Feed Preheat Targeting to Minimize Energy Consumption in Distillation

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Abstract: By exchanging heat with the bottom product or with any other available low-grade heat sources, thermal condition of the feed may be altered to reduce the reboiler duty. A portion of the thermal energy given to the feed reduces the reboiler duty and the rest increases the condenser duty. By splitting the feed and altering the thermal condition of a part of the feed, it is possible to achieve reduction only in the reboiler duty. Based on the thermodynamic analysis of a distillation column, a methodology is developed to target split fraction of the feed for preheating to obtain reduction only in the reboiler duty.

Keywords: Energy conservation; Feed preheating; Distillation column; IRS curves

1. INTRODUCTION

Distillation is one of the common unit operations used in chemical industries. Operating cost of a chemical process plant mainly depends on the operating cost associated with the separation processes. Fifty to eighty percent of the operating cost in a chemical process industry is contributed by separation processes (Soave and Feliu, 2002). Total energy requirement by chemical process industry in United States is over 5 quad/y and distillation process alone consumes about 2.4 quad/y. This amounts to about 3% of the total energy consumed in United States (Ognisty, 1995). Though distillation is energy intensive, it is not energy efficient. Required separation in distillation is possible only if a certain minimum amount of energy is supplied. Therefore, it is necessary to identify different energy conservation opportunities through thermodynamic analysis of a distillation process.

Thermodynamic analysis of a distillation column is important for synthesizing and developing energy efficient distillation processes. Thermodynamic analysis of a distillation column can be addressed through the temperature-enthalpy (*T-H*) curve. The *T-H* curve for a distillation column quantitatively addresses the energy saving potential for possible stand-alone modifications as well as process integration. Bandyopadhyay *et al*. (1999) introduced a novel pair of *T-H* curves, known as the Invariant Rectifying-Stripping (IRS) curves for a distillation column. The IRS curves are invariant to the column configuration (i.e., feed location in the column and number of stages) and depend only on sharpness of separation as well as operating pressure of the column. They are useful for setting quantitative targets such as minimum energy requirement (for condenser and reboiler duties), appropriate feed location, proper feed preheating, scope for side-condensers/reboilers, as well as thermo-economic optimization of a distillation column.

Different schemes are suggested to reduce the energy consumption in distillation. Proper feed location reduces both reboiler and condenser duties. Intermediate reboilers are used when low-grade heat (heat sources which are at lower temperature and lower cost in comparison with the heating medium used in the reboiler) is available. Thermal condition of the feed is important for energy-efficient design of a distillation column. By exchanging heat with the bottom product or with any other available low-grade heat sources, thermal condition of the feed may be altered to reduce the reboiler duty. A portion of the thermal energy given to the feed reduces the reboiler duty and the rest increases the condenser duty. Therefore, there exists an efficiency associated with feed preheating. The efficiency of feed preheating depends on the thermal energy exchanged, the initial condition of the feed, and the operating or design criterion of the column (Liebert, 1993, Bandyopadhyay, 1999). The IRS curves help in predicting simultaneously the decrease in reboiler duty, increase in condenser duty and the location of the feed when the feed is preheated by certain amount (Bandyopadhyay, 1999).

Instead of introducing two phase feed to the column, a part of the feed may be completely vaporized and introduced a few stages below the liquid feed inlet. This way of feed introduction reduces both capital and operating cost of the column (Wankat and Kessler, 1993, Fidkowski and Agrawal, 1995, Soave and Feliu, 2002). Wankat and Kessler (1993), observed that additional separation may be achieved in flash distillation by introducing two-enthalpies, single-composition feed. Fidkowski and Agrawal (1995) applied this split-feed concept to utilized waste heat available in the site. Splitting the feed into two streams and preheating only one of the split-fractions, it is possible to improve feed preheat efficiency. By preheating one of the feed streams 100% preheat efficiency can be achieved (Soave and Feliu, 2002).

In this paper a methodology is developed, based on the IRS curves, to find the appropriate feed splitting to obtain 100% preheat efficiency. The methodology helps in simultaneously targeting to find split fraction of feed for preheating and its location in the distillation column for a given amount of feed preheating. Using this methodology it is possible to target energy-efficient distillation column configuration prior to the detailed design of the column.

