Thermal Coupling Links to Liquid-Only Transfer Streams: A Path for New Dividing Wall Columns

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We propose new dividing wall columns (DWCs) that are equivalent to the fully thermally coupled (FTC) configurations. While our method can draw such configurations for any given n-component mixture ($n \geq 3$), we discuss in detail the DWCs for ternary and quaternary feed mixtures. A special feature of all the new DWCs is that during operation, they allow independent control of the vapor flow rate in each partitioned zone of the DWC by means that are external to the column. Because of this feature, we believe that the new arrangements presented in this work will enable the FTC configuration to be successfully implemented and optimally operated as a DWC in an industrial setting for any number of components. Also, interesting column arrangements result when a new DWC drawn for an n-component mixture is adapted for the distillation of a mixture containing more than n components. © 2014 American Institute of Chemical Engineers *AIChE J*, 60: 2949–2961, 2014
Keywords: distillation, multicomponent distillation, dividing wall column, thermal coupling, fully thermally coupled column, Petlyuk column, minimum energy, operability

Introduction

Thermal coupling links in distillation are known to reduce the overall costs of a configuration on a plant, owing to simultaneous reduction in capital and operating costs.[1–3] Figure 1 shows the fully thermally coupled (FTC) three-component Petlyuk configuration with thermal coupling links at submixtures AB and BC. In this article, A, B, C, D, and so forth, denote pure components with volatilities decreasing in the same order. Streams in the article are named according to the components they predominantly contain. Submixture BC in Figure 1, for example, is assumed to predominantly contain components B and C. Further, in all the figures of the article, unfilled circles denote reboilers, whereas filled circles denote condensers. Furthermore, we refer to the configuration of Figure 1 in the article as the TC-TC configuration. The first and second "TC" denote the thermal coupling links at submixtures AB and BC, respectively.

Despite its potential to significantly reduce the overall costs, the TC-TC configuration, as sketched in Figure 1, has seen limited industrial application. One reason for this is the operability issue that accompanies this TC-TC configuration. In Figure 1, vapor AB is withdrawn from the top of Column 1, and fed to Column 2. This requires the pressure at the top of Section 1b̲ to be greater than that at the bottom of Section 2a̲ (assuming compressors are not used in the transfer line). Further, vapor BC is withdrawn from the top of Section 2d̲, and fed to the bottom of Column 1. This requires the pressure at the top of Section 2d̲ to be greater than that at the bottom of Section 1c̲. Such conflicting pressure requirements in the two distillation columns bring in operational complications to this TC-TC configuration. To overcome these operability issues, Agrawal and Fidkowski[4] proposed the configurations of Figure 2, which are thermodynamically equivalent to the TC-TC configuration of Figure 1. In the configurations of Figure 2, the pressure in one column can be uniformly maintained greater than the other column, which simplifies some of the major operational complications of the TC-TC configuration.

For further savings in plant space and capital costs, the TC-TC configuration can be incorporated into a single shell, popularly called the DWC, as shown in Figure 3.[5] We will, henceforth, refer to this configuration as the TC-TC column. We have adopted a naming system where TC-TC configuration refers to the two-column configuration shown in Figure 1, and TC-TC column refers to the one column system with a vertical partition as shown in Figure 3. Also, note that, later in the article, we refer to the skeleton partitioning arrangement/structure of Figure 3 by the same name (TC-TC column), even when it is used for separating four or higher component feeds. In the case of multicomponent separations using TC-TC column, the submixtures transferred at the thermal couplings will differ from what is shown in Figure 3. Further, for convenience, the different

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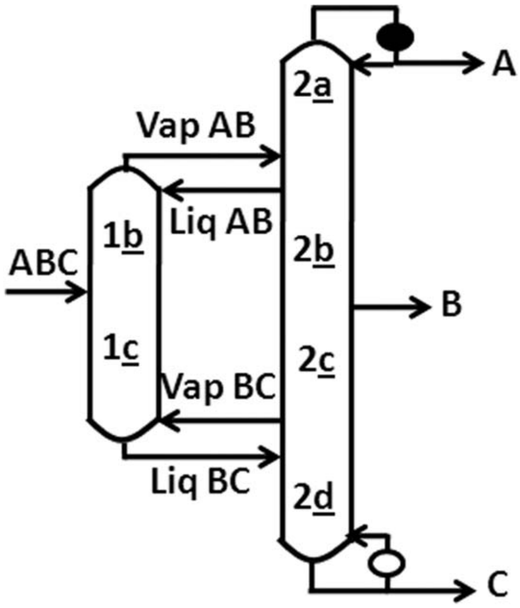

Figure 1. Three-component FTC Petlyuk configuration: the TC-TC configuration.

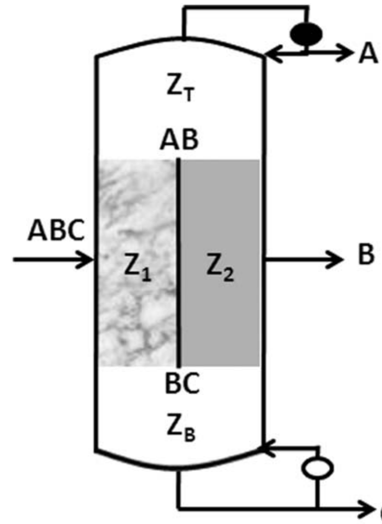

Figure 3. DWC version of the TC-TC configuration: TC-TC column.

parts of DWCs in the article are shaded and named distinctly to represent different zones. For example, the TC-TC column of Figure 3 is divided into four zones, namely Z_T, Z_1, Z_2, and Z_B.

Although the TC-TC column was introduced by Wright[5] as early as 1949, the first industrial application of this column did not happen until the late 1980s.[6] Since then, the use of multicomponent DWCs has seen a rapid increase in several industrial applications.[7,8] Updates on the recent developments in DWCs can be found in the works of Asprion and Kaibel,[9] Dejanovic et al.,[10] and Yildirim et al.[8]

Though the TC-TC column of Figure 3 offers ample opportunity to reduce overall costs, it suffers from somewhat similar operability issues (related to pressure) as the TC-TC configuration of Figure 1. The pressure drop in the TC-TC column is an important consideration for its onsite operation.[11] In the TC-TC column, the pressure drop in the two parallel Zones, Z_1 and Z_2, on either side of the vertical partition, are constrained to be equal. Subject to this constraint and the mechanical resistances in the Z_1 and Z_2 Zones, there is a natural uncontrolled split of the vapor ascending from the Zone Z_B into the Zones Z_1 and Z_2. This uncontrolled split implies that the relative vapor flow rates in Zones Z_1 and Z_2 cannot be manipulated during operation. Though methods to address the control of the vapor split issue during the design and dimensioning phase of the TC-TC column have been proposed,[12,13] none exists for application during online operation that we are aware of, except for an experimental study which uses valves for this vapor split control in an experimental distillation setup that is thermodynamically equivalent to a DWC.[14] This vapor split can significantly affect the product purities, total annualized costs, and has implications on how far the TC-TC column is away from its optimal operation.[2,15,16] Though the liquid split at the top of the vertical partition also can have similar effects, it is generally well controlled during operation, using collectors and distributors. Further, the operable versions of the TC-TC configuration shown in Figure 2 also simplify to the same DWC arrangement of Figure 3. Hence, the operational advantages in the configurations of Figure 2 over the TC-TC configuration are not translated to their dividing wall versions.

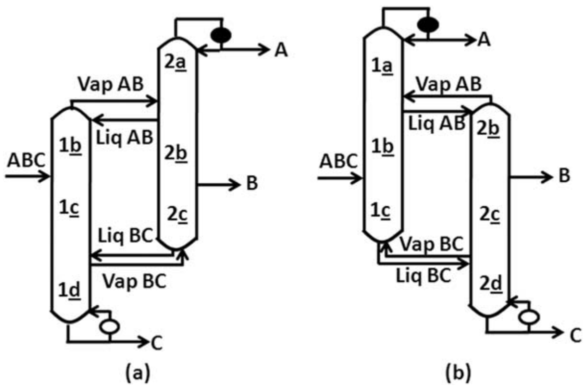

Figure 2. Operable versions of the TC-TC configuration.

