New Thermally Coupled Schemes for Ternary Distillation

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The fully thermally coupled system of distillation columns for ternary separation has two, two-way connections between the columns. New, simplified (and easier to control) systems of columns for ternary separations, with a reduced number of connecting streams, are proposed. The new systems contain one one-way and one two-way connection between the columns. Depending on which connection is located on top and which phase stream (liquid or vapor) is used in the one-way connection, there are four possible configurations for these new systems. For certain feed compositions and relative volatilities of components, these new systems can replace the fully thermally coupled system of columns without any increase in energy demand. The optimum system selected from the four proposed configurations consumes no more, and frequently much less, energy than the side stripper or side rectifier configurations or than a system with a prefractionator.

Introduction

Several configurations of distillation columns are known for ternary separations (King, 1980). Classic configurations include: direct sequence (DS), indirect sequence (IS), column with side rectifier (SR), column with side stripper (SS), single column with side draw, system with a prefractionating column (known also as a separation complex, SC), and fully coupled columns (FC). System SC is shown in Figure 1a while the FC system, as drawn by Petlyuk et al. (1965) is shown in Figure 1b. Systems SR and SS are shown in Figure 2. In these figures feed mixture is ABC with A being the most volatile and C the least volatile component.

Energy demand of these column configurations has been well studied in the literature over the last five decades: Lockhart (1947); Rod and Marek (1959); Petlyuk et al. (1965); Heaven (1969); Hendry and Hughes (1972); Stupin and Lockhart (1972); Hendry et al. (1973); Doukas and Luyben (1978); Hlavacek (1978); Tedder and Rudd (1978); Westerberg (1980, 1985); Nishida et al. (1981); Fidkowski and Krolikowski (1987); Glinos and Malone (1988); Carlberg and Westerberg (1989); Triantafyllou and Smith (1992); Wolff and Skogestad (1995); Finn (1996); Westerberg and Wahnschaft (1996); Christiansen (1997). Several studies have proven that the FC configuration has the lowest energy demand from all the systems of columns for the separation of ideal ternary mixtures into pure product streams (Fidkowski and Krolikowski, 1987). It has been stated that, on average, the FC configuration requires 30% less energy than the corresponding conventional arrangement (Triantafyllou and Smith, 1992; Rudd, 1992). It is also stated that for three-component mixtures, FC is the most efficient arrangement (Rudd, 1992; Triantafyllou and Smith, 1992). Agrawal and Fidkowski (1998a) have shown that

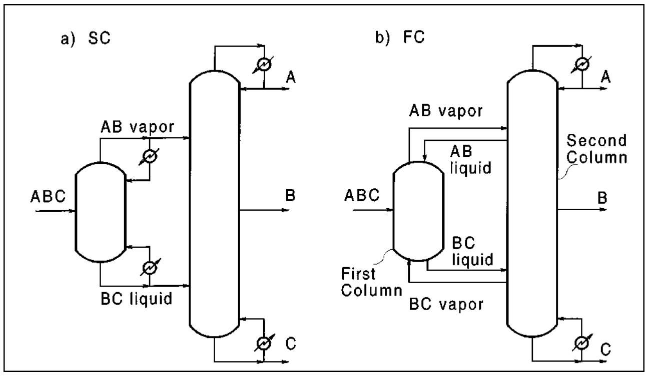

Figure 1. (a) System with a Prefractionating Column (SC); (b) FC of Petlyuk et al. (1965).

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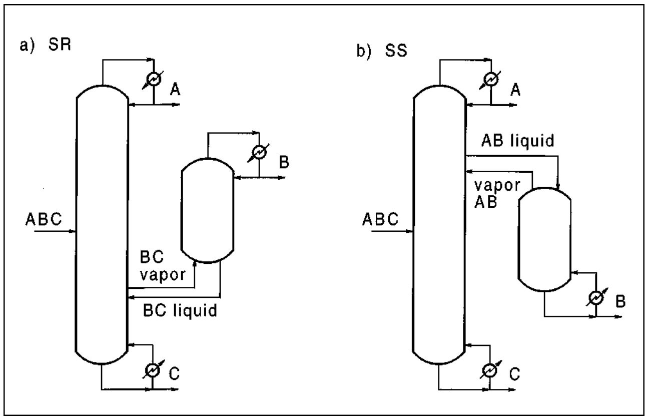

Figure 2. (a) SR; (b) SS.

the statement about the superior thermodynamic efficiency is usually not correct, however, the energy demand in FC configuration is indeed much lower than in conventional systems (savings with respect to conventional systems vary from 10 to 50% depending on relative volatilities and feed composition).

In a fully coupled system of distillation columns, there are two two-way (countercurrent) liquid and vapor exchanges between the two distillation columns. For example, in the FC system of Figure 1b this is realized as follows: the ternary mixture ABC is separated in the first column (prefractionator) into two binary products: AB in the top and BC in the bottom. Top vapor AB is fed into the upper portion of the second distillation column, and, from the same place of the second column, the liquid AB is withdrawn and fed to the top of the prefractionator as reflux. Similarly, bottom liquid BC from the first column is fed to the lower portion of the second column and, simultaneously, vapor BC is withdrawn from the same level of the second column and introduced into the bottom of the prefractionator as boilup. These two-way connections eliminate the need for a reboiler and a condenser for the prefractionator.

The reduced energy demand of an FC configuration makes it very attractive in comparison with other systems. This also leads to smaller column diameters and lower overall heat exchanger areas for the reboiler and condenser. Moreover, the reduced number of reboilers and condensers also contributes to lower capital investment. However, in spite of all these attractive features, the FC configuration has not found a wide industrial use. This is rather surprising, because this configuration has been known for 50 years (Wright, 1949).

The lack of the widespread use of an FC configuration can be partially attributed to the fact that, until recently, all the efforts have concentrated to using either the configuration shown in Figure 1b or the divided wall column. These two FC configurations are perceived to have control difficulties. Especially challenging is the control of flows between the columns of the FC configuration shown in Figure 1b. Vapor AB flows from the top of the prefractionator to the upper section of the second column. This means that the pressure in the top of the prefractionator must be greater than the pressure in the upper section of the second column. On the other hand, vapor BC has to be transferred from the lower section of the second column to the bottom of the prefractionator. Therefore, the pressure in the bottom of the prefractionator has to be lower than the pressure in the lower section of the second column. These requirements can be fulfilled by a special design of column internals, which ensures that the pressure drop in the intermediate part of the second column is higher than the pressure drop across the entire prefractionator. Another way to solve this problem is to use a blower on one of the vapor streams, but this significantly increases capital cost of the plant and may introduce additional pressure disturbances in columns. An additional constraint is the need to enforce the flows of liquid streams (AB and BC) between the columns, in directions countercurrent to the vapor streams. This could be realized by locating the liquid off-takes higher than their destinations, so that the liquids flow by gravitational head; alternatively, pump(s) could be used.

