

Minimum Energy of Multicomponent Distillation Systems Using Minimum Additional Heat and Mass Integration Sections

Zheyu Jiang and Gautham Madenoor Ramapriya

Davidson School of Chemical Engineering, Purdue University, West Lafayette, IN 47907

Mohit Tawarmalani

Krannert School of Management, Purdue University, West Lafayette, IN 47907

Rakesh Agrawal 

Davidson School of Chemical Engineering, Purdue University, West Lafayette, IN 47907

DOI 10.1002/aic.16189

Published online May 8, 2018 in Wiley Online Library (wileyonlinelibrary.com)

Heat and mass integration to consolidate distillation columns in a multicomponent distillation configuration can lead to a number of new energy efficient and cost-effective configurations. In this work, a powerful and simple-to-use fact about heat and mass integration is identified. The newly developed heat and mass integrated configurations, which we call as HMP configurations, involve first introducing thermal couplings to all intermediate transfer streams, followed by consolidating columns associated with a lighter pure product reboiler and a heavier pure product condenser. A systematic method of enumerating all HMP configurations is introduced. The energy savings of HMP configurations is compared with the well-known fully thermally coupled (FTC) configurations. HMP configurations can have very similar and sometimes even the same minimum total vapor duty requirement as the FTC configuration is demonstrated, while using far less number of column sections, intermediate transfer streams, and thermal couplings than the FTC configurations.

© 2018 American Institute of Chemical Engineers *AIChE J*, 64: 3410–3418, 2018

Keywords: multicomponent distillation, distillation sequences, distillation configurations, heat and mass integration, process intensification

Introduction

Distillation is an important separation process that accounts for 90–95% of all separations, and consumes more than 40% of energy in the chemical and refining industry.¹ To separate a multicomponent mixture with n components into n pure products through distillation, a sequence of distillation columns referred to as a *distillation configuration* is usually required. If a distillation configuration uses exactly $(n-1)$ columns for separating an n -component mixture into n product streams, then it is called a *regular-column* distillation configuration.² Regular-column configurations with each column having one reboiler and one condenser are referred to as *basic* distillation configurations.³ A split represents separation of a mixture into two

product streams. Sharp splits produce product streams with no overlapping components, whereas nonsharp splits produce product streams with significant amount of overlapping components. Accordingly, distillation configurations are classified as either *sharp split* configurations if all their splits are sharp or *nonsharp split* configurations if at least one split is nonsharp.

For a given distillation configuration, the total cost comprises of two parts: the capital cost and the operating cost. The capital cost of a configuration depends on the number and sizes of distillation columns, reboilers, condensers, and so forth. Assuming that the unit heating and unit cooling utility costs for all the reboilers and condensers are similar, the operating cost is directly related to the total reboiler heat input, which is correlated to the sum of vapor duty generated at all reboilers. There are several ways to reduce the total costs of a distillation configuration, one of which is through heat and mass integration (HMI) of the distillation columns.^{4–6} The concept of HMI is explained in greater detail in the following paragraph.

One of the first studies of HMI between distillation columns that produce the same pure product streams⁴ is illustrated in Figure 1. In this figure, and also in subsequent figures, *A*, *B*, *C*, and so forth represent pure components with their volatilities decreasing in alphabetical order. Also, unfilled circles designate reboilers, while filled circles designate condensers. In the configuration shown in Figure 1a, both the reboiler of column 2 and the condenser of column 3 produce common product *B*.

Disclaimer: The information, data, or work presented herein was funded in part by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Correspondence concerning this article should be addressed to R. Agrawal at agrawalr@purdue.edu.

© 2018 American Institute of Chemical Engineers

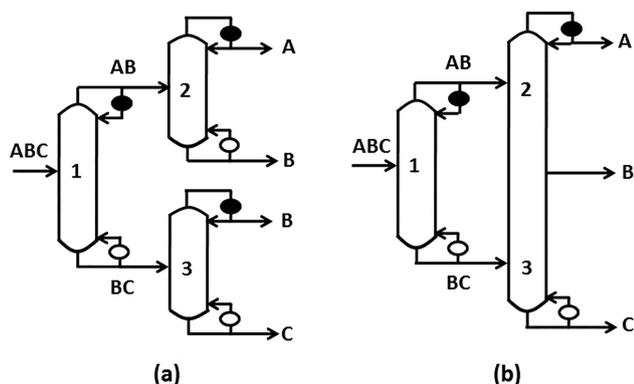


Figure 1. (a) A configuration for ternary separation; (b) the heat and mass integrated configuration derived from configuration of Figure 1a after combining column 2 and column 3 in Figure 1a to form column 2-3.