In this article, we present new DWCs that are not only more operable than the TC-TC column for a three-component feed mixture but also enable operable versions for the feed mixtures containing higher number of components. Further, through modeling, we show that all the new DWCs are equivalent to the TC-TC column (or configuration). Finally, we make some interesting observations when a DWC designed for an *n*-component feed is used to distill a feed mixture containing more than *n* components. We first show how a thermal coupling link can always be converted to an equivalent liquid-only transfer stream and then such configurations can be easily used to generate new DWCs.

Conversion of Thermal Coupling to Liquid-Only Transfer Stream

Distillation configurations with liquid transfers between distillation columns are easier to operate and control than configurations with vapor transfers between distillation columns. Based on this fact, for the distillation of a ternary mixture, Agrawal[17] proposed the three configurations of

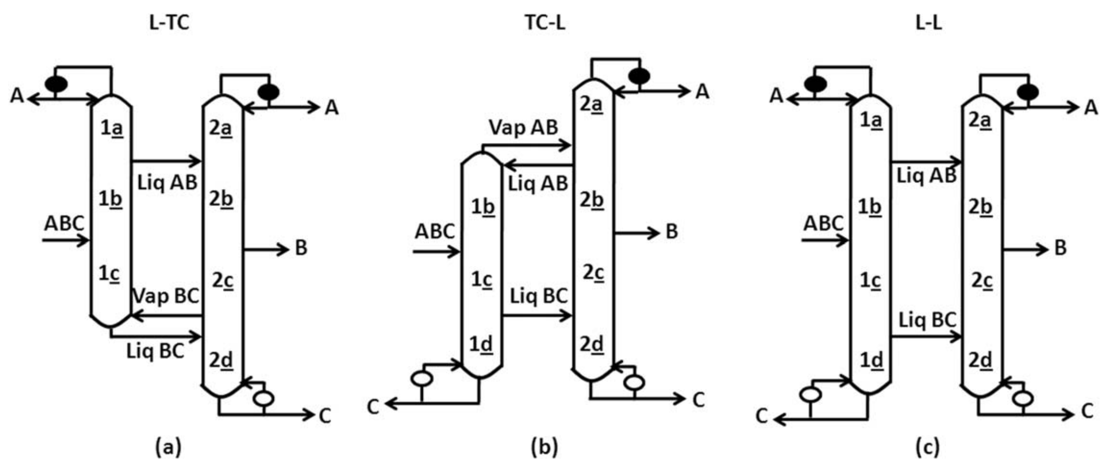

Figure 4. Configurations with reduced number of vapor transfers proposed by Agrawal[17] (a) L-TC configuration; (b) TC-L configuration; and (c) L-L configuration.

Figure 4, which are more operable than the TC-TC configuration of Figure 1. To obtain the configurations in Figure 4 from that in Figure 1, the thermal coupling links at submixture AB or/and CD have been converted to liquid-only transfer streams with the addition of new Sections 1a̲ or/and 1d̲. We refer to the configurations of Figures 4a–c, respectively, as the L-TC, TC-L, and L-L configurations. For example, the L-TC configuration is named so because of the liquid transfer at submixture AB and thermal coupling link at submixture BC.

Based on physical reasoning, Agrawal[17] proposed that the configurations of Figure 4 have the same overall minimum vapor requirement as the TC-TC configuration, and hence, are equivalent to the TC-TC configuration. Here, we show this mathematically by proving that whenever a thermal coupling link in a configuration (e.g., TC-TC configuration) is replaced with a liquid-only transfer stream (e.g., L-TC, TC-L, or L-L configuration), the resulting configuration is always equivalent to the original configuration with the thermal coupling link. To show this proof, we use the arrangements shown in Figure 5. The thermal coupling at the top of Section S2 in Figure 5a is converted to a liquid-only transfer stream in Figure 5b with the addition of a new Section S1. The notation for the symbols used in the figure is provided at the top of the figure. The lettered quantities shown along any section in the figure indicate the respective liquid and vapor flows in the section, after accounting for the relevant mass balances. While the quantities shown adjacent to the left of each section in the figure denote the respective vapor flows, the quantities shown adjacent to the right denote the respective liquid flows in the section. The liquid and vapor flows in Section S2 as well as in Section S4 of both the Figures 5a and b are retained to be the same. Further

$$\frac{L}{V}\text{ ratio in Section S3 of Figure 5a} = \frac{L_{S3}}{L_{S3}+M_{S3}} \qquad (1)$$

In Figure 5b, to constrain that Section S1 be equivalent to Section S3, the number of stages and the L/V ratios in the two sections must be equal. To achieve the equality in L/V

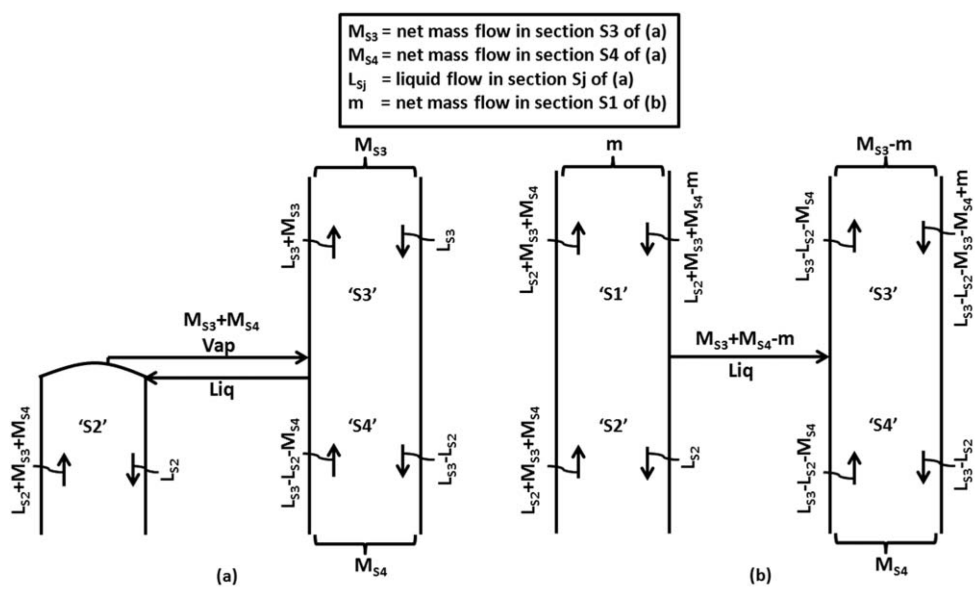

Figure 5. (a) Any thermally coupled arrangement; (b) thermally coupled arrangement of (a) replaced with a liquid-only transfer stream and a new Section S1.