2. INVARIANT RECTIFYING-STRIPPING (IRS) CURVES

As a precursor to the basic theory for 100% feed preheating efficiency, the generation procedure for the IRS curves is briefly outlined below.

2.1 IRS Curves for Simple Column

Detailed derivations of the equations that are employed in this section are given by Bandyopadhyay *et al.* (1999). Let H_R be the minimum condensing load required to cause separation from x to x_D. Then, the overall mass, component, and energy balances for the rectifying section may be combined to obtain the following expression for H_R.

$$H_R = D\left[H_V\left(\frac{x_D - x}{y - x}\right) - H_L\left(\frac{x_D - y}{y - x}\right) - H_D\right] \qquad (1)$$

This enthalpy surplus is then plotted as a function of the equilibrium temperature to give a T vs. H_R curve which may be termed the invariant rectifying (IR) curve.

Similarly, consider the stripping section of a distillation column with H_S denoting the minimum reboiling load required to cause separation from x to x_B. The overall mass, component, and energy balances for the stripping section may be combined to determine H_S from the following equation. This enthalpy deficit is then plotted as a function of the equilibrium temperature to give a T vs. H_S curve which may be termed the invariant stripping (IS) curve.

$$H_S = B\left[H_V\left(\frac{x - x_B}{y - x}\right) - H_L\left(\frac{y - x_B}{y - x}\right) + H_B\right] \qquad (2)$$

Both these curves may be now plotted on the same temperature-enthalpy (T-H) axes to obtain the IRS curves. Note that, the enthalpy surplus (H_R) and the enthalpy deficit (H_S) for a distillation problem may be conveniently calculated using equations (1) and (2) for each stage of a distillation column from the output of a converged simulation. The curves extend from T_D to T_B on the temperature scale.

The invariance of the IRS curves for binary systems may be proven from the fact that a binary system has only two degrees of freedom as per Gibb's phase rule. Therefore, these curves become deterministic on specifying the operating pressure and separation required. Thus, H_R and H_S are functions of temperature only and are invariant to the total number of stages and the location of the feed in the column. For analysis of multicomponent systems, the pseudo-binary concept of light and heavy keys (Dhole and Linnhoff, 1993) may be utilized during the generation of IRS curves. The invariant property of the IRS curves does not hold rigorously for multicomponent systems because the distribution of the components depends on the operating reflux of the column. Stupin and Lockhart (1968) noted that this distribution bears a non-linear relationship for any finite operating reflux. However, the temperature vs. composition (T-x-y) and the enthalpy vs. composition (H-x-y) behaviors of pseudo-binary systems do not change significantly near the minimum reflux for the column (typically, if $N > 3N_{min}$). Therefore, the IRS curves for any pseudo-binary system, generated through a simulation with a high number of stages (i.e., at a low reflux ratio), show near-invariance to the total number of stages and the feed location (as demonstrated by Bandyopadhyay *et al.*, 1999).

2.2 Feed Location and Minimum Energy Targets

The IRS curves may be used to target the feed location and the minimum energy requirement for distillation. The IR curve and the IS curve are not independent, but are related by the overall component, mass and energy balances. Combining the mass, component, and energy balances around the feed stage for a column, the relation between the IR curve and the IS curve can be simplified at the feed stage to give (Bandyopadhyay *et al.*, 1999)

$$H_S = H_R + \Delta \quad \text{at the feed stage} \qquad (3)$$

where $\Delta \equiv Q_r - Q_c = BH_B + DH_D - FH_F$. As Q_r and Q_c are the reboiler and the condenser loads respectively, Δ corresponds to the constant enthalpy difference of the column based on the first law. The following convention may be adopted to translate the IRS curves in accordance with equation (3). Depending on the sign of Δ, the translations may be conveniently classified into two cases: (a) if $\Delta \geq 0$, then only the IR curve is translated to the right by Δ; and (b) if $\Delta < 0$, then only the IS curve is translated to the right by $|\Delta|$. Typical IRS curves for case (b) are shown in Fig. 1. Mathematically, these translations can be conveniently represented as

$$H_{RT} = H_R + \Delta/2 + |\Delta/2| \qquad (4)$$
$$H_{ST} = H_S - \Delta/2 + |\Delta/2| \qquad (5)$$

where H_{RT} and H_{ST} are the enthalpy coordinates for the translated IR curve and translated IS curve, respectively. Note that, although the IR and IS curves are independent of feed condition, the translated curves depend on the thermal condition of the feed. Equations (3) - (5) may be

