More Operable Arrangements of Fully Thermally Coupled Distillation Columns

Rakesh Agrawal and Zbigniew T. Fidkowski
Air Products and Chemicals, Inc., Allentown, PA 18195

Introduction

The fully thermally coupled system of distillation columns (FC system) has been known for several decades (Wright, 1949). Petlyuk et al. (1965) used the following four basic features to define this type of system for separating n-component mixtures.

1. The total number of column sections is equal to $n(n-1)$ instead of $2(n-1)$, as used in conventional schemes.
2. It is sufficient to have only one condenser and one reboiler.
3. The key components in each column are the two components with extreme volatilities.
4. n products of given purities are obtained from the product column.

An FC system for the distillation of three components (also sometimes referred to as the Petlyuk system) is shown in Figure 1. A ternary mixture, ABC, where A is the most volatile component and C is the least volatile component, is separated in the first column (prefractionator) into two binary mixtures: AB in the top, and BC in the bottom. The overhead vapor AB is fed to the upper portion of the product column (level *up* between sections $\underline{3}$ and $\underline{4}$ in Figure 1), and the liquid AB is withdrawn from the same level of the product column and fed to the top of the prefractionator (level t) as reflux. Similarly, the bottom's liquid BC from the first column is fed to the lower portion of the product column (level *lo* between sections $\underline{5}$ and $\underline{6}$), while vapor BC is simultaneously withdrawn from the same level of the product column and introduced in the bottom of the prefractionator (level b) as boilup. These two-way connections eliminate the need for a reboiler or condenser in the prefractionator. As characterized by Petlyuk et al. (1965), the final products A, B, and C are produced from the product column.

It has been proven that this column configuration has the lowest vapor flow necessary for a given separation from all the systems of columns that distill an ideal ternary mixture into pure product streams (Fidkowski and Krolikowski, 1987). It has often been stated that the FC system requires approximately 30% less energy than the corresponding conventional arrangements (Triantafyllou and Smith, 1992; Rudd, 1992). A systematic study of ternary separations by Agrawal and Fidkowski (1998) showed that the total vapor flow in the FC configuration is lower than that of conventional systems (direct and indirect splits arrangements) by 10 to 50%. A distillation column system with low vapor flows requires less energy and has columns with smaller diameters and smaller heat exchangers than conventional systems. Furthermore, the FC system requires only two heat exchangers, whereas other known ternary distillation schemes require three or more. It is clear that both the operating cost and the capital cost of the fully thermally coupled system have the potential to be substantially less than for other known column systems for ternary distillation.

Despite these attractive features, however, the FC system is rarely used in industry. There is only one such known at-

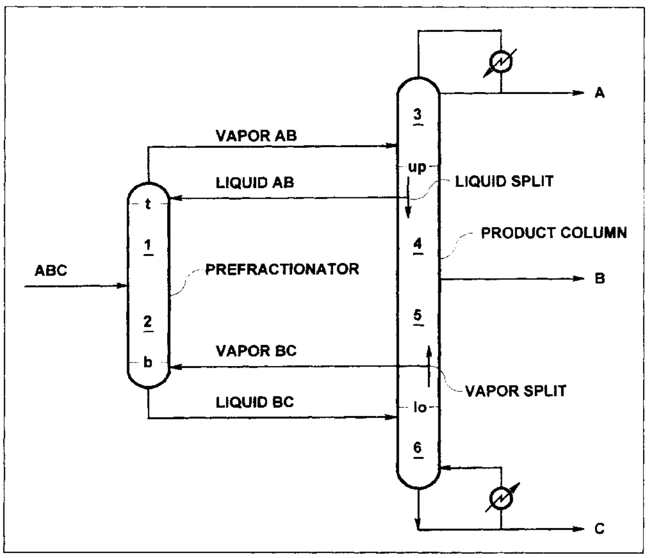

Figure 1. FC system of distillation columns for a ternary mixture.

Correspondence concerning this article should be addressed to R. Agrawal.

tempt to use the arrangement proposed by Wright (Auer et al., 1997). This is rather surprising, since the FC system for ternary separation has been known for nearly 50 years (Wright, 1949).