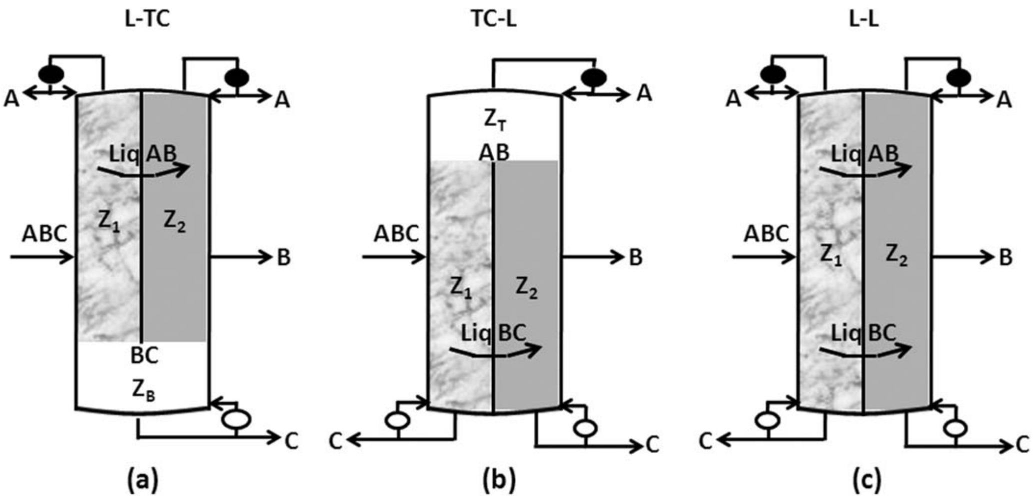

Figure 6. New more operable DWCs derived from Figure 4 (a) L-TC column; (b) TC-L column; and (c) L-L column.

ratios, one degree of freedom is available in the form of the variable "m," the net mass flow in Section S1. Determining the value of "m" that ensures this constraint

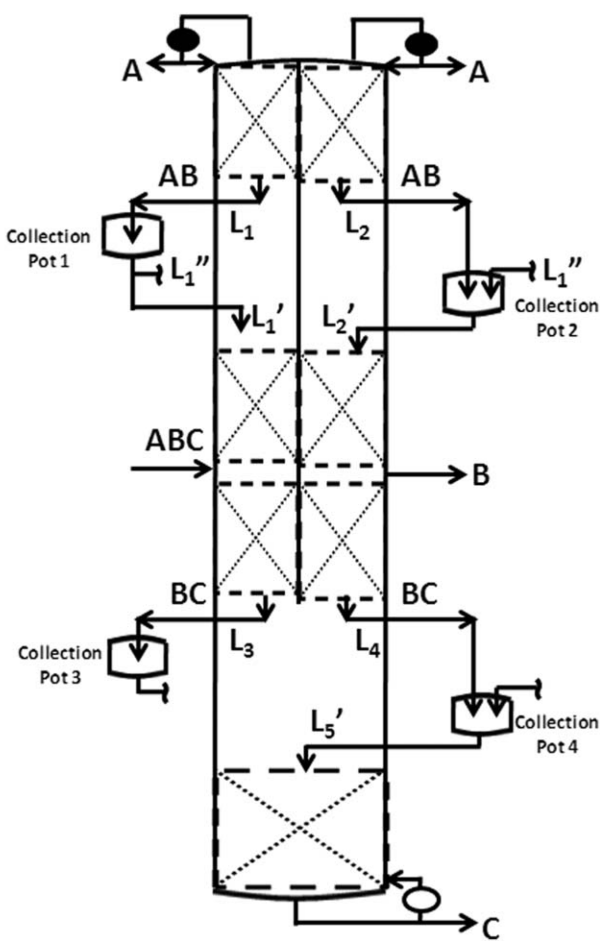

Figure 7. An example depiction of liquid transfers in the L-TC column; some of the collection pots shown, in certain cases, could be eliminated or combined into one pot.

$\frac{L}{V}$ ratio in Section S1 of Figure 5b $= \frac{L}{V}$ ratio in Section S3 of Figure 5b

$$\Rightarrow \frac{L_{S2}+M_{S3}+M_{S4}-m}{L_{S2}+M_{S3}+M_{S4}} = \frac{L_{S3}-L_{S2}-M_{S3}-M_{S4}+m}{L_{S3}-L_{S2}-M_{S4}}$$

$$\Rightarrow m = \frac{M_{S3}(L_{S2}+M_{S3}+M_{S4})}{L_{S3}+M_{S3}} \quad (2)$$

We now substitute "m" to determine the mass flow in the liquid transfer from the first column to the second, and the L/V ratio in Sections S1 and S3 of Figure 5b. It follows that

$$\text{Mass flow in liquid transfer} = M_{S3}+M_{S4}-m = \frac{M_{S4}L_{S3}+M_{S3}(L_{S3}-L_{S2})}{L_{S3}+M_{S3}} \quad (3)$$

which is clearly non-negative because $L_{S3} \geq L_{S2}$. Therefore, the liquid transfer is guaranteed to be in the direction shown in Figure 5b. Further

$$\frac{L}{V} \text{ ratio in Sections S1 and S3 of Figure 5b} = \frac{L_{S3}}{L_{S3}+M_{S3}} \quad (4)$$

which, interestingly from Eq. 1, is the same L/V ratio in Section S3 of Figure 5a. This means that, for the value of "m" given by Eq. 2, the two Sections S1 and S3 in Figure 5b are equivalent to the Section S3 in Figure 5a. The above discussion implies that the mass M_{S3} that is distilled in one Section S3 of Figure 5a is divided between similar, two Sections, S1 and S3, in Figure 5b, which, respectively, distill a mass of "m" and "M_{S3}-m" of the same composition. So, any liquid-vapor traffic in the thermally coupled arrangement of Figure 5a can be identically duplicated in the liquid-only transfer arrangement of Figure 5b. Thus, the two arrangements in Figure 5 are only topologically different, but equivalent in all other aspects, irrespective of the number of components or vapor-liquid equilibrium associated with the distillation sections. A similar proof can be easily derived when a thermal coupling at the bottom of a column is converted to a liquid-only transfer stream.

New, More Operable Three-Component DWCs

We present the new, more operable DWC versions of the L-TC, TC-L, and L-L configurations: the L-TC, TC-L, and

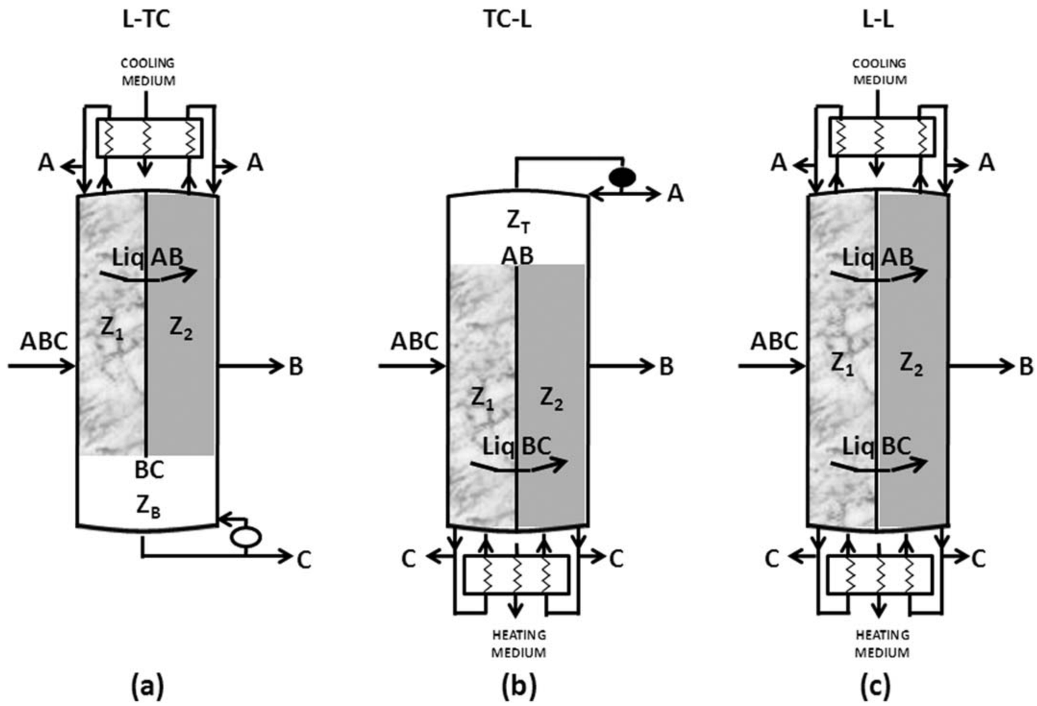

Figure 8. Arrangement of the (a) L-TC; (b) TC-L; and (c) L-L columns with one reboiler and condenser.