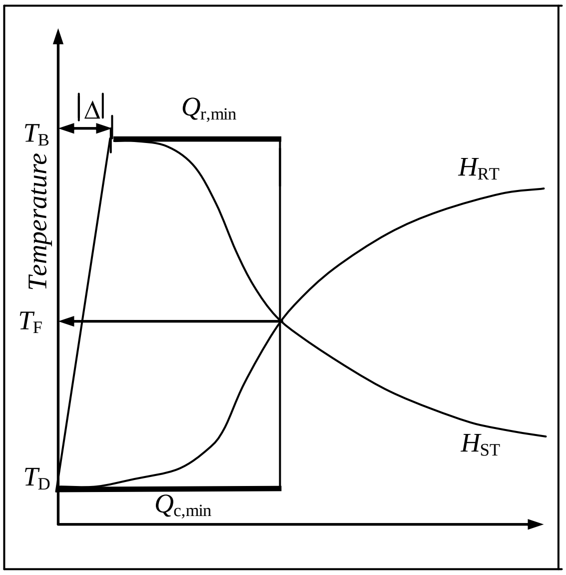

Fig.1 Targeting feed location and minimum energy through IRS curves

combined to obtain

$$H_{ST} = H_{RT} \quad \text{at the feed stage} \tag{6}$$

Equation (6) defines the criterion for appropriately locating the feed in the column. The appropriate location for the feed may be determined in terms of temperature (T_F) by finding the intersection of the translated IRS curves (Fig. 1). A method to convert this target temperature into a stage number for proper feed location has been suggested by Bandyopadhyay *et al.* (1999).

After locating the feed from the intersection point of the translated IRS curves in terms of temperature (T_F), the minimum energy requirements may be also determined from the translated IRS curves. The portion of the IR curve below T_F and the portion of the IS curve above T_F may be circumscribed by a right-angled trapezium. Then, the widths of the parallel sides of the trapezium at the top and bottom define the minimum energy targets for the reboiler and condenser, respectively (see Fig. 1). These minimum energy targets are directly related to the minimum reflux target.

2.3 IRS curves for Multi-feed Column

A complex column with *n* feeds may be decomposed into *n* simple columns. For the *i*-th decomposed column, the overall mass, component, and energy balances may be written as

$$F_i = D_i + B_i \tag{7}$$

$$F_i z_{Fi} = D_i x_D + B_i x_B \tag{8}$$

$$D_i H_D + B_i H_B - F_i H_{Fi} = Q_{ri} - Q_{ci} \equiv \Delta_i \tag{9}$$

where D_i, B_i, and Δ_i are the distillate flow-rate, bottom flow-rate, and enthalpy difference of the *i*-th decomposed column. In the decomposition process, the overall mass, component, and enthalpy balances are conserved (as $D = \Sigma\ D_i$, $B = \Sigma\ B_i$, and $\Delta \equiv Q_r - Q_c = D\ H_D + B\ H_B - \Sigma\ F_i\ H_{Fi} = \Sigma\ \Delta_i$ where the summation, Σ, goes from i = 1 to i = n). It is important to note that the purity and enthalpy of the end products in the *i*-th column are same as that in the original multiple-feed column. Distillate and bottom flowrates (D_i and B_i) may be calculated for the *i*-th decomposed column with feed F_i from the mass balance of the *i*-th column. The enthalpy surplus (H_{Ri}) and the enthalpy deficit (H_{Si}) of the individual decomposed columns may be directly calculated from equations (1) and (2).

Physically, equation (6) signifies the intersection of the *q*-line for a feed with the equilibrium curve on the *x*-*y* diagram. For a multiple-feed column, the intersection of the *i*-th *q*-line with the equilibrium curve is independent of the intersections for the remaining feeds. Similarly, the intersection of the translated IRS curves for the *i*-th decomposed column signifies the appropriate location for the *i*-th feed and is independent of the feed location targets for the other feeds. This independence property allows appropriate location of each feed without assuming any predetermined order for the feeds. Rather, the appropriate order for the feeds may be determined by simply arranging the target temperatures (e.g., feed F_2 is at a higher temperature than feed F_1 in Fig. 2). After locating the feeds from the intersection points of the translated IRS curves, the minimum energy requirement for the complex column may be determined by combining the individual translated IRS curves, as described next.