For certain values of relative volatilities and feed composition, the optimum range of interconnecting flows is relatively wide (Fidkowski and Krolikowski, 1986; Christiansen and Skogestad, 1997) and the control of the interconnecting flows does not have to be very accurate. This fact is utilized in operation of a column with a dividing wall, which is topologically equivalent to the fully coupled system (Fidkowski and Krolikowski, 1987). Certain dividing wall columns were also studied by Kaibel (1987). In many other cases, however, the optimum range of interconnecting flows is narrow and operating the fully coupled system away from its optimum will result in a considerable increase in energy demand.

The other way of solving the control problem in the fully thermally coupled system has recently been proposed by Agrawal and Fidkowski (1998b). By moving the bottom section of the second column together with its reboiler (or the top section with its condenser) to the prefractionator, we obtain a thermodynamically equivalent configuration, which is much easier to control. These modified thermally coupled systems were known earlier (Kaibel, 1988; Smith and Linhoff, 1988), but their improved operability went unnoticed. In these configurations the pressure in one of the columns can be set higher than in the other column and the two vapor interconnecting streams flow in a single direction—from the higher pressure column to that at the lower pressure.

Controllability can also be improved by simplifying the fully coupled system, preferably without any adverse effect on its power saving features. This can be done by removing one of the interconnecting flows between the second and the first column and by reintroducing a reboiler or condenser to the prefractionator. This is shown in Figure 3a, where the top liquid connection (AB) in the fully coupled system has been eliminated and a condenser has been added to prefractionator. We will call this system of columns side Rectifier with direct Vapor connection or RV. Obviously, side Rectifier with direct Liquid connection (RL) is also possible (Figure 3b). Another possibility is shown in Figure 4a, where the bottom vapor connection (BC) from the second column to prefractionator has been replaced by a reboiler BC. We will call this system side Stripper with direct Liquid connection or SL. Finally, side Stripper with direct Vapor connection (SV) is shown in Figure 4b.

In these new systems a heat exchanger (reboiler or condenser) replaces one interconnecting stream between the

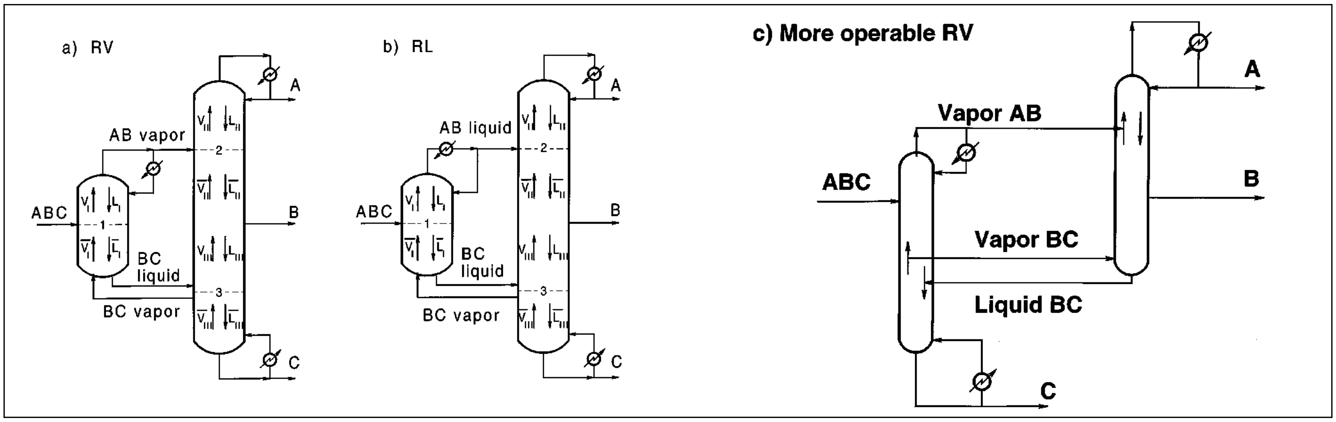

Figure 3. (a) Side rectifier with direct vapor connection (RV); (b) side rectifier with direct liquid connection (RL); (c) more controllable alternative to RV system.

columns. This provides a potential for the new systems to be thermodynamically more efficient, since a possibility of heat exchange at a new temperature level (between the temperature of component *A* and component *C*) has been created.

Furthermore, the new distillation configurations are easier to control than the fully coupled system because of the decreased number of vapor or liquid lines between the columns and the use of an additional condenser or reboiler. The vapor flow control problem in the RV configuration (shown in Figure 3a) is easily solved by rearranging the column sections as described for the FC system in a recent article of Agrawal and Fidkowski (1998b). A more operable RV arrangement is shown in Figure 3c. Note that there is no vapor flow control problem in the SL configuration shown in Figure 4a, because there is only one vapor stream between the columns.

As mentioned above, a wide variety of ternary distillation configurations have been studied for more than 50 years. One might expect that all the possible systems of columns for ternary distillation have already been analyzed. A configuration with two one-way connections between the first and the second column is known (SC); configurations with one two-way connection between the columns are known (SR, SS); obviously, the fully coupled system (FC) with two two-way connections between the column is also known. Surprisingly, systems RV, RL, SL, and SV with one one-way connection and one two-way connection have not yet been proposed in the literature. Obviously, there are several more systems similar to these new configurations. For example, a top vapor connecting stream in the RV system (AB) could be partially liquefied, or, additionally, a liquid stream AB can be introduced to the second column above the vapor AB feed.

The concept of simplifying a thermally coupled distillation configuration can be easily extended to mixtures containing more than three components. Fully thermally coupled and other systems with multiple two-way connections between the columns are well known for multicomponent distillation (Sargent and Gaminibandara, 1976; Agrawal, 1996). In these configurations, some, but not all, of the two-way connections can be suitably modified to one-way connections by proper use of reboilers and condensers. This would lead to numerous new configurations that would be analogous to systems RV, RL, SV, and SL.

The objective of this article is to analyze these new, simpler, and easier to control alternatives to the fully coupled system of columns for ternary distillation. The analysis is performed for ideal mixtures of components with constant relative volatilities and constant molar overflow, assuming isobaric conditions. The ternary feed is assumed to be a saturated liquid. Each of the product streams constitutes a nearly pure component and is withdrawn as saturated liquid. The energy requirements of each of the compared configurations are calculated at minimum reflux conditions.

Equations for Minimum Vapor Flow in RV

The side rectifier with vapor connection (RV) is shown in Figure 3a. All the equations to calculate minimum vapor flow for this system are presented below. RL is discussed in the next section. Similar equations for systems SL and SV are given in the Appendix.

