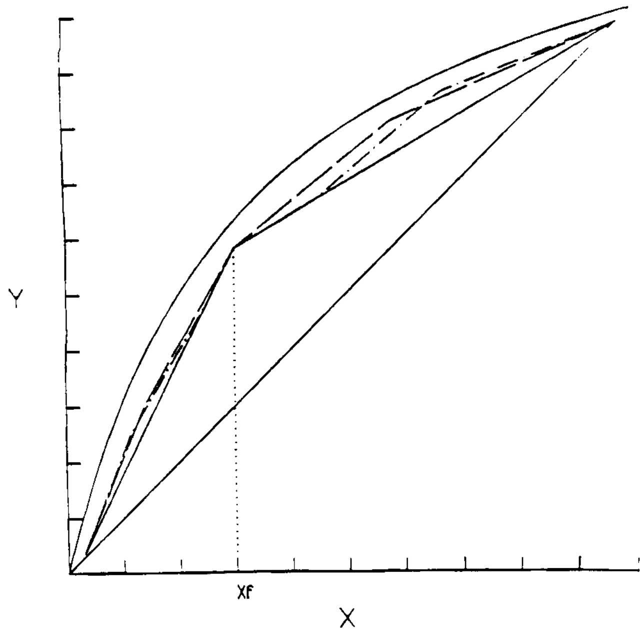

Figure 10. Operating lines corresponding to different points of vapor and liquid removal for a column with both removed, reciprocal phase change, and both streams returned optimally.

——Conventional adiabatic column

— —Deviation from conventional for V and L removed at feed location

— · —Deviation from conventional for V removed above feed, L removed below feed

Flow rates through the sidestreams are the same above and below the feed plate for matching line types, but not for different line types.

Comparison Of The IHOSR Method With Other Methods Of Moving Heat

The three methods of moving heat within a distillation column presented earlier, [(1) moving heat on a plate; (2) moving heat between plates; and (3) withdrawal of a sidestream, heat flow to or from the sidestream, and sidestream return at the level of removal], may be compared to the IHOSR method by examining the minimum temperature differences required to move a given amount of heat. Figure 11A shows a portion of a McCabe-Thiele diagram for separation of a 2 wt.% ethanol-water mixture at the bubble point. It is assumed that a quantity of heat is moved from the rectifying section to the reboiler so that the rectifying section operating line changes from a line with slope $(X_d - Y_f)/(X_d - X_f)$ to a line with slope $(X_d - Y_1)/(X_d - X_1)$. As may be inferred from the analysis of composition changes accompanying heat flow presented in Figure 3, this change in operating lines can be achieved within minimum ΔT between the heat source and heat sink by a vertical discontinuity at X_1 using method 1 or 2, and by a horizontal discontinuity at Y_1 using method 3. The same operating line change can be made using the IHOSR method with vapor withdrawn at the feed plate and returned at the point in the column where $X = X_1$.

The temperature of the heat source vapor during the transfer to the heat sink in both the IHOSR method and method 3 is dependent on the fraction of the vapor condensed since these vapors contain two components. In Figure 11B the temperatures of the IHOSR (dot-dash line) and method 3 (short-dash line) heat source vapors at the column pressure are plotted as a function of the fraction liquid. The temperature of the IHOSR vapor during condensation progresses from the dewpoint to the bubble point for a mixture with overall composition, Y_f. For method 1 or 2 the temperature of the column at the point of heat flow (horizontal long-dash line in Figure 11B) is the bubblepoint of liquid with mole fraction X_1, which is equal to the dewpoint of vapor at Y_1 since X_1 and Y_1 are in equilibrium. As may be seen from Figure 11B, the temperature at the point of heat flow for methods 1 or 2 is equal to the lowest temperature of the IHOSR heat source during condensation at the column pressure, and the highest temperature of the method 3 heat source during condensation at the column pressure. The differences between the heat source temperature profiles in Figure 11B are very significant considering that these profiles span most of the range of temperatures occurring in the column between a reboiler temperature of 100°C and a condenser temperature of 78°C.