2.4 Composite IRS Curves

The portion of the translated IR curve below T_{Fi} and the portion of the translated IS curve above T_{Fi} may be defined as the active portions of the translated IRS curves for the *i*-th decomposed column and consequently the *i*-th feed. Thus,

$$H_{Ai} = \begin{cases} H_{RT\,i} & \text{for} \quad T \le T_{Fi} \\ H_{ST\,i} & \text{for} \quad T > T_{Fi} \end{cases} \tag{10}$$

For the case of a simple column with a single feed, the active portions of the translated IRS curves are circumscribed by a right-angled trapezium to readily define the minimum energy targets for the column (as in Fig. 1). For complex columns, the following procedure is adopted.

Composite IRS curves are generated for the complex column by simply adding the enthalpy coordinates of the translated IRS curves corresponding to all the feeds. The composite IRS curves are shown in Fig. 2 for a typical two-feed column based on the translated IRS curves of the two decomposed columns. The composite IRS curves for the two-feed column are drawn by appropriately adding the IRS curves for the two decomposed columns in three distinct sections demarcated by the feed intersection points. In the section below T_{F1}, the rectifying curves of both the columns contribute to the

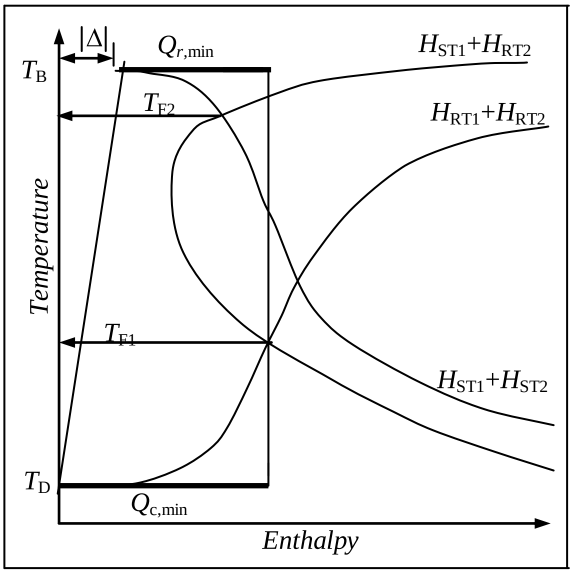

Fig.2 Typical composite IRS curves for two-feed column

active portions. In the section above T_{F2}, the stripping curves of both the columns contribute to the active portions. Between the two feeds (above T_{F1} and below T_{F2}) the stripping curve of the first column and the rectifying curve of the second column contribute the active portions. Hence, the composite IRS curves consist of $H_{RT1} + H_{RT2}$, $H_{ST1} + H_{RT2}$, and $H_{ST1} + H_{ST2}$ (Fig. 2). Thus, to produce the composite IRS curves for the two-feed column, only three curves need to be drawn. By induction, for a column with n feeds, $(n+1)$ curves are to be drawn based on the active portions of the translated IRS curves of the n decomposed columns. The fourth composite IRS curve possible (not shown in Fig. 2), namely $H_{RT1} + H_{ST2}$, is unnecessary because the IR curve for feed F_1 and the IS curve for feed F_2 are not active together in any section. Thus, for section i of an n-feed column,

$$H_A = \sum_{j=1}^{n} H_{Aj} = \sum_{j=1}^{i} H_{STj} + \sum_{j=i+1}^{n} H_{RTj} \qquad i = 0,1,\ldots,n \qquad (11)$$

Equation (11) ensures that the overall mass, component, and energy balances are satisfied in each of the $(n + 1)$ sections of the n-feed column. The active portions of the composite IRS curves (H_A) may be circumscribed by a right-angled trapezium, as described earlier for a simple column with a single feed. As before, the widths of the parallel sides of the trapezium at the top and bottom define the minimum energy targets for the reboiler and condenser, respectively (see Fig. 2). Fig. 2 illustrates the case where one of the intersection points of the composite IRS curves determines the pinch. This is observed to be the case whenever the IRS curves of the individual decomposed columns are monotonic in nature. Note that the composite IRS curves for the complex column are, however, not monotonic.