L-L columns in Figure 6. Note that the same names will be used later when the same structures are used for higher component separations. A distinct feature of all the DWCs of Figure 6 is that the liquid transfers associated with the submixtures AB and BC that are explicitly shown, are made around (or across) the vertical partition. This is achieved by collecting the liquid of desired quantity from an intermediate location of one zone (Z_1), and then feeding it to an intermediate location of the other zone (Z_2), on the other side of the vertical partition. An example of such a liquid transfer is shown for the L-TC column in Figure 7. The liquid flows can be managed either through a gravitational head or by the use of pumps. Valves in the liquid lines (not shown in the figure) could be used to manipulate the liquid split from collection pot 1. There is no vapor exchange between the intermediate locations of the two parallel zones. Thus, the vertical partitions are continuous. Such a construction in all the new DWCs eliminates the constraint that the pressure drop in the two parallel zones, on either side of the vertical partition, be equal. This feature of the new DWCs, as will be seen, makes them more operable than the conventional TC-TC column.

The L-TC column in Figure 6a, like the TC-TC column in Figure 3, has one vapor split at the bottom of the vertical partition. However, the two condensers at A in the L-TC column can be manipulated to create the desired pressure drop in Zones Z_1 and/or Z_2. This can be achieved by either placing a valve in the piping before the condenser, or, by controlling the inlet temperature of the cooling medium within each of the condensing heat exchangers.[18] Alternatively, the heat exchanger may be designed to be a submersible heat exchanger, whereby, submergence of the passage for the condensing fluid can be controlled to tailor the active area through which most of the heat transfer takes place. This will control the condensing temperature, and hence the pressure of the condensing fluid. The control of the pressure at the top of either of the Zones Z_1 or Z_2 will tailor the pressure drop across that zone, and hence the vapor flow rate through that zone. Thus, the L-TC column offers a control mechanism for the vapor split at the bottom of the vertical partition that is external to the column.

Interestingly, the TC-L and L-L columns have no vapor splits. The two reboilers at C can be used to operate each section in the two parallel zones, on either side of the vertical partition, at the desired *L*/*V* ratios. It is worth noting that, in the case of the L-L column, the two parallel zones can be operated like two independent distillation columns, which may give the configuration more flexibility and freedom to operate.

The L-TC and TC-L columns use one more heat exchanger, and the L-L column uses two more than the TC-TC column. Arrangements can be made to each DWC of Figure 6 to reduce the total number of heat exchangers to two. One possible arrangement of the L-TC, TC-L, and L-L columns using one reboiler and one condenser is shown in Figure 8. In the L-TC column of Figure 8a, cooling utility of sufficiently low temperature is used as a common condensing medium to simultaneously condense A vapor streams collected from both the parallel Zones, Z_1 and Z_2. To achieve this, the heat exchanger has two separate passages for the vapor collected from the two zones. To control the vapor flow rates in the two parallel zones, the condenser heat exchanger may be designed so that the condensing fluid in each of the passages can achieve its own desired approach temperature to the cooling medium temperature. This can be implemented in several possible ways. Each passage can be designed with a different active surface area to tailor the approach temperature. Alternatively, the passage for the cooling medium can also be divided into two. The flow rate and inlet temperature of the cooling medium for each of the passages may be independently controlled to allow for differences in the temperature of the condensing fluids.

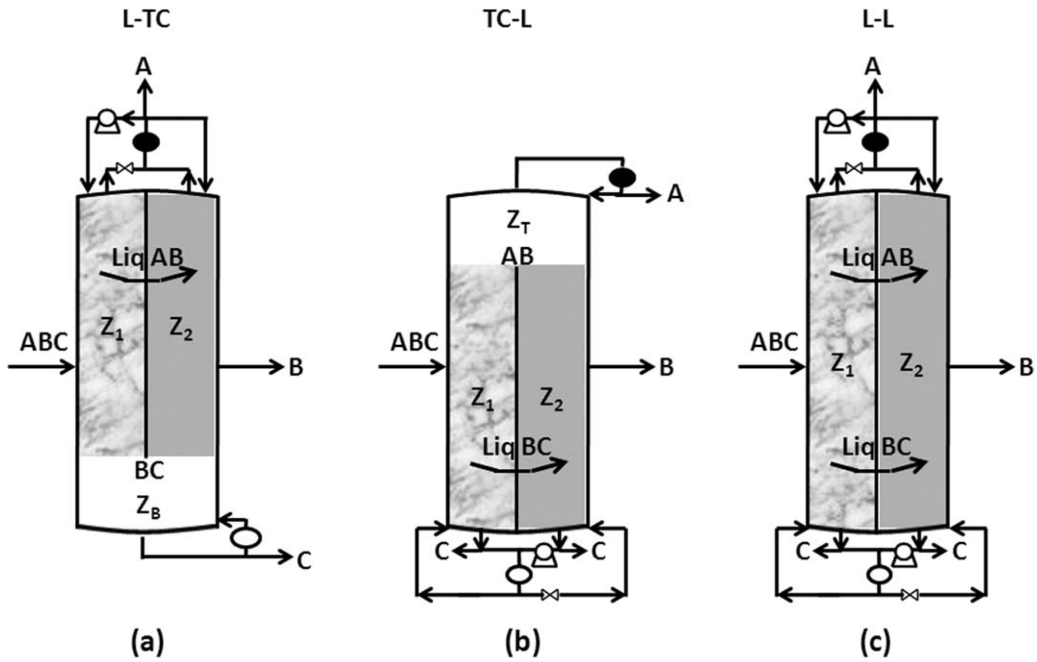

Figure 9. An alternate arrangement of the (a) L-TC; (b) TC-L; and (c) L-L columns with one reboiler and condenser, which uses pumps and throttling valves.

Likewise, in the TC-L column of Figure 8b, C liquid streams collected from the two parallel Zones, Z_1 and Z_2, are fed to two separate passages in the reboiler. A common heating medium of sufficiently high temperature is used to simultaneously vaporize the liquids in the two passages. Similar to the condenser heat exchanger for L-TC column, the vapor boilup rate in each of the passages of the reboiler can be controlled to provide the desired split of vapor flow between Zones Z_1 and Z_2. In the L-L column of Figure 8c, the condenser and reboiler arrangements of Figures 8a and b respectively, are used together.

Figure 9 shows an alternate arrangement for the L-TC, TC-L, and L-L columns with one reboiler and condenser. In the L-TC column of Figure 9a, a throttling valve is provided in the vapor line leaving Zone Z_1 (assuming that the top of Zone Z_1 is at a higher pressure than the top of Zone Z_2) to reduce the pressure of the vapor to that leaving Zone Z_2. The combined vapor is condensed in a single heat exchanger. A part of the condensed pure liquid A is withdrawn as product, whereas the rest is used as reflux to the two zones. The reflux to Zone Z_1 is pumped. Alternatively, the condenser heat exchanger could be located at such a height that liquid reflux to Zone Z_1 could be fed under gravitational head, and if needed, a valve may be used in the liquid feed line to Zone Z_2 to reduce the pressure build-up. In the TC-L column of Figure 9b, a pump is provided in the liquid line leaving Zone Z_2 (assuming that the bottom of Zone Z_2 is at a lower pressure than the bottom of Zone Z_1) to increase the pressure of the liquid to that leaving Zone Z_1. The combined liquid is boiled in the reboiler and used for boilup to the two zones. A throttling valve is used in the vapor line entering Zone Z_2 for reducing the pressure. Alternatively, the bottom of the column with respect to the reboiler inlet could be located at such a height so as to allow liquid drain from Zone Z_2 via gravitational head without the use of a pump. In this case, pressure of the liquid from the bottom of Zone Z_1 to the mixing point is appropriately manipulated. The L-L column of Figure 9c uses the condenser and reboiler arrangements of Figures 9a and b, respectively. In Figure 9, for the purpose of illustration, the throttling valves and pumps are shown before/after streams that enter/leave one of the two parallel zones. In general, depending on the pressure in the two parallel zones of the DWC, the pump and the throttling valves may be switched between either zones; or additional valves or pumps may be used in additional lines to manipulate pressure drops in various lines external to the column.