As a result, this reboiler and condenser can be eliminated by directly stacking column 2 on top of column 3 to form a single heat and mass integrated column, column 2-3 in Figure 1b, with pure component *B* now being produced as a single side-draw product. Evidently, column consolidation by HMI reduces the number of pieces of equipment used. Further, unlike Figure 1a, in Figure 1b, the heat generated at the reboiler of column 2-3 is simultaneously used for two splits: $AB \rightarrow A/B$ and $BC \rightarrow B/C$. Consequently, the overall energy consumption can be reduced using HMI. This is why HMI is of interest.

HMI is not just limited to removing reboilers and condensers associated with the same product streams. Some known examples have been presented for sharp split configurations and include the Brugma configuration,⁵ Cahn and Di Miceli configuration⁶ which is the completely thermally coupled version of the Brugma configuration, and Kaibel configuration⁷ which is the dividing wall column version of the Cahn and Di Miceli configuration. In the basic configuration for six-component separation shown in Figure 2a, the submixture *BC* produced at the reboiler of column 2 is lighter than the submixture *DE* produced at the condenser of column 3, assuming similar operating pressures among all distillation columns.

Likewise, column 4 produces the bottom product *C*, which is lighter than *D*, the product produced at the top of column 5. In this case, a heat and mass integrated configuration, shown in Figure 2b, can be derived from Figure 2a by first eliminating reboilers producing *BC* and *C*, and condensers producing *DE* and *D*, followed by combining columns 2 and 3 as well as columns 4 and 5 to form two new columns (column 2-3 and column 4-5 of Figure 2b).⁵⁻⁸ Two intermediate column sections, illustrated in Figure 2b within a dotted box, are added to the new columns. The intermediate section is provided with sufficient stages to allow a smooth composition transition for the liquid and vapor within the column, between the eliminated reboiler and condenser. Submixtures *BC* and *DE*, as well as *C* and *D*, are now withdrawn as side-draws from the heat and mass integrated column 2-3 and column 4-5, respectively. Note that this kind of HMI differs from that described in Figure 1 because the HMI in Figure 2 is achieved through the use of an additional intermediate section.⁸⁻¹⁰ HMI achieved by means of an additional section is referred to as heat and mass integration with additional section, or simply **HMA**.⁹

From the configuration of Figure 2a, a number of new configurations can be systematically synthesized by introducing HMA between distillation columns. While Figure 2b simultaneously consolidates columns 2 & 3 as well as columns 4 & 5 using two HMAs, alternatively, one may either consolidate only columns 2 & 3, or columns 4 & 5, or columns 2 & 5, or columns 4 & 3 using an HMA, or simultaneously consolidate columns 2 & 5 and columns 4 & 3 using two HMAs. Each column consolidation using HMA leads to a new configuration. Furthermore, as discussed by Shenvi et al.,⁸ additional streams can be strategically withdrawn from certain HMAs in the new configurations. For example, from the introduced *BC-DE* HMA in Figure 2b, either *C*, or *D*, or both *C* and *D* streams as shown in Figure 2c can be withdrawn. Thus, depending on which stream is additionally withdrawn from the introduced *BC-DE* HMA, the configuration in Figure 2b can further lead to three new configurations. In addition, from each one of the new configurations synthesized from Figure 2a using concepts described above, newer derivative combinations can be drawn by using a thermal coupling in place of a heat exchanger at any or all of the submixtures. Figure 3a shows an example configuration derived from the one in Figure 2c after replacing heat exchangers at all submixtures with thermal couplings. In conclusion,