3. FEED PREHEATING TARGETS

Preheating the feed results in changing the feed enthalpy. If Q_F is the amount of heat exchanged with the feed, then the overall enthalpy difference and equation (6) become

$$\Delta_P \equiv D\,H_D + B\,H_B - (F\,H_F + Q_F) = \Delta - Q_F \qquad (12)$$

$$H_S\{T_{FP}\} = H_R\{T_{FP}\} + \Delta_P \qquad (13)$$

where subscript p denotes quantities for the column with preheating. Based on the definitions in equations (4) and (5), it is possible to combine equations (12) and (13) as

$$Q_F = H_{RT}\{T_{FP}\} - H_{ST}\{T_{FP}\} \qquad (14)$$

The important conclusion from the above equation (as highlighted in Fig. 3) is that the enthalpy difference between the translated IRS curves at a certain temperature T_{FP} specifies the amount of heat required to change the feed stage temperature from T_F to T_{FP}.

Equation (12) may be rearranged to obtain a useful relation between the amount of preheating and the changes in the duties of the reboiler and condenser as given below.

$$Q_F = \delta Q_c - \delta Q_r \qquad (15)$$

The change in minimum reboiler and condenser loads by feed preconditioning are shown as $-\delta Q_r$ and δQ_c in Fig. 3. For better geometric understanding, the invariant stripping curve translated horizontally by an additional amount Q_F as well as the trapezium for determining minimum reboiler and condenser loads after feed preconditioning are shown by dashed lines. Note that the translated IRS curves depend on the amount of feed conditioning (because Δ is a function of the feed enthalpy), whereas the IRS curves themselves do not. It is observed on Fig. 3 that preheating has caused the minimum condenser duty to increase by δQ_c and the minimum reboiler duty to decrease by $-\delta Q_r$. Thus, for systems with monotonic IRS curves,

$$\delta Q_c = H_{RT}\{T_{FP}\} - H_{RT}\{T_F\} \qquad (16)$$

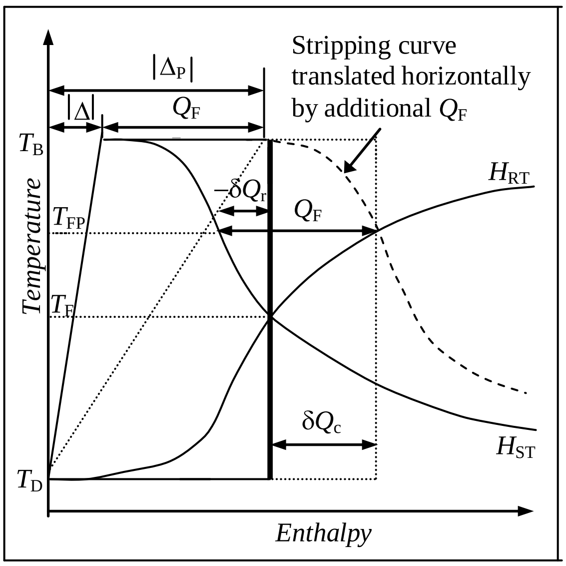

Fig.3 Targeting feed preheat efficiency through IRS curves

$$-\delta Q_r = H_{ST}\{T_F\} - H_{ST}\{T_{FP}\} \quad (17)$$

Equations (15) – (17) indicate that there is an efficiency associated with feed preheating. It may be defined as

$$\eta \equiv -\delta Q_r / Q_F \quad (18)$$

The efficiency η varies with the temperature T_{FP}. Equation (15) shows that the change in the condenser load is the enthalpy difference between the invariant rectifying curve and the vertical line of the (bold) trapezium in Fig. 3. In an analogous fashion, the enthalpy gap between the vertical line of the (bold) trapezium and the invariant stripping curve is the change in the reboiler load.