Minimum vapor flow in the first column of RV can be calculated in the same way as for the fully coupled system (Fidkowski and Krolikowski, 1986)

$$\bar{V}_{\mathrm{I}} = \max_{j=1,2}\left[\frac{\alpha_A A}{\alpha_A-\phi_j}+\frac{\alpha_B B}{\alpha_B-\phi_j}\beta\right] \tag{1}$$

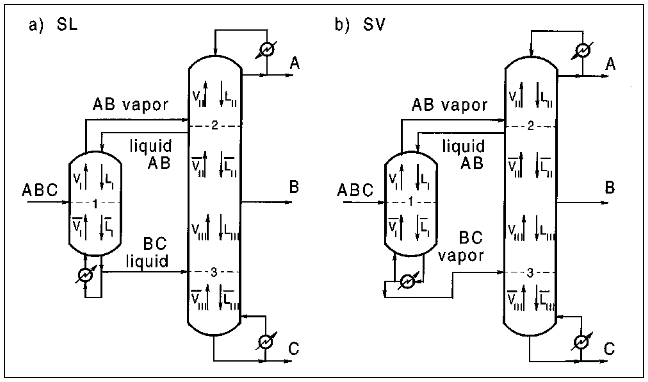

Figure 4. (a) Side stripper with direct liquid connection (SL); (b) side stripper with direct vapor connection (SV).

where α_i is the relative volatility of component i with respect to any component in the mixture, β is the fraction of component B leaving the first column in the distillate, and ϕ_j ($j=1$, 2) is the root of Underwood's equation (Underwood, 1948) for the saturated liquid feed ABC

$$\frac{\alpha_A A}{\alpha_A-\phi}+\frac{\alpha_B B}{\alpha_B-\phi}+\frac{\alpha_C C}{\alpha_C-\phi}=0 \tag{2}$$

Note that minimum vapor flow in the first column reaches its minimum value

$$\overline{V}_{\mathrm{I}}^{\min}=\frac{A\alpha_A+B\alpha_B+C\alpha_C}{\alpha_A-\alpha_C} \tag{3}$$

for a certain distribution of component B between the top and the bottom product of the first column

$$\beta=\beta_P=\frac{\alpha_B-\alpha_C}{\alpha_A-\alpha_C} \tag{4}$$

Minimum vapor flow from the reboiler of the second column is calculated as

$$\overline{V}_{\mathrm{III}}=\max\left\{\overline{V}_{\mathrm{III}}^{\mathrm{lo}},\overline{V}_{\mathrm{III}}^{\mathrm{up}}\right\} \tag{5}$$

where $\overline{V}_{\mathrm{III}}^{\mathrm{lo}}$ is the minimum vapor flow assuming that liquid and vapor are at equilibrium at the lower feed level 3, and $\overline{V}_{\mathrm{III}}^{\mathrm{up}}$ is the minimum vapor flow determined by the "upper pinch" at level 2. These values of minimum vapor flows are calculated from material balances and equilibrium conditions for particular sections of the columns. If the lower pinch controls, these equations, written for the bottom section of the second column, give

$$\overline{V}_{\mathrm{III}}^{\mathrm{lo}}=\frac{Cx_B}{y_B^*-x_B} \tag{6}$$

where x_B is the mole fraction of component B in the liquid at level 3—Figure 3a (lower feed of the second column), and y_B^* is the mole fraction of component B in the vapor phase in equilibrium with this liquid. These mole fractions can be calculated from a material balance for the bottom section of the first column, together with the equilibrium relation, which results in the following quadratic equation

$$ax_B^2+bx_B+c=0 \tag{7}$$

where

$$\begin{aligned} a&=\left[\overline{V}_{\mathrm{I}}+B(1-\beta)+C\right](\alpha_B-\alpha_C)\\ c&=-\alpha_C B(1-\beta)\\ b&=-a-c+\alpha_B C \end{aligned} \tag{8}$$

The only feasible root ($0\le x_B\le 1$) of Eq. 7 is

$$x_B=\frac{-b+\sqrt{b^2-4ac}}{2a} \tag{9}$$

After calculating x_B from Eq. 9, we can determine y_B^* from the equilibrium relation (in the binary mixture BC) and calculate $\overline{V}_{\mathrm{III}}^{\mathrm{lo}}$ from Eq. 6.

When the upper pinch controls, the minimum vapor flow from the bottom reboiler ($\overline{V}_{\mathrm{III}}^{\mathrm{up}}$) can be determined from the balance and equilibrium equations for section II of the second column of the RV system

$$\overline{V}_{\mathrm{III}}^{\mathrm{up}}=\frac{\alpha_B}{\alpha_A-\alpha_B}(A+\beta B)+\overline{V}_{\mathrm{I}} \tag{10}$$

A typical curve for minimum vapor flow in RV as a function of β is shown in Figure 5. As for the FC system (Fidkowski and Krolikowski, 1986), we observe a characteristic flat region where minimum vapor flow holds its minimum value. This region is $\beta_P\le\beta\le\beta_R$, where β_P is the value of β given by Eq. 4 where vapor flow in the first column has its minimum value and β_R is the value of β for which $\overline{V}_{\mathrm{III}}^{\mathrm{lo}}=\overline{V}_{\mathrm{III}}^{\mathrm{up}}$. Sometimes, however, only one minimum point at $\beta=\beta_P$ is observed and β_R is beyond (0,1) range.

It is also worth noting that for very small values of β, that is, in cases where there is no component B in the top vapor connection between the prefractionator and the second column, then the RV system reduces to a side rectifier. This can be written symbolically as

$$\text{if}\quad \beta\to 0\quad \text{then}\quad \mathrm{RV}\to\mathrm{SR} \tag{11}$$

System RV operating at $\beta=0$ is shown in Figure 6. Minimum vapor flow at the lower pinch (B/C separation) controls and it is equal to the minimum vapor flow in the side rectifier. The topology of the RV system is such that it cannot look exactly like a side rectifier. The major difference is that the RV system does not have a condenser for pure component B. Instead, to condense B, it uses the condenser for A, located on top of the second column, together with a "swap section," located just above B off-take in the second column. The purpose of the swap section is to exchange the vapor flow (and liquid flow) of one component (for example, B in the bottom of the swap section) for the vapor flow (and liquid

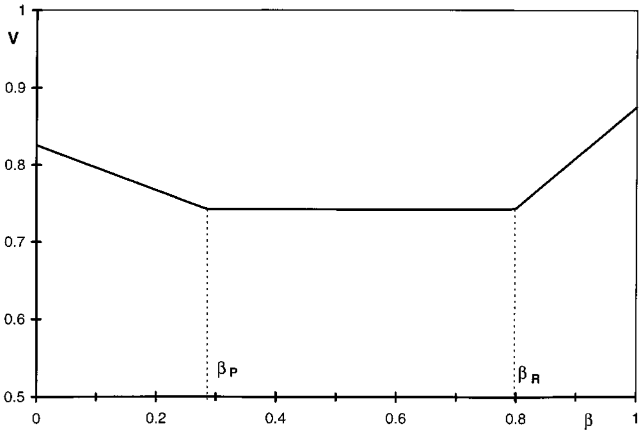

Figure 5. Minimum vapor flow as a function of β for RV.

$\alpha_A=6.25$; $\alpha_B=2.50$; $A=0.1$; $B=0.1$.