One reason why the cryogenic gas-separation industry has not embraced this system was given by Agrawal and Fidkowski (1998); this was that thermodynamic efficiency of FC is often worse than in other systems, since the heat has to be supplied at the highest temperature (boiling point of the least volatile product C) and rejected at the lowest temperature (boiling point of component A). However, thermodynamic efficiency is somewhat less important for higher temperature applications. In these applications, unlike in cryogenic distillation, the utilities (in forms of steam and cooling water) may be readily available and an FC system (consuming the smallest amount of these utilities) can be one of the most economical configurations.

However, the primary reason for not using the FC system is because of its complexity and control difficulties. Several studies on the dynamics and control of ternary FC systems (both the dividing-wall column of Wright (1949) and the system shown in Figure 1) are known in the literature (for example, Wolf et al., 1993; Abdul Mutalib and Smith, 1998). A dividing-wall distillation column is topologically equivalent to the FC system of Figure 1, the only difference being that the prefractionator and the product columns are both contained in one shell. There are two manipulated variables that have major impacts on the overall energy consumption for a given separation:

1. The vapor split (between section $\underline{2}$ and section $\underline{5}$) at the lower level (*lo*) of the product column, or the flow rate of the vapor BC to the prefractionator (see Figure 1).
2. The liquid split (between section $\underline{1}$ and section $\underline{4}$) at the upper level (*up*) of the product column, or the flow rate of the liquid AB to the prefractionator.

It is impractical to manipulate the vapor split in a dividing-wall column (Abdul Mutalib and Smith, 1998). Although it is easier to manipulate the liquid split, this variable is usually also left uncontrolled, and the operating values of both splits result from the natural balancing of flow resistances inside the column. Because the operator cannot directly control either of these splits, two very important degrees of freedom are lost. For certain feed compositions and relative volatilities, the optimal operating range of manipulated variables can be quite wide. The FC system is not sensitive to changes within this range of manipulated variables (Fidkowski and Krolikowski, 1986; Christiansen and Skogestad, 1997). This feature was used in the design of the dividing-wall column, where naturally occurring splits of vapor happen to be in the optimal range for these variables. Depending on relative volatilities and feed composition, however, there are many other separation tasks where the optimal operating range of manipulated variables is narrow, requiring precise control of the liquid and vapor splits. Without precise control, the energy required for a given separation might be much higher than the optimum value, so that much of the advantage of the minimum boilup of the FC system would be lost. Even if the design of such a column configuration could ensure operation at the optimal point, a system without these controls would lack operating flexibility.

More Operable Arrangements

The objective of this work is to propose new, modified structures of distillation columns that retain all the advantages of the FC system but are more amenable to control.

Let us analyze in detail the reasons why the control difficulties exist in the FC system. Especially challenging is the control of vapor flows between the columns. Vapor AB flows from the top of the prefractionator (t) to the upper feed level in the product column (*up*). This implies that the pressure in the top of the prefractionator is greater than the pressure in the upper section of the product column. On the other hand, vapor BC has to be transferred from the lower section of the product column (*lo*) to the bottom of prefractionator (b). Therefore, the pressure in the bottom of the prefractionator has to be lower than the pressure in the lower section of the product column. All the pressures (P) have to satisfy the following inequality

$$P_{\text{lo}} > P_b > P_t > P_{\text{up}}. \tag{1}$$

The pressure in the prefractionator is therefore neither uniformly higher nor uniformly lower than the pressure in the product column. The pressure drops in each of the column sections are very important, since

$$P_{\text{lo}} - P_{\text{up}} > P_b - P_t. \tag{2}$$

Careful control of the pressure profiles in the intermediate part of the product column (sections $\underline{4}$ and $\underline{5}$) and in the prefractionator (sections $\underline{1}$ and $\underline{2}$) to satisfy the constraint given by Eq. 1 is crucial for proper operation.

Another way to control the flow of vapor streams between the columns is to use a compressor. This would definitely increase the capital cost of the plant and may still result in control difficulties.

Control of liquid stream AB can be realized with a valve, provided that its off-take from the product column is sufficiently higher than the top of the prefractionator column. Otherwise a pump and control valve can be added to stream AB. It should be noted that any change in the AB liquid split at the upper level of the product column (*up*) will change the pressure drops in sections $\underline{1}$, $\underline{2}$, $\underline{4}$, and $\underline{5}$, thus causing a change in the BC vapor split at the lower level (*lo*).