3.1 Feed Preheat Targeting by Feed Splitting

It is possible to split the feed into two parts and the thermal condition of one of the split-fractions may be altered. This way of introducing feed preheating leads to 100% preheat efficiency. Let the split-fraction be f that is preheated by Q_F and the other fraction $(1 - f)$ be left unaltered. To generate the composite IRS curves and to address feed preheating effects, this two-feed column can now be decomposed into two single feed columns, as discussed earlier. Overall mass balance of the two decomposed columns reveals that the distillate and bottom flow-rates are related to the original column [$D_1 = (1 - f)\,D$, $D_2 = f\,D$, $B_1 = (1 - f)\,B$, and $B_2 = f\,B$]. Enthalpy difference of the decomposed columns reveals that

$$\Delta_1 \equiv (1 - f)\,[D\,H_D + B\,H_B - F\,H_F] = (1 - f)\,\Delta \quad (19)$$
$$\Delta_{2P} \equiv f\,[D\,H_D + B\,H_B - F\,H_F] - Q_F = f\,\Delta - Q_F \quad (20)$$

Rectifying and stripping curves for the decomposed columns are calculated to be,

$$H_{RT1} = (1 - f)\,H_{RT} \quad (21)$$
$$H_{RT2P} = f\,H_{RT} \quad (22)$$
$$H_{ST1} = (1 - f)\,H_{ST} \quad (23)$$
$$H_{ST2P} = f\,H_{ST} + Q_F \quad (24)$$

Intersection of H_{RT2P} and H_{ST2P} indicates the location of the preheated split-fraction in the column (in temperature scale denoted as $T_{FP} > T_F$). Combining these equations, the composite IRS curves for the complex column are given by (Fig. 4),

$$H_{RT1} + H_{RT2P} = H_{RT} \quad (25)$$
$$H_{ST1} + H_{RT2P} = (1 - f)\,H_{ST} + f\,H_{RT} \quad (26)$$
$$H_{ST1} + H_{ST2P} = H_{ST} + Q_F \quad (27)$$

For 100% preheat efficiency, pinch should be controlled by the unaltered split-fraction. Maximum Q_F that can be utilized for 100% preheat efficiency should have two pinch points and both should lie on the same vertical line (points B and D as shown in Fig. 4). Point D signifies the feed location point for the unaltered fraction of the feed. This controls the pinch point and hence the minimum energy required in the column. As a portion is preheated, a new feed location point is developed (point B). Whenever these two points have the same enthalpy value, minimum condenser duty (and hence the minimum reflux ratio) remains same as the original column. Constancy of the condenser load ensures 100% preheat efficiency. Criterion of two pinch points for 100% preheat efficiency translates into the following mathematical relations.

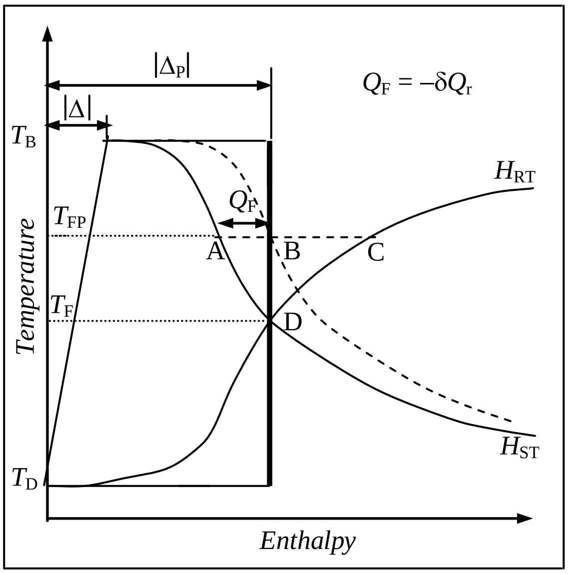

Fig.4 Feed preheat targeting by feed splitting through composite IRS curves

$$H_{RT1}\{T_F\} + H_{RT2P}\{T_F\} = H_{ST1}\{T_{FP}\} + H_{ST2P}\{T_{FP}\} \quad (28)$$
$$H_{ST1}\{T_{FP}\} + H_{RT2P}\{T_{FP}\} = H_{ST1}\{T_{FP}\} + H_{ST2P}\{T_{FP}\} \quad (29)$$

This may be simplified to

$$Q_F = H_{RT}\{T_F\} - H_{ST}\{T_{FP}\} = f\,[H_{RT}\{T_{FP}\} - H_{ST}\{T_{FP}\}] \quad (30)$$

Rearranging this, the relation between the preheated split-fraction of the feed and the IRS curves can be expressed as

$$f = [H_{RT}\{T_F\} - H_{ST}\{T_{FP}\}] \,/\, [H_{RT}\{T_{FP}\} - H_{ST}\{T_{FP}\}] \quad (31)$$

Equations (30) and (31) can be interpreted through Fig. 4. If the feed location temperature of the preheated split fraction is raised to T_{FP}, the amount of preheat required is shown by the line segment AB [equation (30)]. To achieve 100% preheat efficiency, the fraction of the split-feed can also be addressed form Fig. 4. This is given by the ratio of line segment AB to the line segment AC [equation (31)].