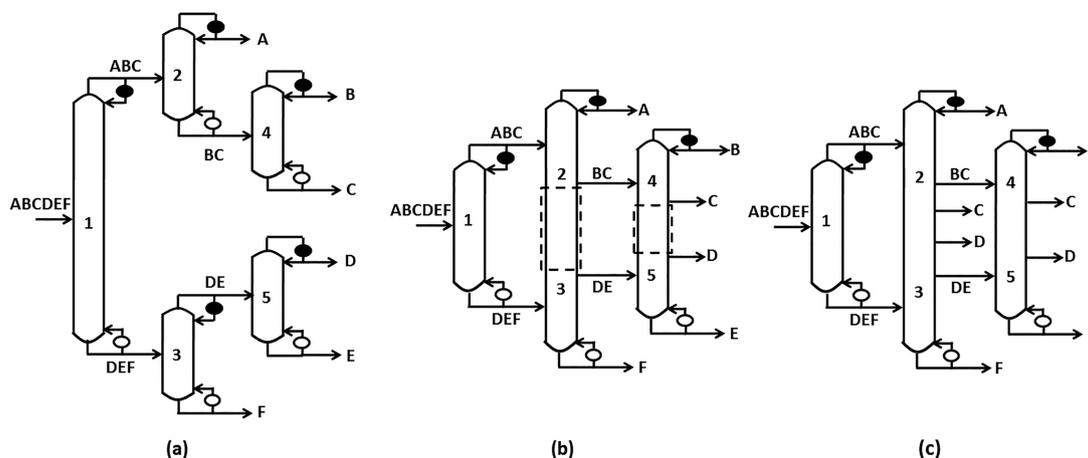


Figure 2. (a) A configuration for six-component separation; (b) the heat and mass integrated configuration with two HMAs highlighted in the dotted boxes; (c) a new configuration derived from strategically withdrawing streams *C* and *D* as side-draws in column 2-3.

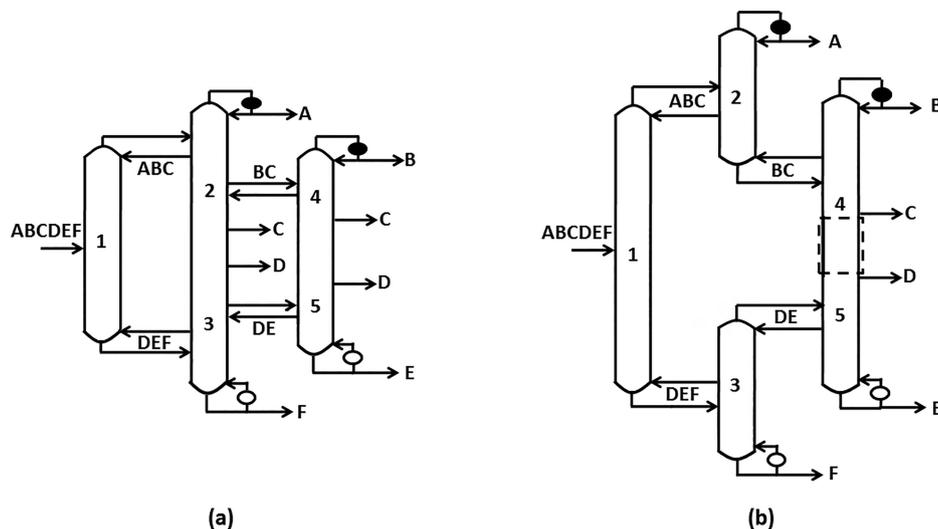


Figure 3. (a) A configuration derived from the configuration in Figure 2c by introducing thermal couplings at all submixtures; (b) A HMP configuration that is thermodynamically equivalent to the configuration in Figure 3a.

starting from a flowsheet synthesized by, for example, the SA method,^{11,12} the concept of HMA can further lead to numerous distillation configurations.

Each configuration in the large set of configurations that are synthesized using the concept of HMA is associated with a unique overall cost. However, if energy consumption is the criterion for choosing a configuration, a number of configurations from the large set of HMA configurations can be easily discarded based on certain critical observations. Here, we present how one can concentrate only on a unique subset with certain characteristics to identify the most energy efficient HMA configuration. Consider the example flowsheet shown in Figure 2a. Among all the new HMA configurations synthesized from this initial flowsheet, the configuration that will always have the lowest heat duty requirement is shown in Figure 3b. The configuration in Figure 3b is obtained from the one in Figure 2a by *first replacing all submixture heat exchangers with thermal couplings, and then introducing an HMA between the condenser at final product D and reboiler at final product C*. The configuration of Figure 3b has the unique feature of the existence of a thermal coupling at every submixture, and HMA only between pure component products. By virtue of this feature, observe that the vapor leaving the top of column 3 at temperature T_{DE} (T_X represents the vapor temperature in a column at the stage producing X) progressively produces products at temperatures T_D , T_C , and then T_{BC} . In contrast, when HMA is directly introduced between the condenser at DE and reboiler at BC as in Figure 2b, the heat/vapor at temperature T_{DE} is directly degraded to temperature T_{BC} to produce BC without producing C and D , implying less separation work by this vapor when compared to the configuration in Figure 2c. And it has greater irreversibility due to greater temperature difference between the eliminated BC reboiler and DE condenser. Introducing thermal coupling at BC and DE in the configuration of Figure 2c results in the configuration of Figure 3a which requires either the same or less heat duty compared to the original configuration of Figure 2c.¹³ The configuration in Figure 3a can be shown to be thermodynamically equivalent to the configuration in Figure 3b.^{14–16} Based on this line of reasoning, it follows that no other configuration derived from the flowsheet of Figure 2a that uses an HMA can have a heat duty requirement as low as the one in Figure 3b.