For the heat pump to operate, the temperature of the heat source must be made greater than that of the heat sink. This may be achieved by investing work to raise the pressure of the heat source vapor prior to heat transfer to the heat sink, or by decreasing the pressure of the heat sink liquid, evaporating the heat sink liquid, and investing work to compress the resultant vapor back to the column pressure. Figure 11B demonstrates that the temperature of the IHOSR heat source is closer to the heat sink temperature than is the heat source temperature for methods 1 and 2; and that the temperature of the heat source for methods 1 and 2 is closer to that of the heat sink than is the heat source temperature for method 3. Because a larger inherent temperature difference between the heat source and heat sink requires a larger pressure ratio to achieve heat transfer from heat source to heat sink, the magnitude of the inherent temperature differences is reflected in the heat pump COP (coefficient of performance). COP values for this example are 20.1 for the IHOSR method, 13.2 for methods 1 and 2, and 11.1 for method 3, assuming a 75% isentropic compression efficiency and a mean driving force for heat transfer of 8°C. For comparison the COP for an overhead-to-reboiler heat pump with all of the overhead vapor compressed is 8.9 for this example with the same assumptions as above. The use of a mean driving force for heat transfer does not consider the temperature or heat transfer coefficient of superheated vapor, and assumes that liquid and vapor are in equilibrium during phase change. Investigation of the subtleties of heat transfer and heat exchanger design for IHOSR applications await further study.

The analysis presented above establishes that the IHOSR method involves a smaller inherent temperature difference, and therefore allows more efficient heat pumps to move a given amount of heat compared to other methods considered. It may be shown by a similar analysis that more heat can be moved by the IHOSR method for a given inherent temperature difference between heat source and heat sink.

Examples Of IHOSR Distillation And Comparison With An OTR Heat Pump

Table 1 presents a summary of heat, work, and stage requirements, together with various operating parameters, for three selected separations achieved by conventional distillation, IHOSR distillation, and distillation with an overhead-to-reboiler (OTR) heat pump. Example 1 involves separating a 1 wt.% ethanol-water mixture to distillate and bottoms of ≃91

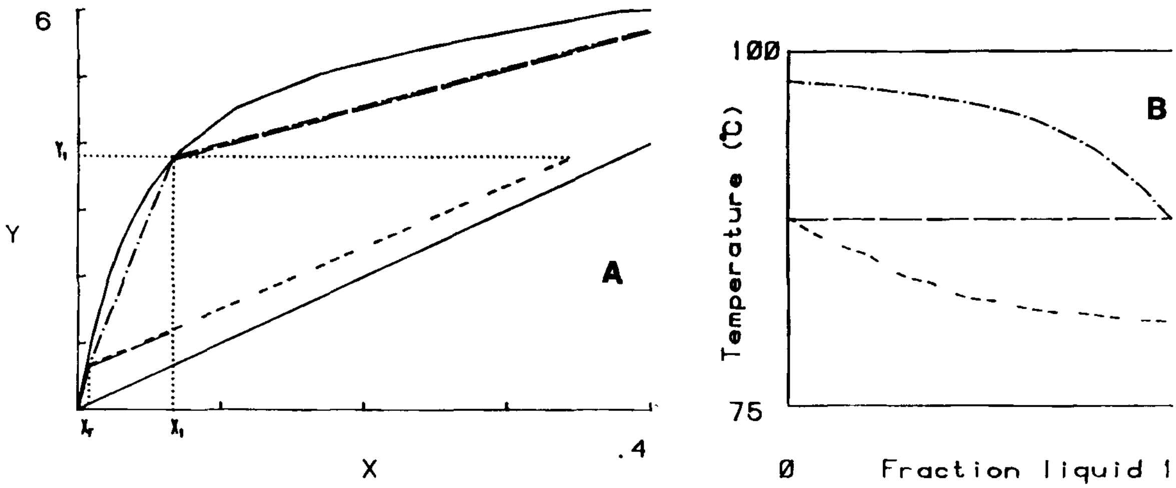

Figure 11. Operating lines (A) and temperature profiles at 1 atm (B) for distillation of a dilute ethanol-water feed with a specified amount of heat moved from the rectifying section to the reboiler by various methods.