With the TC-TC, L-TC, TC-L, and L-L columns being equivalent to each other, we also expect the height of these columns for any given application to be not significantly different from each other. The additional capital cost in the new DWCs of Figure 6 (or 8 or 9 or their variants) is, therefore, expected to be only due to the use of additional heat exchangers/pumps/valves and a longer vertical partition. The additional equipments account for better operability in the new DWCs.

Operational Flexibility of the L-TC, TC-L, and L-L Columns

For the TC-TC configuration of Figure 1, Fidkowski and Krolikowski[2] identified, for ideal saturated liquid feed mixtures, under constant molar overflow conditions, a range of vapor splits from Section $2\underline{d}$ to Sections $1\underline{c}$ and $2\underline{c}$, over which the total minimum vapor requirement of the configuration remains optimal. As the TC-TC column in Figure 3 is equivalent to the TC-TC configuration, a wide window of optimal vapor splits can be useful for the operation of the TC-TC column. For example, in the TC-TC column of Figure 3, if there is a wide range of vapor flow from Zone Z_B to Zone Z_1 (and consequently Z_2) that allows for optimal operation, then there is more leeway/flexibility in the vapor

Table 1. List of Representative Ternary Feed Compositions used for Simulation Results in Table 2

Feed Composition (f)	A	B	C
abC	0.1	0.1	0.8
aBc	0.1	0.8	0.1
Abc	0.8	0.1	0.1
ABC	0.33	0.33	0.34
ABc	0.45	0.45	0.1
AbC	0.45	0.1	0.45
aBC	0.1	0.45	0.45

"Abc," for example, implies large quantities of A and small quantities of B and C.

Table 2. Optimal Vapor Flow rate Range for Section 1c̲ in the TC-TC, L-TC, TC-L, and L-L Configurations, as Percent of the Total Minimum Vapor Requirement

$[\alpha_{AB},\alpha_{BC}]$	f	$\Delta V/V_{min}$ (%)
[2.5,2.5]	abC	46.9
	aBc	38.1
	Abc	16.3
	ABC	20.4
	ABc	14.8
	AbC	0.9
	aBC	40.6
[1.1,1.1]	abC	36
	aBc	4.2
	Abc	32.4
	ABC	2.6
	ABc	9.3
	AbC	0.2
	aBC	15.4

Description of feed composition f (abC, aBc, etc.) is provided in Table 1.

split at the bottom of the vertical partition for close to optimal operation, and vice versa.

Fidkowski and Krolikowski[2] studied the optimal operation range of the TC-TC configuration for the first four ternary feed compositions listed in Table 1. To span the spectrum of possible representative compositions for ternary feeds, we extend our study to include three more feed compositions, added at the bottom of Table 1. Their[2] optimization model is solved using Branch-And-Reduce Optimization Navigator (BARON)[19] within General Algebraic Modeling System (GAMS)[20] with a tolerance of 0.001. The BARON solver ensures global optimality of the obtained solutions. The results for all the feed compositions, and two sets of relative volatilities are shown in Table 2. Table 2 lists the optimal range of vapor flow in Section 1c̲ for the TC-TC configuration, as percent of its total minimum vapor requirement. Thus, for the TC-TC configuration in Figure 1, for a given feed, if the calculated range for the vapor flow rate in Section 1c̲ is from V_1 to V_2 over which the total minimum vapor flow rate remains at V_{min}, then $\Delta V = V_2 - V_1$, and the value $100 \times \Delta V/V_{min}$ is listed in Table 2. As the vapor and liquid traffic in Section 1c̲ of the TC-TC configuration can be identically retained in the same section of the L-TC, TC-L, and L-L configurations without raising the overall heat duty, these configurations also have the same optimal range of vapor flow in this section as the TC-TC configuration. Thus, the results in Table 2 also apply to the L-TC, TC-L, and L-L configurations.

From Table 2, we note that there are a number of feed conditions, especially when the relative volatilities are low, where the split of the vapor between two Zones Z_1 and Z_2 in Figures 3 and 6 must be controlled within a narrow range for avoiding the suboptimal operation. For example, for case AbC with both the relative volatility sets, and cases aBc and ABC with $[\alpha_{AB},\alpha_{BC}] = [1.1,1.1]$, the allowed variations in the optimal vapor flow rate for Section 1c̲ are substantially small. For these cases, the vapor split across Zones Z_1 and Z_2 must be controlled carefully. Otherwise, the heat duty will increase. The greatest advantage of the new L-TC,

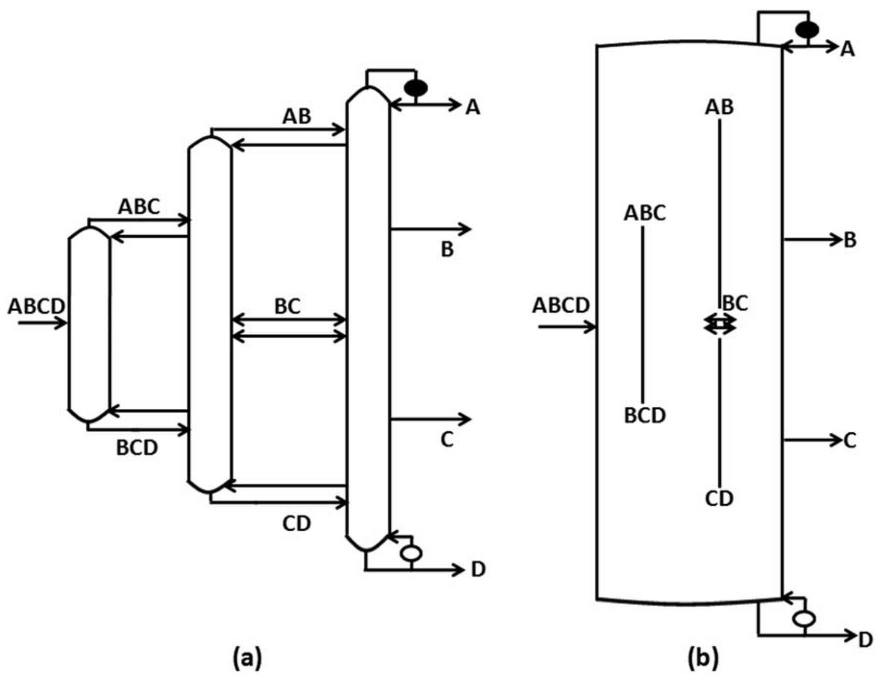

Figure 10. (a) Four-component FTC configuration; (b) dividing wall version of the configuration in (a).

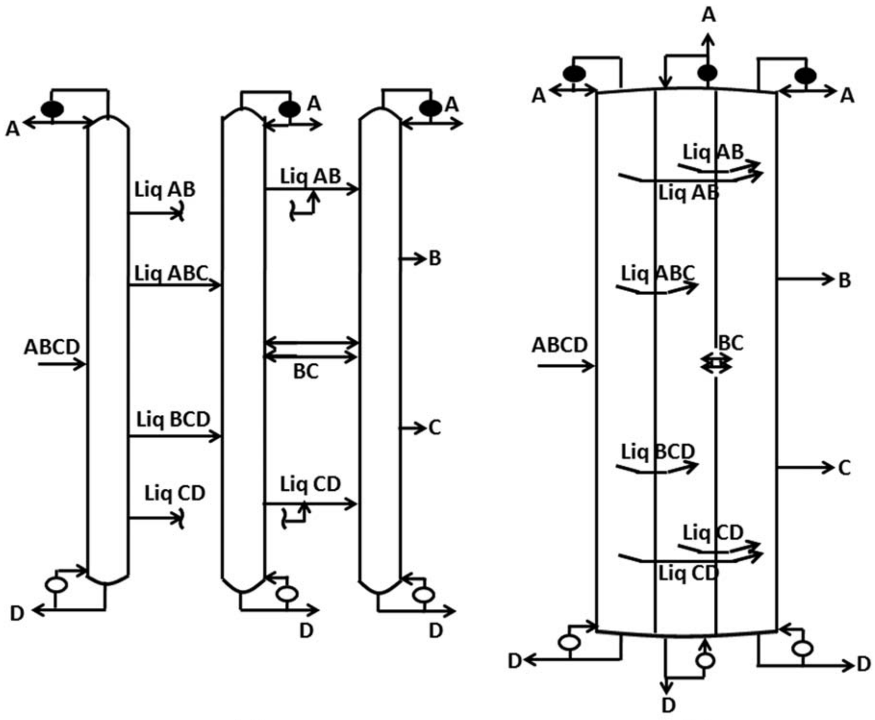

Figure 11. (a) A configuration equivalent to the FTC configuration of Figure 10a[17] and (b) DWC version of the configuration in (a).