Configurations such as the one in Figure 3b are easily identified and obtained from the set of basic configurations, after replacing all submixture heat exchangers with thermal couplings and performing HMA between pure component heat exchangers (if such a possibility exists). We refer to this resulting unique set of configurations as **HMP** configurations, that is, Completely Thermally Coupled Heat and Mass Integrated Configurations with Additional Section at Final Product Ends. The least heat-duty-consuming configuration that uses an HMA belongs to the set of HMP configurations. Rong et al.¹⁷ studied the HMP configurations, but those only with sharp splits. Meanwhile, several optimization-based techniques^{18–20} have been developed to design energy efficient heat integrated thermally coupled configurations. But these approaches do not explicitly consider HMP configurations. In this work, we systematically generate the entire set of HMP configurations and show that it is the nonsharp HMP configurations that are likely to have a lower heat duty requirement than the sharp HMP configurations. Finally, we make some interesting comparisons with the well-known fully thermally coupled (FTC) configuration, which is known to consume the least heat duty among all configurations for any given separation.^{21–23}

Enumeration of HMP Configurations

Recently, Shah and Agrawal^{11,12} successfully generated the complete search space of all sharp and nonsharp split basic distillation configurations using a simple-to-use six-step method. This powerful synthesis tool enables us to, for the first time, enumerate all sharp and nonsharp split HMP configurations. For each configuration generated by the SA method, we can determine, through a simple screening algorithm, *if there simultaneously exists any pure component product produced at reboilers that is lighter than any final pure component product produced at a condenser*. If so, this configuration will correspond to a candidate configuration for HMP. As an illustration, let us consider the basic configuration shown in Figure 4a. The corresponding matrix generated by the SA method is shown in Figure 4b. From each submixture node (including the main feed) present in the matrix as a “parent,” we can emanate a horizontal branch and a downward diagonal branch to the right. The first non-zero node that the horizontal

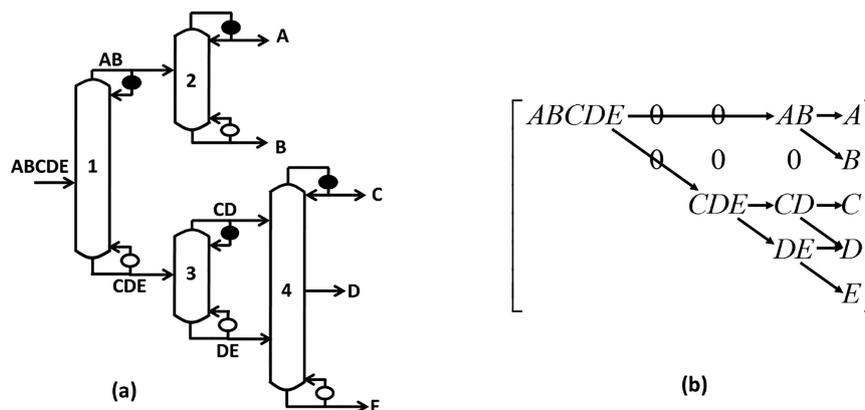


Figure 4. (a) Example basic distillation configuration at the end of the SA method^{9,10} for five-component separations; (b) The matrix representation corresponding to the basic configuration in Figure 4a.

branch meets will be the top product that the submixture produces (“top child”), whereas the first non-zero node that the downward diagonal branch meets will be the bottom product that the submixture produces (“bottom child”). For example, submixture *CDE* in the configuration of Figure 4b splits into top product *CD* and bottom product *DE*. This means that, for each pure product node in the matrix, we can easily backtrack to identify its “parent” node by traversing the matrix horizontally and diagonally upward to the left. If the pure product node is produced solely as a top or a bottom product, then it must be accordingly associated with a condenser or reboiler in the basic configuration. For instance, as indicated by the matrix in Figure 4b, pure component product *B* is produced at a reboiler and pure component product *C* is produced at a condenser. As component *B* is lighter than component *C*, the basic configuration of Figure 4a is a candidate for HMP. Notice that, if a pure product is simultaneously produced by two different “parents” as both the top and bottom product, then it actually corresponds to a side-draw product. For example, as shown in Figure 4b, the pure product stream *D*, which is simultaneously produced as a bottom product of “parent” *CD* and top product of “parent” *DE*, is a side-draw product and therefore is not associated with any heat exchanger. This example demonstrates that, by simply examining the “parent” nodes of all pure component products in the matrix generated by the SA method, we can quickly determine if the corresponding basic configuration is a valid candidate for HMP, and when needed, it can be added as an additional step to the six-step SA method (See Figure 5).