— · —IHOSR method

— —Strategy *b*, Figure 2.

----Strategy *f*, Figure 2.

—Heat sink temperature for all methods (Figure 11 (B)).

The temperature of a stream at a given pressure, overall composition, and fraction liquid is found from the equilibrium and a flash calculation.

wt.% and ≅0.01 wt.%, respectively; the IHOSR strategy involving vapor withdrawal at the feed plate and subsequent condensation in the reboiler is used for this example. Example 2 involves an *n*-hexane/*n*-octane mixture with mole fraction 0.1 separated into a distillate and bottoms with mole fraction 0.99 and 0.01, respectively; the IHOSR strategy used for this example involves withdrawal of vapor at the feed plate and liquid just below the feed plate (at $X = 0.075$). Example 3 involves separating a 10 wt.% ethanol-water feed to a distillate and bottoms of 95 wt.% and ≅0.1 wt.%, respectively; the IHOSR strategy for this separation involves adding heat from the overhead vapor to the rectifying section to increase the internal reflux ratio in the vicinity of a tangential pinch. Operating lines and apparatus for these three separations by the IHOSR method are shown in Figures 12, 13, and 14, respectively.

The sidestream flows in Table 1 are calculated by choosing an approach of the operating line to the equilibrium curve at the point of sidestream return, calculating the slopes of the operating line above and below the point of sidestream return, and then calculating the sidestream flow necessary to bring about this change in L/V using Eq. 7. Condensate returned to the column is assumed to be saturated liquid because isenthalpic flashing to reduce the pressure of the condensate results in production of an amount of vapor having a negligible effect on the slope of the McCabe-Thiele q line.

The ratios of heat saved to work invested presented in Table 1 are higher for the IHOSR method than for the OTR heat pump by factors of from 2.4 to 5.2. These ratios indicate the greater efficiency of the IHOSR method resulting from the smaller temperature difference between the heat source and heat sink.

The three example separations illustrate different cases with respect to the comparative merits of the distillation methods considered. Although it has its limitations, a useful index for comparison of processes requiring both heat and work is the "heat equivalent" input defined as $q_{reb} + 3w$. Based on the heat equivalent input, IHOSR distillation appears to be preferred over an OTR heat pump for example 1, and both heat pump methods are preferred over conventional distillation. The IHOSR method is the preferred method for example 2 also, but the OTR heat pump is less attractive than both IHOSR and conventional distillation. The difference in the ranking of distillation methods for examples 1 and 2 is due principally to the larger temperature difference between the condenser and the reboiler in example 2 (≅57°C) as compared to example 1 (≅22°C). Example 2 demonstrates the important point that an IHOSR heat pump can be attractive in a case where the total column temperature drop is too great to make an OTR heat pump attractive. In example 3 the IHOSR and OTR heat pumps are both preferred over conventional distillation, but this time the OTR technique is the most attractive. Example 3 is a case where the heat equivalent input is made smaller by moving more heat with lower efficiency via the OTR heat pump rather than moving less heat with greater efficiency via an IHOSR heat pump.

An important difference between the IHOSR and OTR techniques that is not indicated by comparisons based on the equivalent heat input is that with the IHOSR method the overhead vapor is available for heat integration with a subsequent process, or for a second heat pump using the overhead vapor as the heat source; that is not the case with the OTR method. Since the actual separation work is typically less than 10% of the heat equivalent input (Freshwater, 1951; Mix et al., 1978), it is clear that most of the available work invested in the reboiler is still available in the somewhat cooler overhead vapor after separation is achieved. Thus, the incentive to use the overhead vapor in some subsequent process is strong, and the choice between the IHOSR and OTR approaches to using heat pumps might well hinge on the difference between the potentials of these two methods for heat integration. A further advantage of the IHOSR technique that is not reflected in the equivalent heat comparisons is that the simultaneous requirement of the IHOSR method for both heat and, in relatively smaller