Fidkowski and Agrawal (1995) discussed the case where a portion of the bubble point feed is preheated to its dew point. They further assumed that system obeys constant molar overflow (i.e., $H_V - H_L = \lambda$, constant) with liquid distillate and bottom products (i.e., $H_B = H_D = H_L$) and derived an expression to find the maximum amount of preheat which can be supplied to a fraction of feed with 100% efficiency. The same expression can be directly derived from equation (30) after substituting the similar simplified assumptions.

$$Q_{P\max} = \lambda\left[F - D\left\{\frac{x_D - x(z_F)}{z_F - x(z_F)} - \frac{x_D - z_F}{y(z_F) - z_F}\right\}\right] \quad (32)$$

To design an energy efficient distillation column with 100% preheat efficiency following methodology may be adopted. From the base simulation of the column, IRS curves can be generated using equations (1)-(5). Location of the feed and the minimum energy required can now be calculated from the IRS curves. For a given amount of feed preheat, the split-fraction and its location in the column can be targeted based on equations (30) and (31).

4. ILLUSTRATIVE EXAMPLE

To demonstrate the potential of the described methodology, an illustrative example of benzene-propane has been considered. For this example, the simulations are performed using the DESIGN-II software based on the problem data given in Table 1 (Soave and Feliu, 2002). Variation of the feed preheat duty and the maximum split-fraction corresponding to 100% preheat efficiency, for this example is shown in Fig. 5. Detailed simulations, performed to verify these targets are also shown in Fig. 5. Same methodology may be applied to columns with side-products.

5. CONCLUSION

Knowledge about the behavior of a distillation column for different feed conditions is essential because it is one of the most important parameters for design and optimization of the column with the background process. Even for debottlenecking and utilization of the waste heat in the plant, the effect of thermal condition of the feed on the overall utility consumption is vital information. The thermal condition of the feed influences the thermodynamic efficiency of a distillation column. Optimal thermal condition of the feed contributes significantly in increasing the thermodynamic efficiency of a cryogenic distillation column, since work (rather than heat) is being utilized in sub-ambient processes such as gas separation.

In this paper a methodology is developed, based on the IRS curves, to find the appropriate feed splitting to obtain 100% preheat efficiency. The methodology helps in simultaneously targeting to find split fraction of feed for preheating and its location in the distillation column for a given amount of feed preheating. Using this methodology it is possible to target energy-efficient distillation column configuration prior to the detailed design of the column.

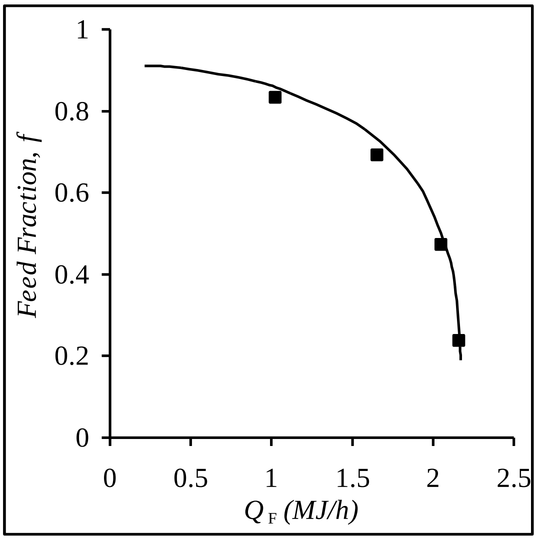

Fig.5 Relation between feed split-fraction and preheat duty for 100% preheat efficiency for the benzene-propane example

Table 1. Data for benzene-propane example

System		Benzene-Propane
Thermodynamic Method		Modified PR
Column and Feed Pressure		15 bar
Feed Data	Flow-rate	100 kg-mol/h
	Composition	80% benzene
	Temperature	20°C
Specifications	Top	99.9% Propane
	Bottom	99.9% Benzene

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