Table 1 summarizes our enumeration results of HMP configurations for up to six-component mixture separations. The second and third column of Table 1, respectively, list the total number of basic configurations in the defined search space

Table 1. The Number of Basic Configurations That are Candidates for HMP and the Number of HMP Configurations for up to Six-Component Separation

Number of Components	Total Number of Basic Configurations in Search Space	Number of Basic Configurations That are Candidates for HMP	Number of Sharp Split Basic Configurations That are Candidates for HMP
4	18	1	1
5	203	15	6
6	4373	282	26

obtained directly from the SA method^{11,12} and the subset of basic configurations identified as HMP candidates through the additional step described above. Note that HMP configurations are absent for binary and ternary separations. As an example, all 15 basic configurations that are candidates for HMP for five-component separations are explicitly shown in Figure 6. These candidate basic configurations are obtained by following the steps illustrated in Figure 5 and refers to the value of *j*. Out of the 15 configurations, notice that for some configurations, there exists multiple possible ways of introducing an HMA. For instance, in the basic configuration of Figure 6a, the reboiler of column 2, which produces pure product *B*, can be heat and mass integrated with either the condenser of column 3 or column 4, which produces heavier product *C* or *D*, respectively. It means, from this particular basic configuration, two possible HMP configurations can be derived. To account for this multiplicity, which is referred to as *k_i* in Figure 5, one needs to add yet another additional step to the SA method, whereby, reboilers and condensers associated with pure components are examined for all feasible heat and mass integrations. The total number of possible HMP configurations is presented in the last column of Table 1. The fourth column of Table 1 lists the number of sharp split basic candidate configurations for HMP configurations. These values are consistent with Rong et al.’s derived results.¹⁷ It is clear that as the number of components increases, the number of sharp split HMP configurations forms a decreased fraction among all HMP configurations. We shall see later that sharp split HMP configurations generally have much higher minimum total vapor duty requirements (V_{\min}^{tot}) than nonsharp split HMP configurations.

It is worth noting from Figure 6 that, for five-component distillation systems, the minimum number of distillation column sections for HMP are obtained from basic configurations involving only sharp splits. Thus, configurations 6(a), (b), (d), (e), (h), and (l), which have eight column sections, result in nine sections for the corresponding HMP configurations. The configurations in Figures 6k, o result in maximum number of column sections of 13 among five-component HMP configurations. The rest of the HMP configurations derived from Figure 6 have 11 column sections. For a six-component distillation system, a HMP configuration involving sharp splits only has the minimum number of 11 column sections, whereas the maximum number of sections for a nonsharp split configuration is 21.

As discussed earlier, the configuration shown in Figure 3b is an example HMP configuration out of the 348 possible HMP configurations for separating six-component mixtures. A