TC-L, and L-L columns is that it allows for such tight control of vapor flow on each side of the vertical partition. This preserves the lower heat duty requirement, and ensures the purity of the intermediate product B.

There is yet another flexibility of the L-TC, TC-L, and L-L columns of Figure 6, which is missing from the TC-TC column of Figure 3. Once physically built, they also allow operation in the side rectifier and side stripper modes. For example, in the L-L column, if no liquid BC is transferred across the vertical partition, with only the liquid AB transfer, the column could produce B from the bottom of Zone Z_2. In this case, no B may be produced from an intermediate location of Zone Z_2. This will be analogous to the operation of a side stripper. In an alternate case, where liquid BC is transferred but no liquid AB is transferred, B could be produced from the top of Zone Z_2 of the L-L column, leading to the operation similar to a side rectifier. Thus, a L-L column, once built, can be operated as a FTC column/side rectifier/side stripper. Similarly, without any liquid transfer across the vertical partition, L-TC and TC-L columns could be operated in the side rectifier and side stripper modes, respectively. This added flexibility can be quite advantageous, as, for certain feed conditions, a side rectifier or a side stripper may be thermodynamically more efficient than the FTC TC-TC

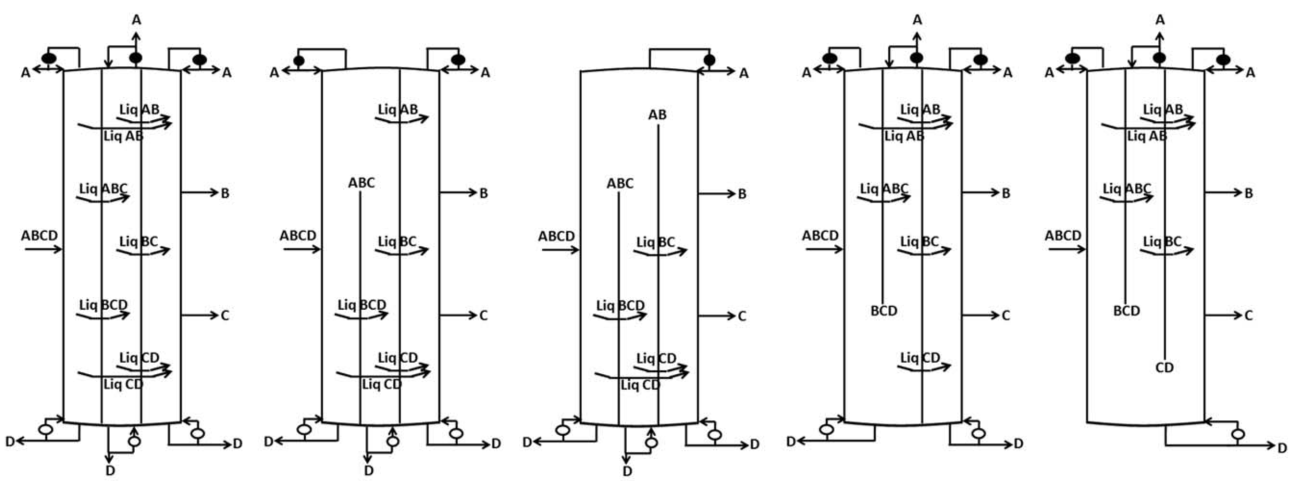

Figure 12. (a) Simplified four-component DWC with only liquid splits; (b–e) dividing wall variants of Figure (a), with thermal couplings at submixture(s) (b) ABC; (c) ABC and AB; (d) BCD; (e) BCD and CD.

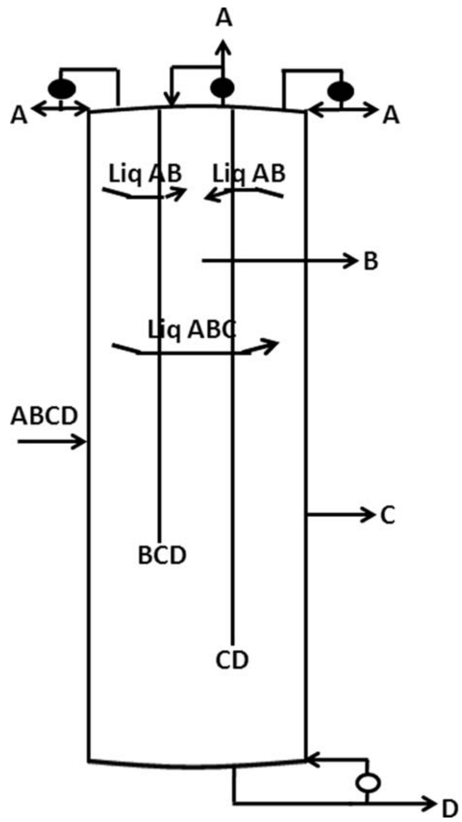

Figure 13. More operable DWC derived from the four-component satellite column.[23]

configuration.[21] Conversely, a DWC already built on a plant to operate in the side rectifier/side stripper mode can be suitably modified to operate as a L-TC/TC-L column, respectively.

New *n*-Component DWCs

Generally, the overall cost saving from DWCs significantly increases with the number of components in the feed. In this section, we demonstrate that our method, by providing new operable DWCs, enables the use of DWCs for the distillation of feeds containing more than three components. We illustrate the method by drawing new, more operable, standalone DWCs that separate a four-component feed into four pure products. The focus here will be on the DWCs derived from the FTC configuration, although when needed, DWCs for partially thermally coupled configurations could also be drawn through the method described here. Following the same principles, similar DWCs for higher number of components can be drawn.

The FTC four-component configuration and its dividing wall derivative are shown in Figures 10a and b, respectively. The DWC in Figure 10b has still not found industrial application.[10] A major factor which has impeded its industrial implementation is that it has three vapor splits, one at the bottom of each vertical partition, which cannot be independently controlled during operation by external means. Thus, industrial application of this DWC comes with the potential danger of operation far away from optimality, resulting in a significant reduction in benefits that could be reaped from this configuration.

The FTC equivalent three-column configuration, shown in Figure 11a, with all liquid transfers and only one vapor transfer between distillation columns, was suggested by Agrawal.[17] A dividing wall version of this configuration is shown in Figure 11b. The DWC has only one vapor split at the intermediate location of submixture BC, which can be controlled by the condensers and reboilers (or valves) at A and D, respectively, as discussed earlier for the ternary feeds. A simplified version of the DWC in Figure 11b is shown in Figure 12a, with three parallel zones and only liquid splits. The DWC in Figure 12a differs from that in Figure 11b only due to the mode of transfer of submixture BC. For most applications, we expect the minimum energy requirement of the DWC in Figure 12a to be comparable to that in Figure 11b. Each zone in Figure 12a may be operated akin to a separate distillation column.

Many variants of the DWC of Figure 12a (or 11b) can be drawn by introducing thermal coupling links at different submixtures.[22] Four other such more operable variants are shown in Figures 12b–e. While the DWCs of Figures 12b and c have no vapor splits, the DWCs of Figures 12d and e, respectively, have one and two. The vapor splits in the Figures 12d and e can be controlled by the condensers at A. We believe that the more operable four-component DWCs presented in this work will enable the industrial implementation and optimal operation of the FTC configuration as a DWC.