In summary, the major disadvantage of the current configuration is that the vapor stream has to be transferred back (from the product column to the prefractionator) and forth (prefractionator to product column), which means that neither of the columns has a uniformly lower or higher pressure than the other column. Consequently, small pressure drops in the internal column sections play a very significant role in determining the vapor splits. If the vapor flows were transferred from one column to the other, in one direction only, it would be a simple matter to use the control valves in the vapor line(s) to make the pressure in the source column high enough to ensure stable control.

The unidirectional flow of vapor streams between the columns can be obtained from the FC system of Figure 1 by physically moving section $\underline{6}$, together with its reboiler, from the product column to below section $\underline{2}$ in the prefractionator

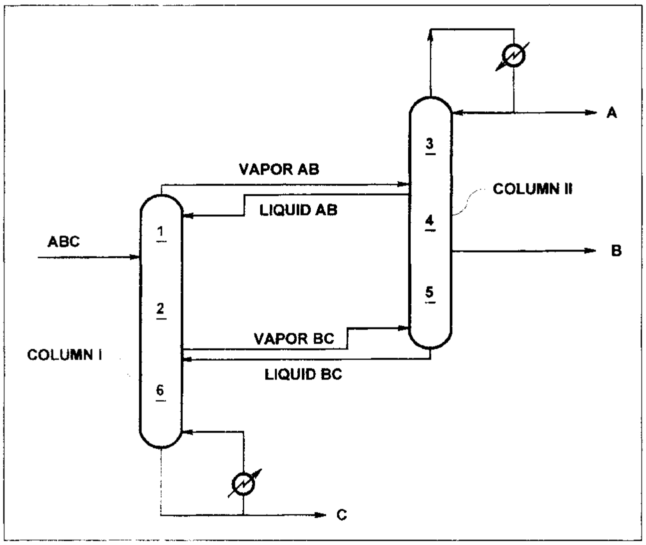

Figure 2. First new arrangement of the FC configuration for a ternary mixture.

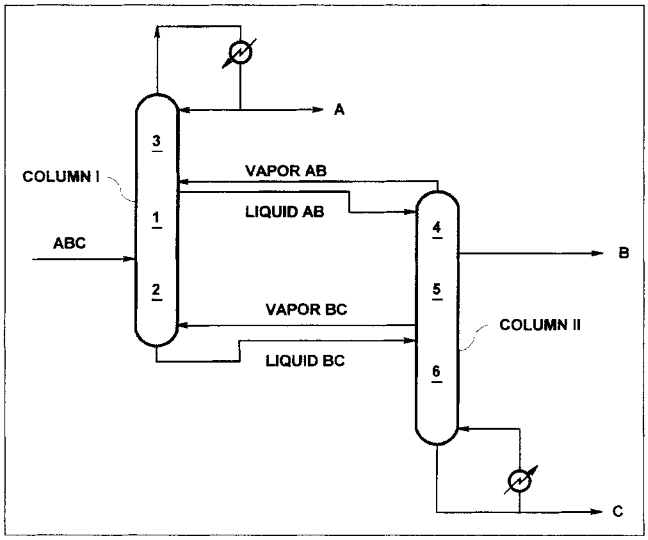

Figure 3. Second new arrangement of the FC configuration for a ternary mixture.

column, as shown in Figure 2. In this configuration, both vapor streams (*AB* and *BC*) are transferred from column I to column II. In order to operate this configuration, it is necessary that for both vapor streams (*AB* and *BC*) the pressure at the withdrawal location in column I be greater than the corresponding pressure at the feed location in column II. Although it is not absolutely essential, for ease of operation, the pressure at any point in the entire first column (column I) can be maintained at a slightly higher pressure than for any point in the second column (column II), that is,

$$P_{\mathrm{I}} > P_{\mathrm{II}}. \tag{3}$$

The internal pressure drops inside the columns are now much less important for their operation, since the pressure in the first column can be made arbitrarily high (obviously within certain limits, since too high a pressure would have an adverse effect on the separation). The ratio of vapor flows can easily be controlled by a control valve installed on either of the vapor lines (*AB* or *BC*). For optimal performance, it is also desirable to control the liquid flows by one of the methods previously mentioned.