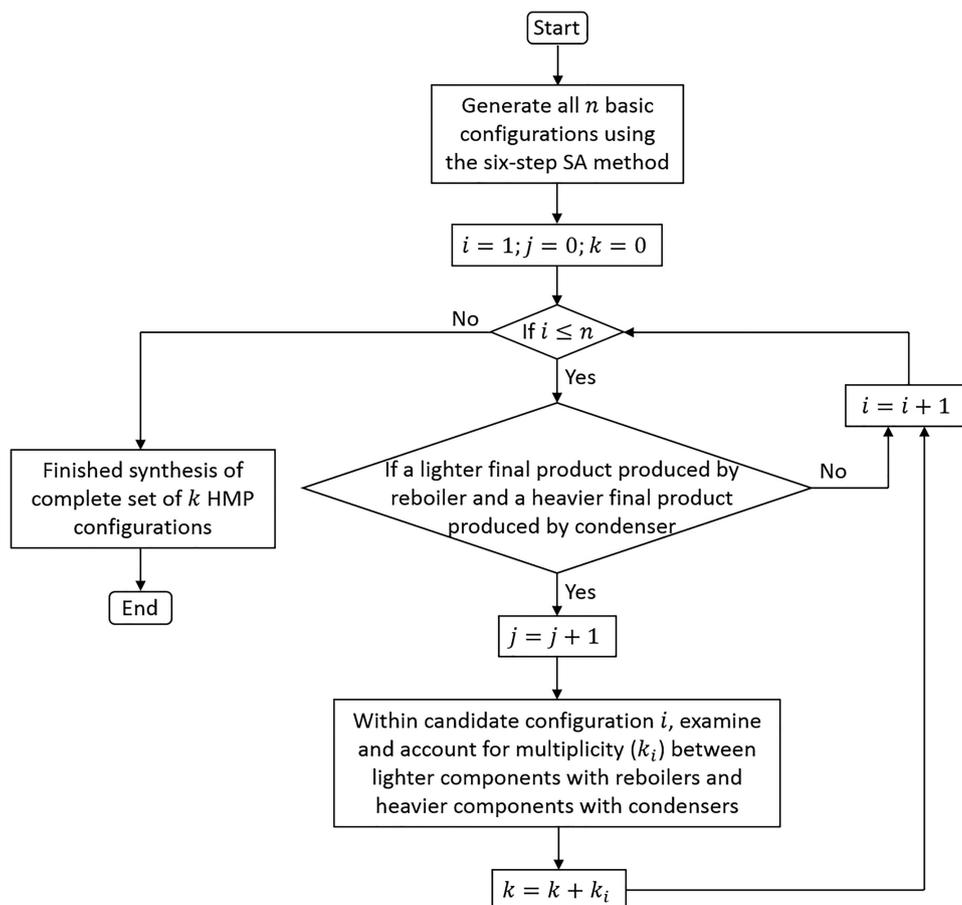


Figure 5. Additional steps for the SA method to synthesize HMP configurations.

By the end of the synthesis process, the value of j is the total number of HMP candidate basic configurations, and k_i stands for the number of possible HMP configurations that can be derived from basic configuration i after accounting for multiplicity. The total number of HMP configurations is given by $k = \sum_i k_i$.

more operable version of this configuration, obtained after rearranging sections between distillation columns,^{14–16} is shown in Figure 7a. A dividing wall column version of the configuration of Figures 3b/7a is also synthesized and illustrated in Figure 7b.^{24,25} Note that for a six-component distillation, while a dividing wall column arrangement in a single column shell will usually require four dividing walls, the HMP version in Figure 7b requires only three dividing walls.

Comparing Performances of HMP Configurations with the FTC Configuration

Here, we demonstrate through case studies for five-component mixture separations, that the minimum total vapor duty requirement of basic configurations can be significantly reduced by introducing HMP. In addition, we show that HMP configurations can often even have the same minimum total vapor duty requirement as the FTC configuration, which is known to always yield the lowest total vapor duty requirement among all configurations in the search space.^{21–23}

The total vapor duty requirement calculation at minimum reflux for any configuration is formulated as a nonlinear programming (NLP) problem based on vapor duty estimation using Underwood's method²⁶; and NLP optimization solvers such as GAMS/BARON²⁷ guarantee that each configuration is solved to global optimality.^{26,28} For illustration purposes, we focus on ideal saturated liquid feed mixture separations. The

feed flow rate is 1 kmol/s. The products leave the distillation system as saturated liquids. For five-component feed mixtures, 31 different representative feed compositions can be formulated,²⁹ depending on whether each component in the feed is rich or lean ($2^5 - 1$). For example, "ABCdE" implies that the feed is rich in components A, B, E and lean in components C and D. Lean component, if there's any, is assigned a mole fraction of 0.05 in the feed, while rich components share the leftover mole fraction evenly. As a special case, an equimolar mixture is represented as ABCDE.

Consider the HMP configuration shown in Figure 8b, which is derived from the basic configuration of Figure 6k. We evaluate this configuration for minimum total vapor duty requirement. The relative volatility set considered for evaluation, between each consecutive component in the feed is $\{\alpha_{AB}, \alpha_{BC}, \alpha_{CD}, \alpha_{DE}\} = \{1.1, 1.1, 2.5, 2.5\}$, and some of the results are summarized in Table 2. For the feed composition of abcDE, the V_{\min}^{tot} for FTC configuration is 1.42 kmol/s. The HMP configuration has a V_{\min}^{tot} of 1.47 kmol/s, only 3.2% higher than that of the FTC configuration, as opposed to the original basic configuration which requires a V_{\min}^{tot} of 3.28 kmol/s. This indicates that by introducing HMP to the basic configuration, a significant energy saving can potentially be obtained. Moreover, under the same relative volatility set, for five feed compositions – Abcde, ABcDE, AbcdE, ABcde, and AbcDE, the HMP configuration has the same V_{\min}^{tot} as the FTC configuration. At the same time, this HMP configuration uses