Table 1. Heat, Work, and Stage Requirements and Various Operating Parameters for Selected Separations by IHOSR and Conventional Distillation, and Distillation with an Overhead-to-Reboiler Heat Pump

Example	Mixture Components	Separation X_f	X_d	X_b	Distillation Method	q_{reb} (Kcal/gmol dist.)	w (Kcal/gmol dist.)	Ideal Stages	Pressure Ratio of Compressor	Mol Vapor Compressed/ Mol Dist.	Heat Saved/ Work Invested*	$q_e + 3W$
1	Ethanol H_2O	0.003937	0.8000	0.00004	Conventional	195.7	—	35	—	—	—	195.7
					IHOSR	23.74	7.017	48	1.49	17.0	24.5	44.8
					Overhead-to Reboiler	—	21.96	35	2.95	20.2	8.9	65.9
2	*n*-Hexane/ *n*-Octane	0.100	0.9900	0.0100	Conventional	31.72	—	14	—	—	—	31.7
					IHOSR	13.80	1.240	24	1.72	2.20	14.5	17.5
					Overhead-to Reboiler	—	11.50	14	5.04	4.20	2.8	34.5
3	Ethanol H_2O	0.04167	0.8814	0.00042	Conventional	73.07	—	60	—	—	—	73.0
					IHOSR	34.92	1.775	57	1.40	5.55	21.5	40.2
					Overhead-to-Reboiler	—	8.16	60	2.95	7.54	9.0	24.5

Heat, work and stage requirements, pressure ratios, and sidestream flows are calculated making use of the graphical method based on the McCabe-Thiele method presented in the text.

The work requirement for the overhead-to-reboiler case is calculated assuming that all of the overhead vapor is compressed. Compression work requirements are based on a 75% isentropic efficiency and a pressure ratio sufficient to obtain a mean ΔT for heat transfer of $\approx 8°C$ (actual values ranged between 8.0 and 8.2°C for different cases).

The mean ΔT for heat transfer is equal to the average temperature difference between the heat source vapor and the heat sink liquid for fractions of liquid of these respective streams between 0 and 1 at intervals of 0.01. The temperature of a stream at a given pressure, overall composition, and fraction liquid is found from the equilibrium relationship and a flash calculation. The temperature of superheated vapor is not considered.

*The ratio of heat saved to work invested is the ratio of the difference of q_{reb} for the conventional case and q_{reb} when heat pumps are used, to w.

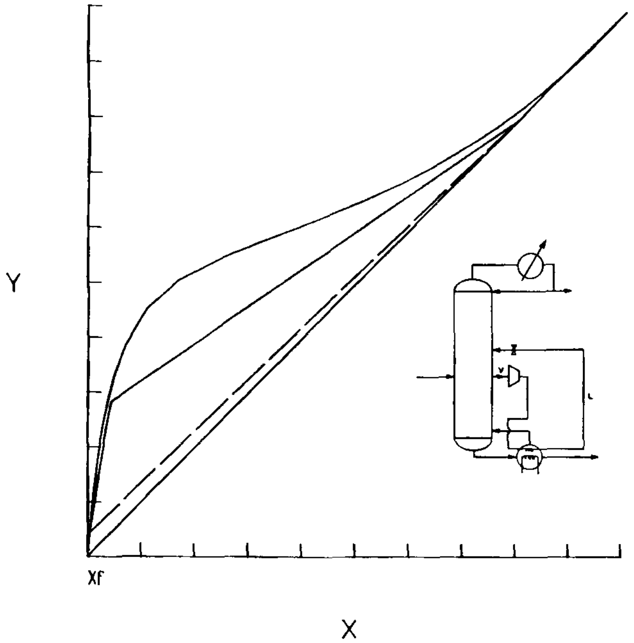

Figure 12. Separation of a dilute aqueous ethanol mixture by conventional and IHOSR distillation.
— —Conventional adiabatic column
——Deviation from conventional for IHOSR method
Operating lines (upper two) correspond to example 1 in text and Table 1.