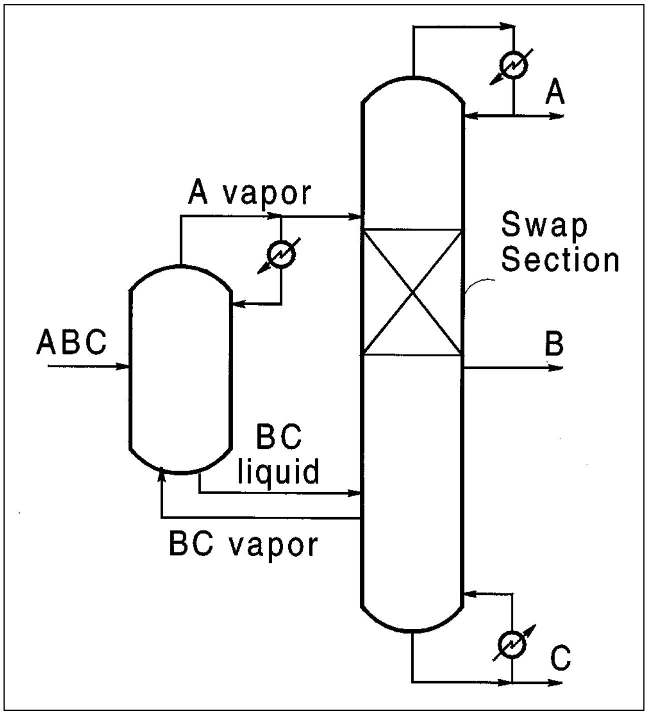

Figure 6. RV system operating at $\beta = 0$.

flow) of the second component (A in the top of the swap section). This swap enables the use of condenser A indirectly to provide liquid reflux B to the distillation section immediately below the swap section, which operates at total reflux.

On the other end of the β region, if all component B is passed from the first to the second column through the top vapor connection, then there is no need for the bottom connections and the RV system of columns reduces to the indirect split configuration with a vapor AB connection between the columns

$$\text{if} \quad \beta \to 1 \quad \text{then} \quad \text{RV} \to \text{IS} \tag{12}$$

Equations for Minimum Vapor Flow in RL

The side rectifier with liquid connection (RL) is shown in Figure 3b. This system should be easier to control than the RV system, because the top connection AB between the columns is a liquid stream, rather than vapor. All the equations for the minimum vapor flow in the RL system are the same as in RV system, except one. The one that is different is the equation for the minimum vapor flow when the upper pinch controls. For the RL system, instead of Eq. 10, the following expression should be used

$$\bar{V}_{\text{III}}^{\text{up}} = \frac{\alpha_A A + \alpha_B \beta B}{\alpha_A - \alpha_B} + \bar{V}_{\text{I}} \tag{13}$$

Note that the difference between minimum vapor flows in RL and RV for the cases when the upper pinch controls is

$$\left(\bar{V}_{\text{III}}^{\text{up}}\right)_{RL} - \left(\bar{V}_{\text{III}}^{\text{up}}\right)_{RV} = A \tag{14}$$

However, when the lower pinch controls, the minimum vapor flows in RV and RL are exactly the same and are given by Eq. 6. In such a case, the RL system may be more convenient than the RV system because it may be easier to control.

Comparison of Energy Requirements in Alternative Configurations

Various kinds of comparisons of the known column configurations can be carried out, especially that there are at least four independent variables for each system, that is, two relative volatilities and two mole fractions of components in the feed. The objective of the following calculations is to compare the simplified systems (RV, RL, SL, and SV) with the fully coupled system (FC) and also with side rectifier (SR), side stripper (SS), and separation complex (SC), to determine:

(1) How big is the energy penalty (if any) for the simplifications made?

(2) Is there any energy advantage from using the new systems (RV, SL) instead of SR, SS, or SC?

(3) If the answer to the previous question is positive, then when should the RV system be used and when the SL system?

(4) How big is the energy penalty (if any) for using RL over RV or SV over SL?

Comparison between RV, SL and FC

Initially, we compared the best configuration (that is, with lower minimum vapor flow), chosen from RV or SL systems, with the fully coupled system. The comparison was carried out assuming that the AB split and the BC split is either easy or difficult, which gives four possible combinations for the pair of these binary splits (A/B, B/C), namely: (easy, easy); (easy, difficult); (difficult, easy); and (difficult, difficult). We arbitrarily chose the value of relative volatility in a binary mixture equal to 2.5 for an easy split and 1.1 for a difficult split. Tedder and Rudd (1978) proposed the Ease of Separation Index (ESI) that could also be used as an alternate method to classify each separation

$$\text{ESI} = \frac{K_A/K_B}{K_B/K_C} = \frac{\alpha_A}{\alpha_B^2} \tag{15}$$

The results are shown on feed composition triangles in Figures 7a–7d. In a major part of the composition space, the optimum system chosen from RV or SL has almost the same total minimum vapor flow as does the FC system. This demonstrates the attractiveness of RV and SL and proves that the energy penalty for simplifying the FC system (to obtain RV or SL, which should be easier to control) is usually insignificant. Especially when the two splits are dissimilar, the optimum system selected from RV or SL has practically the same minimum vapor flow as FC over almost the entire possible feed composition range (Figures 7b and 7c). The vapor flow in the FC system is significantly smaller only for a very small feed composition region, close to pure component A in Figure 7b ($\text{ESI} > 1$) and close to pure component C in Figure 7c ($\text{ESI} < 1$). When the splits are similar, that is, for $\text{ESI} = 1$ (Figures 7a and 7d), there is a region near the center of the composition triangle where the minimum vapor flow for the best of RV or SL may be up to 40% higher than that in FC. Replacing FC with either RV or SL would not be recom-