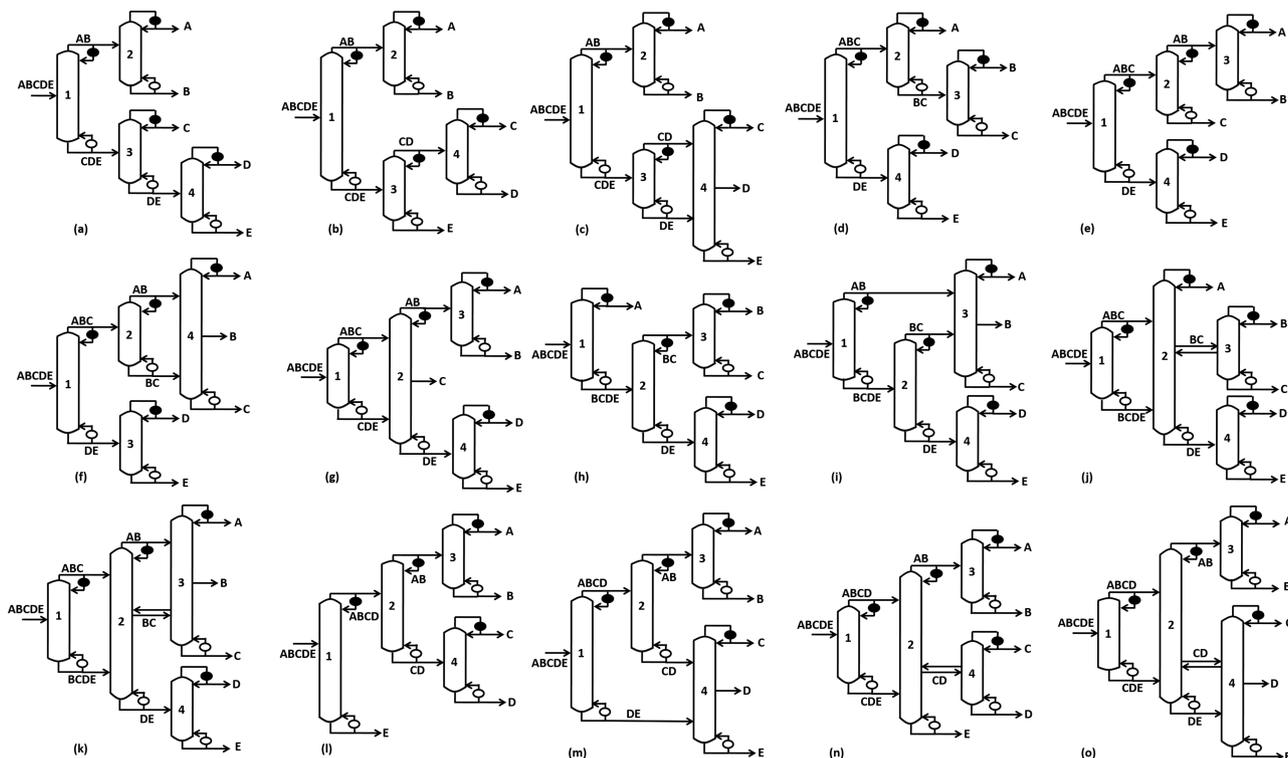


Figure 6. All 15 basic configurations that are candidates for HMP for five-component separations.

Note that configurations 6a and 6e can individually undertake two different HMPs. Also, configurations of Figures 6a, b, d, e, h, and l are sharp split configurations.

only 13 column sections and transfers 5 submixtures between distillation columns, as opposed to 20 sections and 9 intermediate transfer streams in the FTC configuration. For the relative volatility set considered above, extensive calculations for all configurations in the previously known search space generated by the SA method^{11,12} indicate that no other configuration with less than 14 column sections gives the same V_{\min}^{tot} as the FTC configuration.