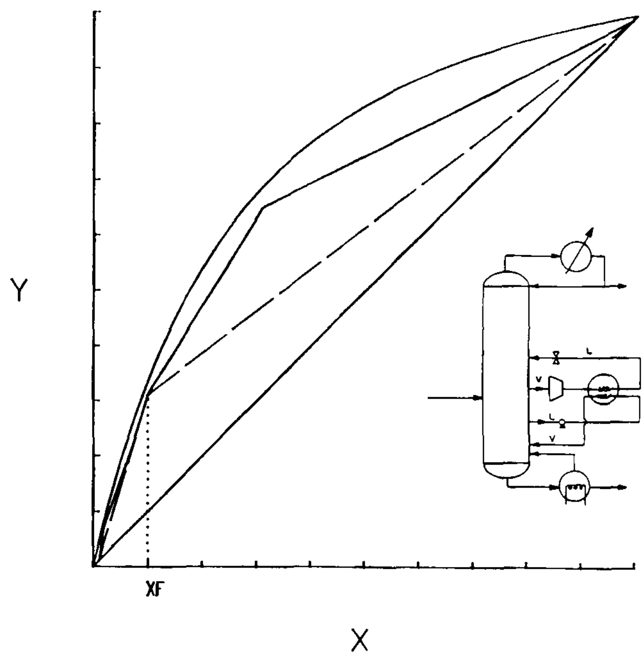

Figure 13. Separation of an N-hexane/N-octane mixture by conventional and IHOSR distillation.
— —Conventional adiabatic column
——Deviation from conventional for IHOSR method
Operating lines (upper two) correspond to example 2 in text and Table 1.

amounts, work is compatible with at-plant cogenerative production of heat and work.

Discussion

By returning sidestreams at the point where the compositions of the withdrawn stream and the column stream of the same phase are the same, the free energy of mixing accompanying sidestream return is minimized. Thus, the IHOSR technique may be viewed as taking advantage of the effective rectification achieved when a vapor is condensed to a liquid of the same composition and/or the effective stripping achieved when a liquid is evaporated to a vapor of the same composition.

In terms of temperature/heat-flow relationships, the IHOSR technique allows more heat to be moved for a given mean temperature difference between the heat source and heat sink, or alternatively a smaller mean temperature difference for the same amount of heat moved, compared to the other methods of moving heat examined. It is interesting to note that the best method of moving heat within a distillation column among those examined appears to be by sidestream withdrawal, phase change, and optimal sidestream return, whereas the worst method is very similar, differing only in the point of sidestream return. Comparison of the heat source temperature profiles in Figure 11b and also the COP values for the associated heat pumps, 20.1, 13.2, and 11.1, demonstrates that the practical consequences of the choice of the method of moving heat can be significant.

As may be seen from the *X-Y* diagrams in Figures 6, 8, 10, 12, 13, and 14, the manipulation of the internal reflux ratio that accompanies reducing the external heat requirement by the IHOSR technique results in an operating line that more nearly takes on the shape of the equilibrium curve than is possible with