While we have shown the more operable DWCs derived from the FTC configuration, other such more operable DWCs derived from the various well-known four-component configurations can be drawn, which may offer other benefits. An example DWC, similar in skeleton structure to the one in Figure 12e, but equivalent to the four-component satellite column[23] is shown in Figure 13. A feature of this DWC, that is absent in the rest of the DWCs presented so far, is that the intermediate volatility products B and C are produced from the intermediate locations of two different partitioned zones.

In this work, we focused on the new, more operable DWCs derived primarily from the FTC multicomponent configurations. However, using the concept proposed by Agrawal,[17] any thermal coupling link can be converted to a liquid-only transfer. Such a liquid transfer can be incorporated in a DWC as explained in this article. Our proposed method can also be easily applied to feeds containing more than four components. As shown earlier for three-component DWCs in Figures 8 and 9, the total number of condenser and reboiler heat exchangers in the new DWCs can be reduced.

Application of the New *n*-Component Dividing Wall Structures to Feeds with More Than *n* Components

Our new *n*-component skeleton dividing wall structures presented earlier can be easily adapted to separate a multicomponent feed containing more than *n* components. In such cases, product streams enriched in different components will be produced. However, the possible product streams and the number of operating modes increase rapidly with the number of components in the feed. Any of these operating modes can be included within a larger flow sheet that separates multicomponent mixtures into component product streams. We will first illustrate the adaptation of the various operating modes of the L-TC, TC-L, and L-L columns, originally drawn for the distillation of a ternary feed, to a quaternary feed mixture, ABCD. Then, as a generalization of our

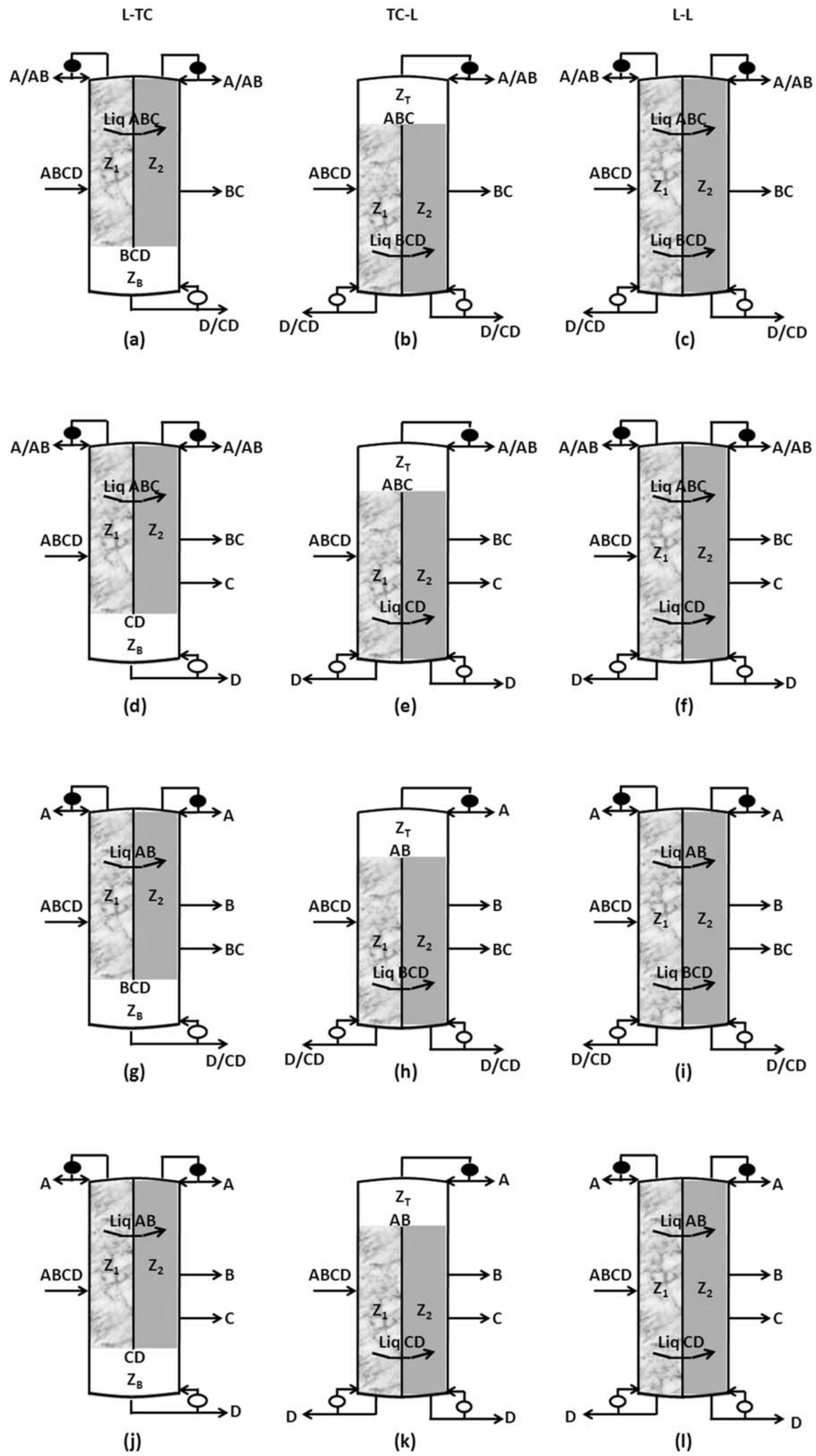

Figure 14. Separation of a four-component feed using the L-TC, TC-L, and L-L column structures; the notation such as A/AB means that one has a choice to produce either pure A as in a sharp separation or a mixture AB as in a nonsharp separation.

approach, we will distill a quinary mixture using one of our quaternary skeleton dividing wall structures.

The L-TC, TC-L, and L-L columns have two submixture transfers from intermediate locations, one above the feed and the other below the feed (AB and BC in the earlier studied three-component case). When a quaternary feed mixture ABCD is distilled in these columns, there are two possible submixtures, ABC or AB, which could be transferred from an intermediate location above the feed. Similarly, from an intermediate location below the feed, the two possible

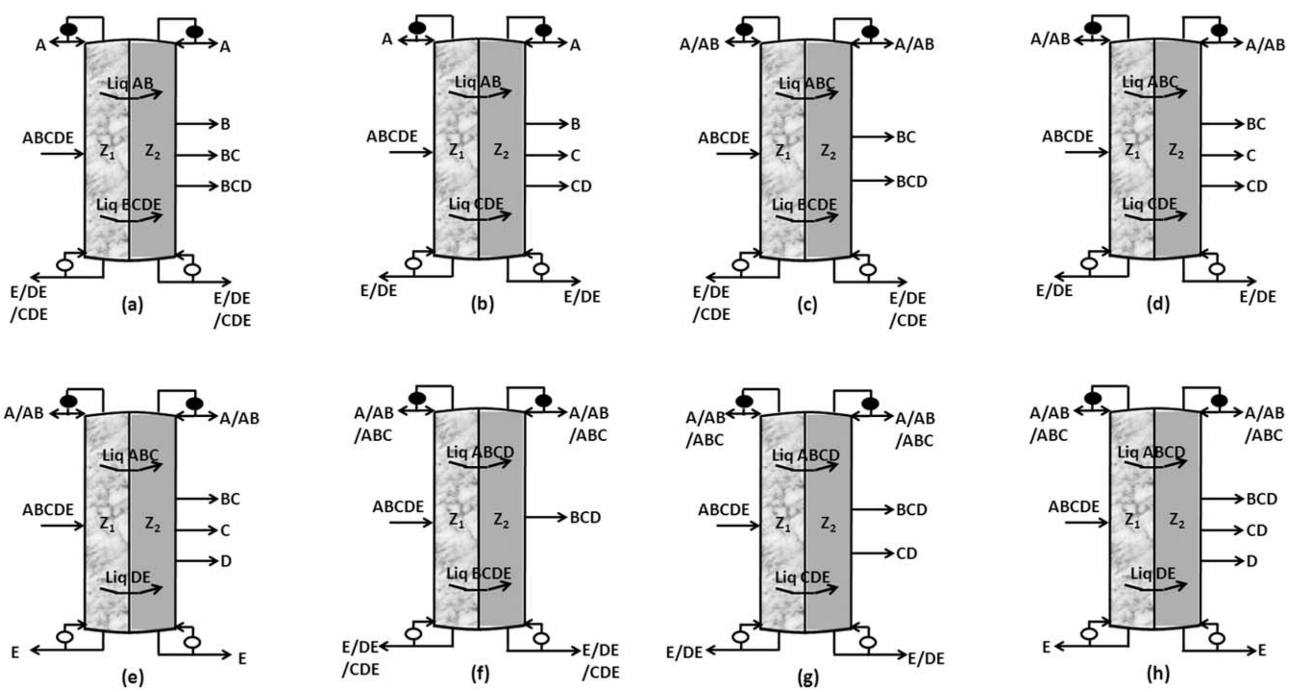

Figure 15. Separation of a five-component feed using the L-L column structure.