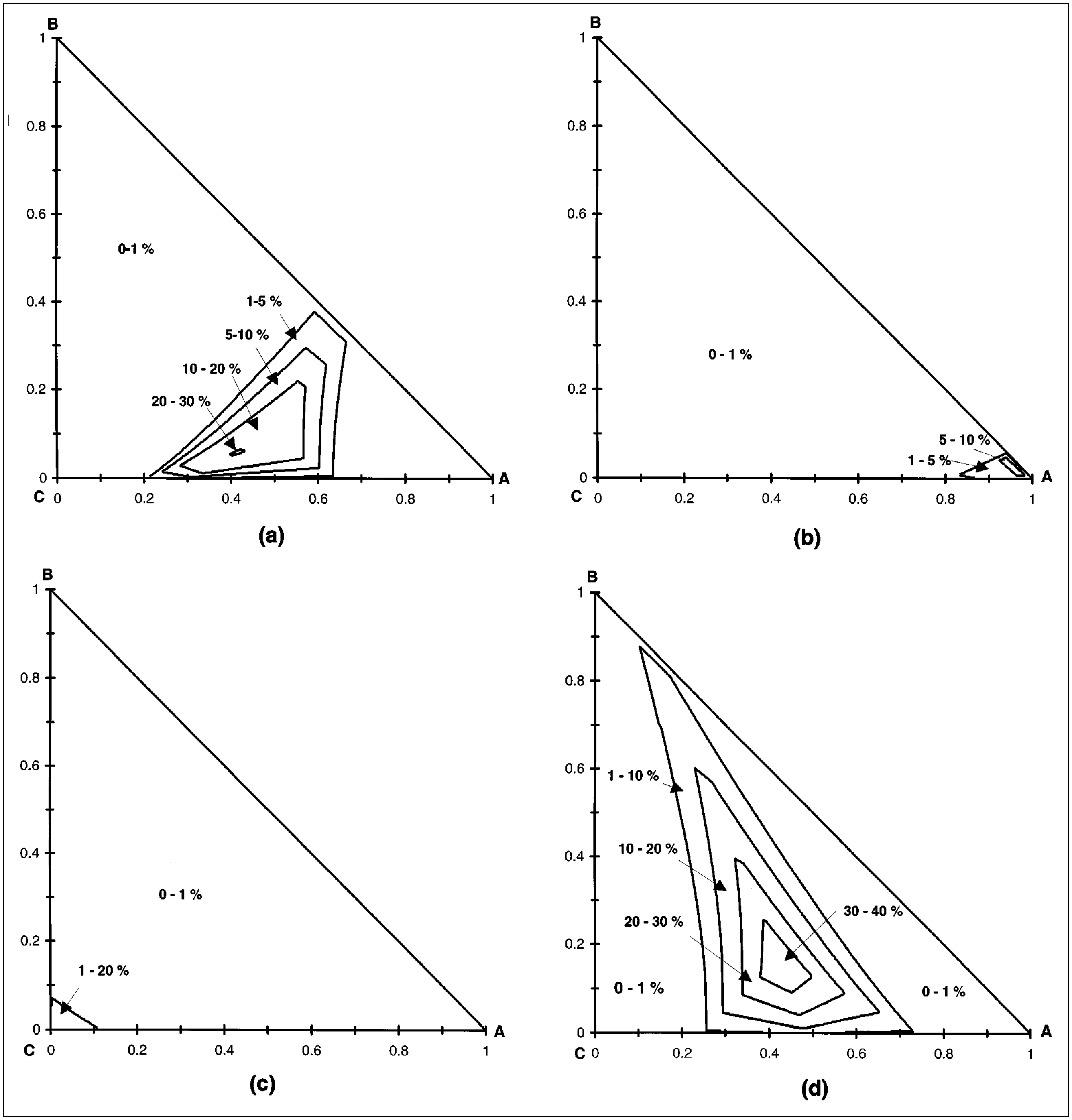

Figure 7. Relative energy penalty in terms of vapor flows for using the better of RV or SL instead of FC.

It is expressed as $(\min(V_{RV}, V_{SL}) - V_{FC})/V_{FC}$ as a function of feed composition on composition triangles, for the following values of relative volatilities: (a) $\alpha_A = 6.25$, $\alpha_B = 2.50$, (ESI = 1); (b) $\alpha_A = 2.75$, $\alpha_B = 1.10$, (ESI = 2.27); (c) $\alpha_A = 2.75$, $\alpha_B = 2.5$, (ESI = 0.44); (d) $\alpha_A = 1.21$, $\alpha_B = 1.10$, (ESI = 1).

mended in this region. Outside this feed composition region, however, the minimum vapor flow for either RV or SL is practically equal to the minimum vapor flow for FC.

Comparison of RV and SL with SC, SS and SR

It is well known (Fidkowski and Krolikowski, 1987, 1990) that systems for ternary separation can be ordered, according to their energy demands, as follows: energy demands are the lowest in the FC system; the second best (with respect to the first law of thermodynamics) is the group of distillation systems consisting of SS, SR, and SC, where the total minimum vapor flows in SS and SR are always exactly the same for a given mixture, and SC can consume either less or more energy than SR. For certain feed compositions and relative volatilities, the minimum vapor flow in one of the systems from the second group can be very close to the minimum vapor flow in FC. Therefore, we need to examine if there is any energy advantage in using the new systems (RV or SL) instead of SR, SS, or SC. To do this, we compared the energy demand of the best system from the {SR, SS, SC} group with that of the best system from the {RV, SL} group. The results are shown in Figures 8a–8d. We see in Figure 8a for the (easy, easy) split that in certain composition regions there is a significant advantage in using the RV or SL systems instead of SR, SS or SC. Energy savings in these regions are up to 20–30% of the total energy used by FC. Comparing Figure 8a with Figure 7a, we see that in these regions minimum va-

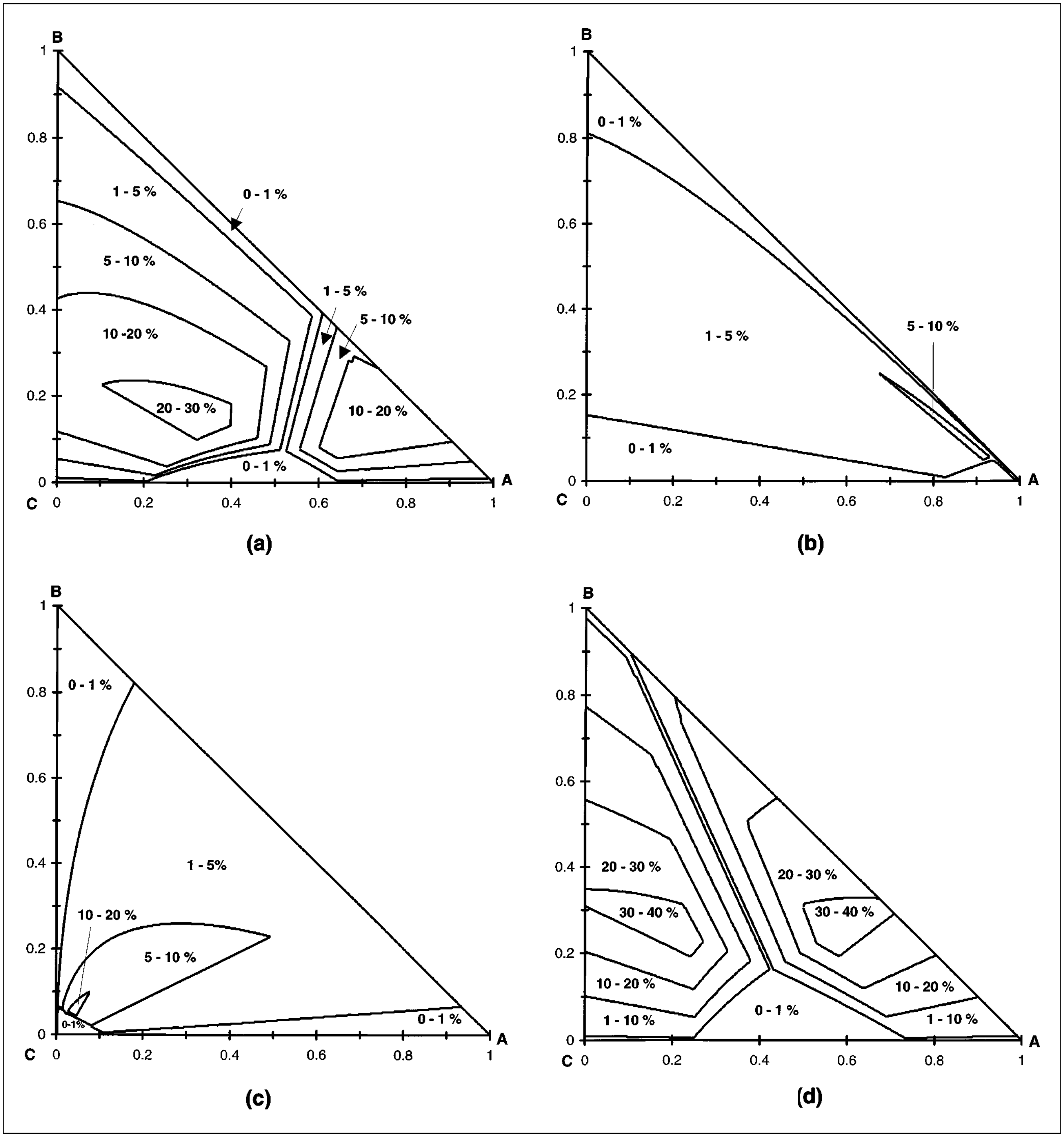

Figure 8. Relative energy penalty in terms of vapor flows for using the better of SR or SC instead of the better of RV or SL.