Another possible configuration where both interconnecting vapor streams go in the same direction is shown in Figure 3. This configuration was made from the FC system (Figure 1) by physically moving section 3, together with its condenser, to the prefractionator, above section 1. For operation of this configuration, it is necessary that for both vapor streams (*AB* and *BC*), the pressure at the withdrawal location in column II be greater than the corresponding pressure at the feed location in column I. For ease of operation, one may operate this configuration so that the pressure at any point in the entire first column (column I) is slightly lower than the pressure at any point in the second column (column II).

$$P_{\mathrm{I}} < P_{\mathrm{II}}. \tag{4}$$

Notice that in this case, products *B* and *C* are produced from a distillation column that is at slightly higher pressure than the distillation column receiving feed *ABC*. This configuration has the same advantages as the one shown in Figure 2: the pressure drops inside the columns are not important for operability and the unidirectional, interconnecting vapor flows can easily be controlled.

Conclusions

The vapor flows in the new arrangements of the FC system for ternary separation given in Figures 2 and 3 are much easier to control than is the FC system shown in Figure 1. The difficulty of controlling the transfer of vapor streams between the columns at certain rates or proportions has been solved by physically rearranging the distillation sections and either the reboiler or the condenser in the FC system configuration shown in Figure 1. In the new arrangements, the condenser and the reboiler are installed in different columns. This modification results in physically separated distillation columns of different pressures, with the slightly higher pressure column containing the reboiler and the slightly lower pressure column containing the condenser. The flow of interconnecting vapor streams is unidirectional, from the slightly higher pressure column to the slightly lower pressure column.

Since the new arrangements are topologically equivalent to the FC system shown in Figure 1, the benefit of the minimum energy demand (in comparison with other systems) is retained. It is worth noting, however, that neither of the new arrangements meets condition 4 of Petlyuk et al. (1965), that is, all three products are *not* obtained from the same product column.

Although the new arrangements may not look very elegant, because they lack the symmetry of the FC system shown in Figure 1, they are certainly easier to design and operate.

The concept presented in this article can easily be extended to more complicated systems of columns for separating mixtures containing more than three components.

Literature Cited

Abdul Mutalib, M. I., and R. Smith, "Operation and Control of Dividing Wall Distillation Columns," *Trans. Inst. Chem. Eng.*, **76** (Part A), 308 (1998).

Agrawal, R., and Z. T. Fidkowski, "Are Thermally Coupled Distillation Columns Always Thermodynamically More Efficient for Ternary Distillation?" *Ind. Eng. Chem. Res.*, **37**, 3444 (1998).

Auer, H., U. Eiden, G. Schuch, and J. Thiel, "Separation of a Ternary Mixture Containing Salt Using a Dividing Wall Column," AIChE Meeting, Los Angeles (1997).

Christiansen, A. C., and S. Skogestad, "Energy Savings in Complex Distillation Arrangements: Importance of Using the Preferred Separation," AIChE Meeting, Los Angeles (1997).

Fidkowski, Z. T., and L. Krolikowski, "Thermally Coupled System of Distillation Columns: Optimization Procedure," *AIChE J.*, **32**, 537 (1986).

Fidkowski, Z. T., and L. Krolikowski, "Minimum Energy Requirements of Thermally Coupled Distillation Systems," *AIChE J.*, **33**, 654 (1987).

Petlyuk, F. B., V. M. Platonov, and D. M. Slavinskii, "Thermodynamically Optimal Method of Separating Multicomponent Mixtures," *Int. Chem. Eng.*, **5**, 555 (1965).

Rudd, H., "Thermal Coupling for Energy Efficiency," *The Chemical Engineer, Distillation Suppl.*, p. 514 (Aug. 27, 1992).

Triantafyllou, C., and R. Smith, "The Design and Optimisation of Fully Thermally Coupled Distillation Columns," *Trans. Inst. Chem. Eng.*, **70**, 118 (1992).

Wolff, E. A., S. Skogestad, and K. Havre, "Dynamics and Control of Integrated Three-Product (Petlyuk) Distillation Columns," AIChE Meeting, St. Louis, MO (1993).

Wright, R. O., *Fractionation Apparatus*, U.S. Patent No. 2,471,134 (1949).

Manuscript received June 29, 1998.

Correction

In the article titled "Molecular-Thermodynamic Framework for Asphaltene-Oil Equilibria" by J. Wu, J. M. Prausnitz, and A. Firoozabadi (May 1998, p. 1188), the superscript *id* in Eq. 10 should refer to an ideal-gas mixture of asphaltene and resin molecules (not resin segments) at system temperature and concentration; N_i in Eq. 11 should be the number of molecules i, i.e., asphaltene or resin chain.