submixture transfers are BCD or BC. This implies that, for each of the three vertical partitioned columns shown in Figure 6, we have four possible combinations of the two submixtures. Figure 14 shows these combinations.

Some interesting observations can be made from Figure 14. . When compared to the TC-TC column for separating ABCD (not shown), the L-TC, TC-L, and L-L columns of Figure 14, apart from better vapor split control, offer an additional flexibility to produce two different products from the top or/and bottom of the column. For example, in the L-TC and L-L columns of Figures 14a and c, stream A can be produced as a product from the top of one zone, whereas stream AB may be produced as a product from the top of the other. Similarly, in TC-L and L-L columns of Figures 14b and c, one has an option to produce stream D from the bottom of one zone, and CD from the bottom of the other zone. Furthermore, in some of the DWCs of Figure 14, one sidedraw stream may be withdrawn from zone Z_2, if desirable, instead of two. For example, from Zone Z_2 of Figure 14f, instead of withdrawing two sidestreams, BC and C, a

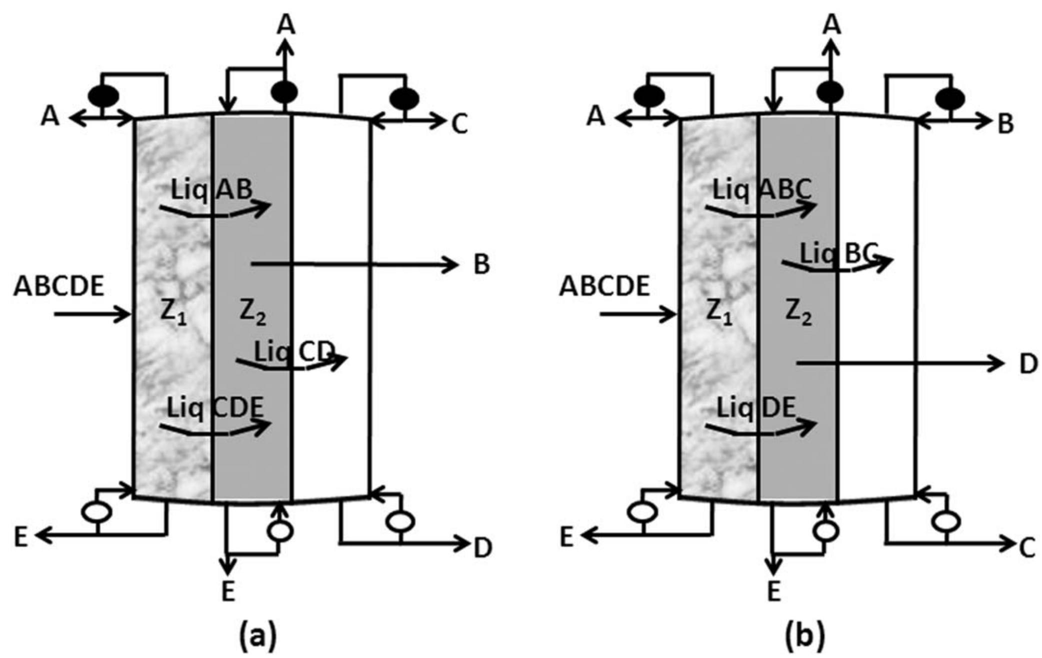

Figure 16. DWCs obtained by adding an extra zone to the DWCs of Figures (a) 15a; (b) 15b to produce pure products.

single sidestream C may be withdrawn. In such a case, the two separations taking place in Zone Z_2 are ABC->AB\C and CD->C\D.

An interesting case emerges in Figures 14j through 14l, where all the products may be produced with high purity. The sequence of component splits/separations shown in Figures 14j–l, using the TC-TC column, has been known in the past.[6,24,25] The use of our new L-TC, TC-L, and L-L columns instead, allows for a better control of vapor flow on each side of the vertical partition. This makes it easy to control the production of pure B and C product streams from an operating plant, and also allows the column to be operated closer to its designed optimal heat duty.

Based on the observations made for quaternary mixtures, the various operating modes from the use of the L-L column to separate a quinary mixture are shown in Figure 15. Some of the intermediate withdrawal streams from Zone Z_2 of these distillation columns may be eliminated, if desired. It is clear that the concept can also be applied to L-TC and TC-L columns. The DWCs of Figure 15 can be further extended to produce streams of pure products. As an example, extensions to DWCs of Figures 15b and e to produce streams of pure products are shown in Figures 16a and b. These DWCs have been obtained by adding an extra distillation zone to those in Figures 15b and e. The intermediate volatility components, B, C, and D, are produced from the ends of a zone in these DWCs. Interestingly, the skeleton partition structure with three parallel zones in the DWCs of Figure 16 is the same as that shown in Figure 12a, a standalone DWC for separating a quaternary feed mixture. This generalizes our concept of using the n-component skeleton dividing wall partition structure, and adapting it for the distillation of a mixture with more than n components.

Conclusions

DWCs are finding increasing prominence industrially for multicomponent separations. The DWCs, derived from the FTC configurations, are of special interest because of their low heat duty requirements. However, the heat duty and cost benefits from such DWCs are susceptible to the vapor split at the bottom of any of its vertical partitions, which is unregulated during operation. This susceptibility increases as the number of components in the feed increases because of the increase in the number of vapor splits in the DWC.

To reduce the operational difficulties from the dividing wall derivative of the three-component FTC Petlyuk column (called TC-TC column), we introduced new more operable DWCs, the L-TC, TC-L, and L-L columns in this article. The new DWCs are derived from distillation configurations by transforming a thermal coupling link to a liquid-only transfer stream. We show that such transformations are equivalent to the originally thermally coupled configuration. The new DWCs are characterized by longer continuous vertical partitions and liquid transfers of submixtures around the vertical partitions, which makes them more operable. Whereas the L-TC column has one vapor split, the TC-L and L-L columns have no vapor splits. Moreover, the vapor split in the L-TC column can be easily controlled during online operation.

To derive heat duty benefits for higher component systems, we extended the framework to draw new and operable DWCs for any n-component mixture with n greater than three. We illustrated the method by drawing novel, operable, FTC equivalent four-component DWCs. More generally, any thermal coupling link in a distillation configuration can be converted to a liquid-only transfer, as proposed by Agrawal,[17] and incorporated into a DWC as presented in this article. We believe this concept will, for the first time, enable the industrial practitioners to successfully implement and optimally operate the n-component ($n \geq 3$) FTC configuration in a DWC.

We demonstrate an interesting extension whereby a new dividing wall configuration drawn for an n-component mixture can be easily adapted to distil a mixture containing more than n components. Thus, we show the use of ternary DWCs such as the L-TC, TC-L, and L-L columns for the distillation of a four-component and a five-component mixture.

The findings in the article indicate that the new DWCs are attractive and promising candidates for industrial application. An extensive design and control study, as has been devoted to the conventional TC-TC column, will increase the rate of industrial implementation.

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