It is expressed as $(\min(V_{SR}, V_{SC}) - \min(V_{RV}, V_{SL}))/V_{FC}$ as a function of feed composition on composition triangles, for the following values of relative volatilities: (a) $\alpha_A = 6.25$, $\alpha_B = 2.50$; (b) $\alpha_A = 2.75$, $\alpha_B = 1.10$; (c) $\alpha_A = 2.75$, $\alpha_B = 2.5$; (d) $\alpha_A = 1.21$, $\alpha_B = 1.10$.

por flow for the best of RV or SL is practically equal to the minimum vapor flow for the fully coupled system. The savings are even greater, up to 40% of the total energy used by FC, for the (difficult, difficult) split shown in Figure 8d. In Figure 7d we see that in these composition regions minimum vapor flow for the best of RV or SL is practically equal to the minimum vapor flow for the FC system. On the other hand, for the (easy, difficult) split and the (difficult, easy) split, shown in Figures 8b and 8c, the advantage of using RV or SL instead of SR, SS or SC is not that significant—the maximum energy savings are in the range 5–10% of the total energy used by FC. Therefore, we conclude that the biggest energy gains resulting from using RV or SL instead of SR, SS, or SC are for ternary mixtures with relatively similar difficulty of binary splits, that is, for mixtures with ESI close to 1.

Comparison of RV with SL

Knowing that the use of RV or SL configurations may be advantageous, we should be able to select the best of these two for a given separation, that is, for a given feed composition and for given relative volatilities. In order to develop selection criteria, we compared the minimum vapor flows for RV and SL on the composition triangles for the same relative volatilities discussed above. Results are shown in Figures 9a–9d. We see that for the cases in Figures 9a and 9d, where the two splits are similar ($\mathrm{ESI} = 1$), the RV system requires less energy for mixtures containing more of component C than A, and the SL system is better for mixtures richer in A and leaner in C. When the split between A and B is easy while the split between B and C is difficult ($\mathrm{ESI} > 1$) as in Figure 9b, RV is optimal in the entire composition range. For feed compositions close to pure component B and close to pure component C, the energy demand for the SL system matches that for RV. For the case in Figure 9c with a difficult split between A and B and an easy split between B and C ($\mathrm{ESI} < 1$), the SL system is optimal in the entire composition range, except for the regions close to pure component A or pure component B, where the energy demand for SL or RV are practically the same.

Comparison of RL with RV and SL

As discussed above, the RL system could be easier to operate than the RV system, because the top connection AB between the columns is a liquid stream, rather than a vapor (Figure 3). To determine, if it is possible to use the RL system rather than the RV system without any significant energy penalty, we compared corresponding minimum vapor flows on the composition triangles. Results are shown in Figures 10a–10d. We see that the minimum vapor flow in RL is equal to the minimum vapor flow in the RV system in the significant part of the region where RV is superior to SL. For $\mathrm{ESI} = 1$, the RL system is equivalent to the RV system in about half of this region (Figures 10a and 10d compared to Figures 9a and 9d); for $\mathrm{ESI} > 1$, the minimum vapor flow for RL is equal to the minimum vapor flow for RV over almost the entire composition triangle (Figure 10b); for $\mathrm{ESI} < 1$, the RL system is not favorable (Figure 10c). However, for this case the SL system is superior to RV (Figure 9c), and there is little energy incentive to use either RL or RV. One common feature for Figures 10a–10d is that when a mixture is lean in the most volatile component A, the energy demand for RL is similar to that for RV. The minimum vapor flow for the RL system is the same as for the RV system for those relative volatilities and feed compositions for which the lower pinch controls in RL.

A similar discussion could be presented if it were desirable to substitute the SL system for SV. However, the SV system is probably more difficult to control than SL, because the liquid connection is replaced by a vapor stream. Also, the minimum vapor flow for the SV system cannot be lower than that for the SL system (Appendix). Consequently, there is not much incentive for this substitution.

The optimality regions for RV, RL, and SL depend on which pinch controls for a given system. The composition regions where the upper or the lower pinch controls are different for different systems. An approximate rule is that if the lower pinch controls in the FC system, then the RV system will consume less energy than SL does; if the upper pinch controls in the FC system, then the minimum vapor flow for SL will be lower than the corresponding minimum vapor flow for the RV system.

Conclusions

The fully coupled system of distillation columns for ternary separations is perceived as difficult to control, mainly because of the two two-way connections between its columns. Control difficulties will be reduced for systems of two coupled columns with a reduced number of interconnecting streams. New systems of columns for ternary separation, namely: side rectifier with direct vapor connection (RV), side rectifier with direct liquid connection (RL), side stripper with direct liquid connection (SL), and side stripper with direct vapor connection (SV), with one one-way connection, and one two-way connection, have been proposed.

Systems RV and SL can provide power savings equivalent to the FC system. This occurs over almost the entire feed composition range, when relative volatilities are such that one of the splits from the two given splits A/B and B/C is easy while the other one is difficult, that is, ESI differs significantly from 1. If the two splits are relatively similar (the value of ESI is close to 1) and feed compositions are close to the middle of the composition triangle, then the total minimum vapor flow for configurations RV and SL can be significantly higher than minimum vapor flow in the FC system.

Systems RV and SL can use up to 40% less energy than the best system selected from side rectifier, side stripper, or separation complex. The advantages are most pronounced for mixtures where both the splits are relatively similar (ESI values close to 1).

For mixtures with similar relative volatilities between the two pairs A/B and B/C (ESI close to 1), the minimum vapor flow for RV is smaller than the minimum vapor flow for SL for feed compositions richer in component C than in component A; the SL system is more attractive than RV for mixtures richer in component A than in component C. If relative volatility between A and B is much higher than the relative volatility between B and C (ESI is significantly greater than 1), the optimality region for the RV system dominates