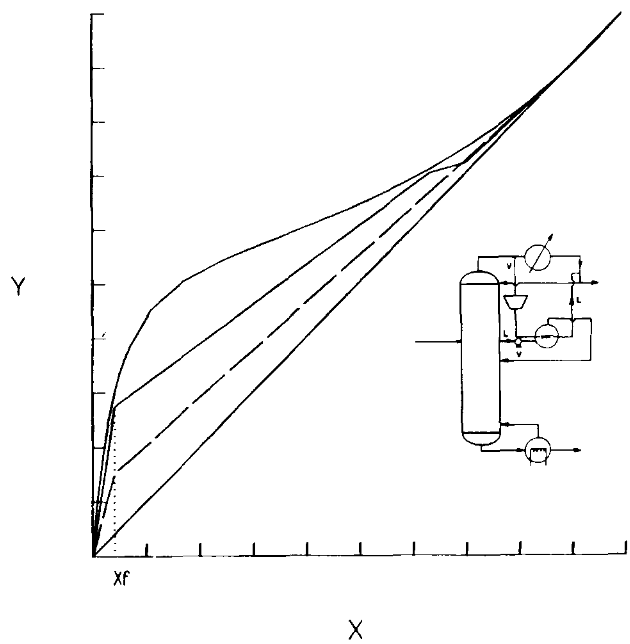

Figure 14. Separation of an ethanol-water mixture with a tangential pitch.
— —Conventional adiabatic column
——Deviation from conventional for IHOSR method
Operating lines (upper two) correspond to example 3 in text and Table 1.

an adiabatic column. A reasonably good fit between the operating line and equilibrium curve may very often be obtained with a single compressor. When the operating line is made to approach the equilibrium curve, the driving force for mass transfer is reduced. Accordingly, an IHOSR column usually requires more stages than a conventional column as long as no pinch points are approached, although exceptions to this rule may be observed in cases with a tangential pinch such as example 3.

The ability to manipulate the internal reflux ratio so that the operating line approaches the equilibrium curve is not unique to the IHOSR system. In particular, distillation with secondary reflux and vaporization (SRV distillation) is based on such manipulation (Mah et al., 1977). Although a detailed comparison of SRV and IHOSR distillation is not undertaken here, several important differences between these methods may be noted. In the case of SRV distillation, all of the vapor flow at the feed plate, which corresponds to the maximum vapor flow in an SRV system, is compressed, whereas IHOSR distillation requires that only the vapors participating in heat exchange need be compressed. SRV distillation and related strategies (Haselden, 1977; Seader, 1980) are usually presented with small amounts of heat exchange at many points, whereas IHOSR distillation typically involves relatively large changes in liquid and vapor flows at one or a few discreet points. Thus the IHOSR technique requires no internal heat exchangers, and fewer heat exchangers of any kind, than does SRV distillation. Moreover, the points of heat addition and removal in the IHOSR method are chosen to involve the minimum ΔT whereas the compressor in SRV distillation must provide a driving force for heat transfer at the least favorable points of heat transfer. We suspect that, in some cases at least, an optimization of the location of intermediate heat transfer in the SRV method with minimization of $q_{reb} + 3w$ as the objective function would result in most of the heat transfer at the points chosen in the IHOSR method. Preliminary considerations suggest that the SRV approach is best suited to separations in which there is an approximately equal temperature drop in the rectifying and stripping sections, and in which the amount of heat that can be moved from the rectifying section is approximately equal to the amount of heat that can be added in the stripping section. By contrast, the IHOSR technique is constrained by neither of these factors, and may in fact be best suited to separations with unequal temperature drop and capacity to accommodate heat flow in the rectifying and stripping sections.

The choice of whether or not to use a particular heat pump strategy will ultimately be decided on the basis of economics, an issue that has not been addressed in this paper. An economic analysis of an ethanol recovery process using IHOSR and extractive distillation (described in Lynd and Grethlein, 1984) indicates that the capital costs of this process are slightly lower than those for conventional distillation because of the smaller column diameters, smaller steam plant, and reduced number of stages made possible in part by an IHOSR heat pump.

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Notation

B = molar flow of bottoms
D = molar flow of distillate
F = molar flow of feed
f = molar liquid fraction
K = ratio of vapor and liquid mole fractions at equilibrium
L = molar flow of liquid
Q = heat flow added to the column at locations other than the reboiler
q = energy to bring feed to saturated vapor state/latent heat
q_{reb} = heat flow to reboiler per mole distillate
S = molar flow of sidestream
V = molar flow of vapor
w = shaft work per mole distillate
X = mole fraction of liquid phase
Y = mole fraction of vapor phase
Z_f = overall mole fraction of feed
λ = latent heat of vaporization

Subscripts

b = bottoms
d = distillate
r = rectifying section
s = stripping section

Superscripts

$'$ = location just above a point of heat or mass addition or removal
$''$ = location just below a point of heat or mass addition or removal

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