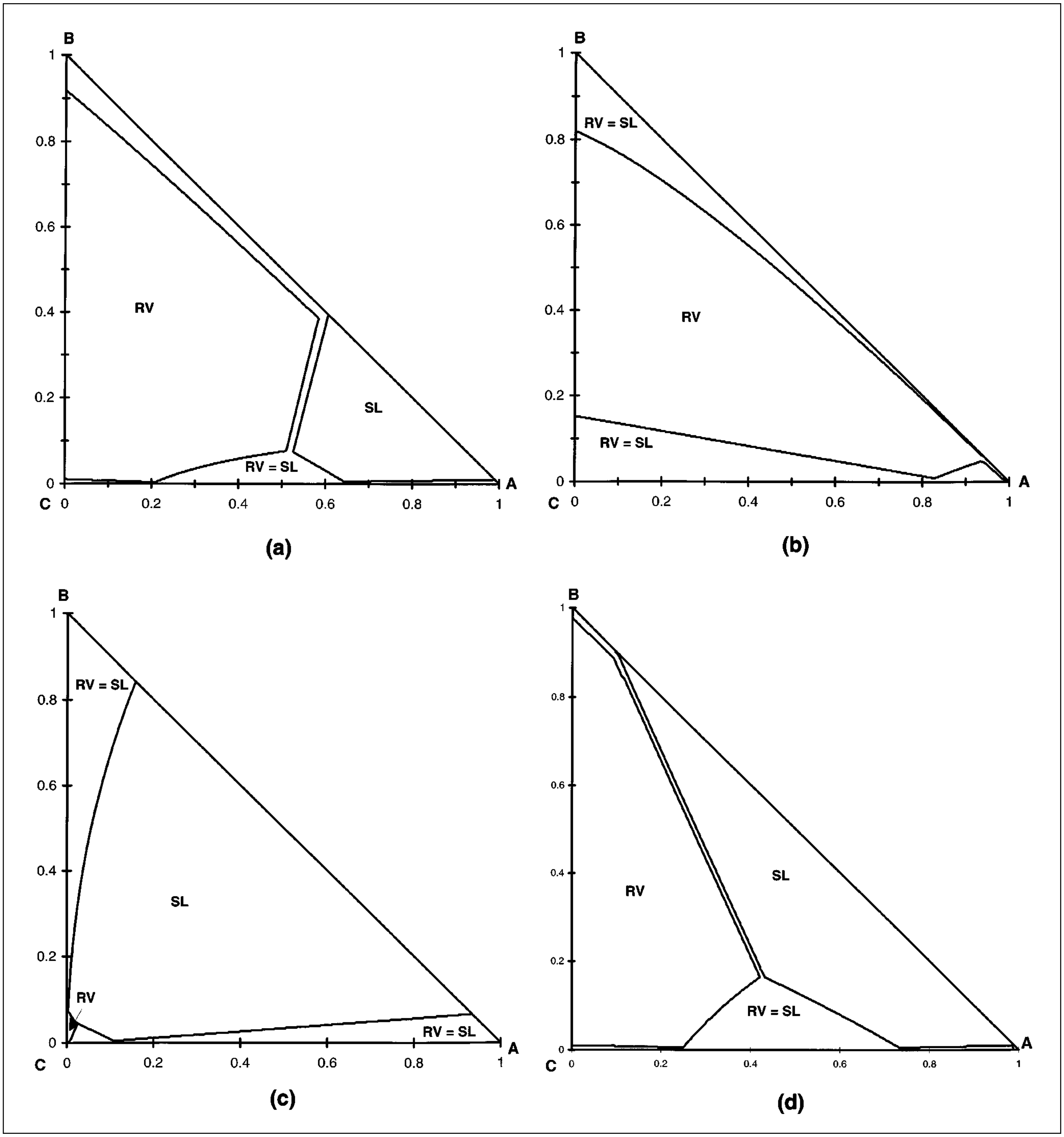

Figure 9. Comparison of minimum vapor flows for RV and SL on composition triangles, for the following values of relative volatilities.

(a) $\alpha_A = 6.25$, $\alpha_B = 2.50$; (b) $\alpha_A = 2.75$, $\alpha_B = 1.10$; (c) $\alpha_A = 2.75$, $\alpha_B = 2.5$; (d) $\alpha_A = 1.21$, $\alpha_B = 1.10$. Region RV: $V_{RV} < V_{SL}$; Region SL: $V_{RV} > V_{SL}$; Region RV = SL: $V_{RV} \approx V_{SL}$.

almost the entire range of feed compositions. For a mixture with low relative volatility between *A* and *B* and high relative volatility between *B* and *C* (ESI significantly less than 1), the SL system is optimal over almost the entire range of feed compositions.

For mixtures that are fairly lean in the most volatile component *A*, the minimum vapor flow for RL is comparable to that for RV irrespective of relative volatilities. When the relative volatility between *A* and *B* is much higher than the relative volatility between *B* and *C* (ESI significantly greater

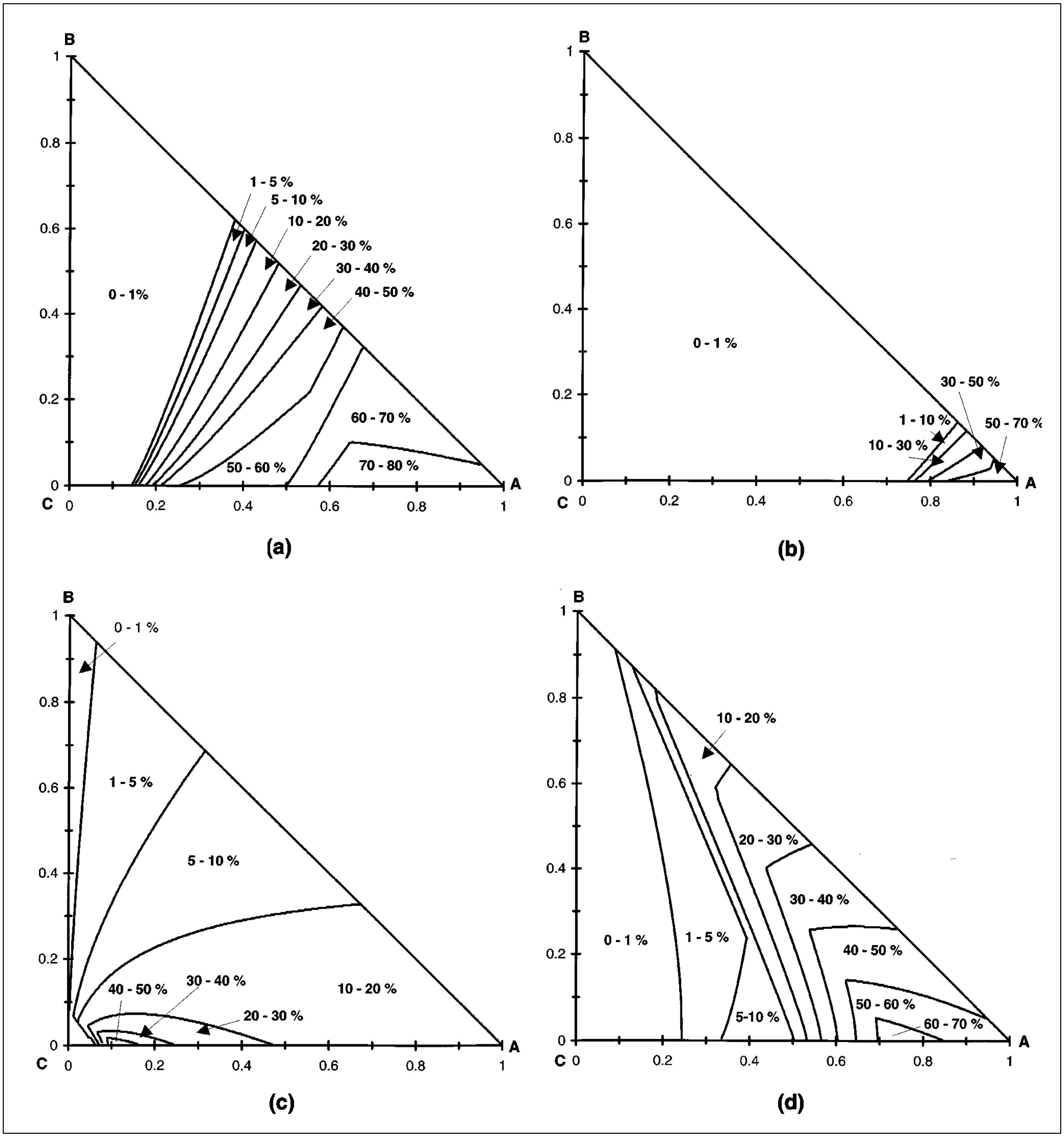

Figure 10. Relative energy penalty in terms of vapor flows for using RL instead of RV or SL.

It is expressed as $(V_{RL} - \min(V_{RV}, V_{SL}))/V_{FC}$ as a function of feed composition on composition triangles, for the following values of relative volatilities: (a) $\alpha_A = 6.25$, $\alpha_B = 2.50$; (b) $\alpha_A = 2.75$, $\alpha_B = 1.10$; (c) $\alpha_A = 2.75$, $\alpha_B = 2.5$; (d) $\alpha_A = 1.21$, $\alpha_B = 1.10$.

than 1), the minimum vapor flow for the RL system is comparable to the minimum vapor flow for the RV system for almost all feed compositions. In such cases, RV can easily be replaced by RL. When the relative volatilities between the two binary pairs *A/B* and *B/C* are similar (ESI close to 1), there is still quite a significant region of feed compositions where the RL system can be used instead of RV without any penalty in energy requirement. For mixtures with the relative volatility between *A* and *B* much lower than the relative volatility between *B* and *C* (ESI much lower than 1), the SL system requires less energy than does RV and, therefore, there is no energy incentive to use either RL or RV.

The minimum vapor flow for the FC system is significantly lower than for RV or SL only when relative volatilities between A/B and B/C are similar and the feed mixture contains comparable amounts of all three components. For all other cases, the minimum vapor flows for RV or SL are comparable to that for FC. When the relative volatilities for A/B and B/C are quite dissimilar, the differences in minimum vapor flows for various thermally coupled schemes are not large.

Notation

a, b, c = coefficients defined by Eq. 8 and Eq. B5
A, B, C = flow rates of components A, B, C in the feed, kmol/s
K = equilibrium coefficient
V = vapor flow rate, kmol/s

Subscripts

P, R = point P, R in Figure 5
I, II, III = section of a given system, Figures 1–5

Superscripts

* = in equilibrium
$^-$ = section of column below the feed

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Appendix: Equations for Minimum Vapor Flow for SL

Minimum vapor flows in the first column of SL are identical to those for RV and can be calculated from Eqs. 1–4.

The minimum vapor flow from the reboiler of the second column of SL is calculated identically as for RV as

$$\bar{V}_{\mathrm{III}} = \max\left\{\bar{V}_{\mathrm{III}}^{\mathrm{lo}}, \bar{V}_{\mathrm{III}}^{\mathrm{up}}\right\} \tag{A1}$$

where $\bar{V}_{\mathrm{III}}^{\mathrm{lo}}$ is the minimum vapor flow assuming that the lower pinch controls (at level 3) and $\bar{V}_{\mathrm{III}}^{\mathrm{up}}$ is the minimum vapor flow when the upper pinch controls (at level 2). The values of minimum vapor flows are calculated from material balances and equilibrium conditions for the particular sections of the columns.

If the lower pinch controls we obtain

$$\bar{V}_{\mathrm{III}}^{\mathrm{lo}} = \frac{(1-\beta)B\alpha_B + C\alpha_C}{\alpha_B - \alpha_C} \tag{A2}$$

If the upper pinch controls

$$\bar{V}_{\mathrm{III}}^{\mathrm{up}} = \frac{A(1-x_A)}{y_A^* - x_A} - \bar{V}_{\mathrm{I}} \tag{A3}$$

where x_A is the mole fraction of component A in the liquid at level 2—Figure 4 (upper feed of the second column) and y_A^* is the mole fraction of component A in the vapor phase in equilibrium with this liquid. These mole fractions can be calculated from material balance of the top section of the first column together with the equilibrium relation, which results in the following quadratic equation

$$a x_A^2 + b x_A + c = 0 \tag{A4}$$

where

$$\begin{aligned} a &= -\left[\bar{V}_{\mathrm{I}} - (A + \beta B)\right](\alpha_A - \alpha_B) \\ c &= -A\alpha_B \\ b &= -a - c + \beta B \alpha_A \end{aligned} \tag{A5}$$

The only feasible root ($0 \le x_A \le 1$) of Eq. A4 is

$$x_A = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \tag{A6}$$

After calculating x_A from Eq. A6, we can determine y_A^* from the equilibrium relation (in the binary mixture AB) and calculate $\bar{V}_{\mathrm{III}}^{\mathrm{up}}$ from Eq. A3.

For very small values of β, that is, for the case where there is no net transfer of component B through the top connections between the prefractionator and the second column, the SL system reduces to a direct split. This can be written symbolically as

$$\text{if} \quad \beta \to 0 \quad \text{then} \quad \mathrm{SL} \to \mathrm{DS} \tag{A7}$$

On the other hand, if all component B is passed from the first to the second column through the top connections, then there is no need for the bottom connection and the SL system of columns reduces to the side stripper configuration.

$$\text{if} \quad \beta \to 1 \quad \text{then} \quad \mathrm{SL} \to \mathrm{SS} \tag{A8}$$

System SV shown in Figure 4b differs from SL (shown in Figure 4a) in that it has a vapor (rather than a liquid) connection BC between the columns, and, therefore, SV can be more difficult to control. If the upper pinch controls, then the expression for the minimum vapor for SV will be identical to that for SL—Eqs. A4–A6, so SV does not offer any energy advantage over SL. If the lower pinch controls, then we obtain for SV the equation analogous to Eq. A2

$$\bar{V}_{\mathrm{III}}^{\mathrm{lo}} = \frac{((1-\beta)B + C)\alpha_C}{\alpha_B - \alpha_C} \tag{A9}$$

and the total vapor flow for SV is

$$V_{\mathrm{SV}} = \frac{((1-\beta)B + C)\alpha_B}{\alpha_B - \alpha_C} + \bar{V}_{\mathrm{I}} \tag{A10}$$

which is greater than the total vapor flow for SL. In this case

$$V_{\mathrm{SL}} = \frac{(1-\beta)B\alpha_B + C\alpha_C}{\alpha_B - \alpha_C} + \bar{V}_{\mathrm{I}} \tag{A11}$$

The difference between total vapor flows when lower pinch controls is

$$V_{\mathrm{SV}} - V_{\mathrm{SL}} = C \tag{A12}$$

We conclude that SV system may be more difficult to control than the SL system and that it does not provide any energy savings. Therefore there is no incentive to use SV instead of SL.

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