Now, let's examine another HMP configuration shown in Figure 8c, which is derived from the basic configuration in Figure 6o. The relative volatility set considered for evaluation between each consecutive component in the feed is given by $\{\alpha_{AB}, \alpha_{BC}, \alpha_{CD}, \alpha_{DE}\} = \{2.5, 2.5, 1.1, 1.1\}$. Among all 31 ($2^5 - 1$) representative feed compositions, for 18 of them, the HMP configuration has the same V_{\min}^{tot} as the FTC configuration. Also, for 7 other feed compositions, the V_{\min}^{tot} for this

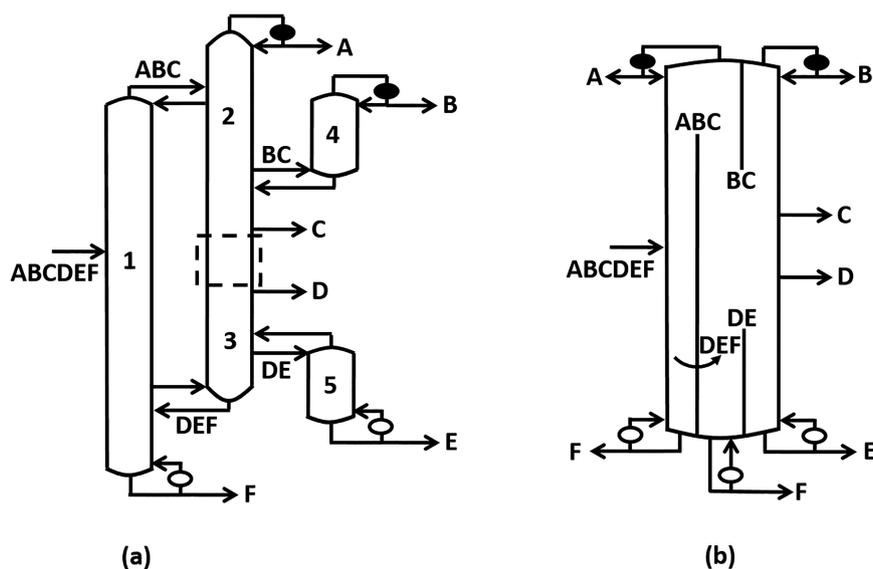


Figure 7. (a) A more operable version of the HMP configuration shown in Figures 3b; (b) a dividing wall column synthesized from the configuration of Figure 7a.

Note that the thermal coupling at submixture DEF of Figure 7a is converted into a liquid-only transfer stream¹⁹ in Figure 7b, indicated by the curved arrow.

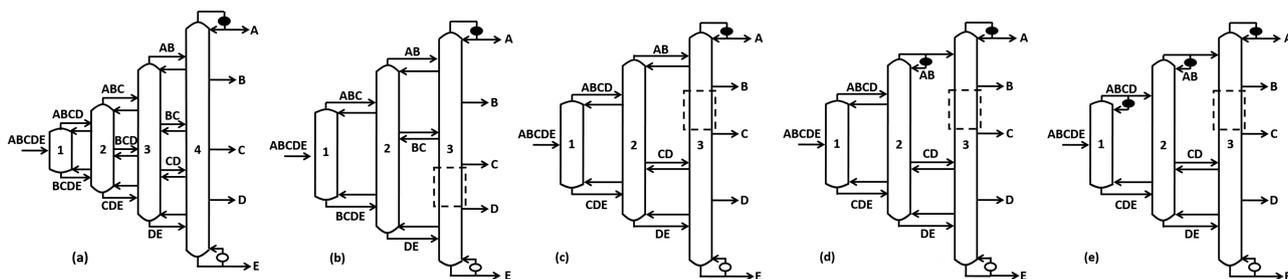


Figure 8. (a) The fully thermally coupled (FTC) configuration for five-component separation; (b) the HMP configuration derived from the basic configuration of Figure 6k; (c) the HMP configuration derived from the basic configuration of Figure 6o; (d) a configuration derived from configuration of Figure 8c by replacing thermal coupling at *AB* with condenser; (e) a configuration derived from configuration of Figure 8d by replacing thermal coupling at *ABCD* with condenser.

Table 2. Minimum Total Vapor Duty Requirement per Mole of Feed for the Configuration of Figure 6k, Its Completely Thermally Coupled Version, the HMP Configuration of Figure 8b, and the FTC Configuration

Feed Composition	Configuration of Figure 5k	Configuration of CTC Figure 5k ^a	HMP Configuration of Figure 7b	FTC Configuration
abcDE	3.28	2.35	1.47	1.42
Abcde	13.99	9.51	9.43	9.43
ABIDE	7.23	5.70	5.29	5.29
AbcdE	8.12	5.38	5.29	5.29
ABcde	11.65	9.28	9.20	9.20
AbcDE	6.54	4.47	3.94	3.94

The relative volatility set is $\{\alpha_{AB}, \alpha_{BC}, \alpha_{CD}, \alpha_{DE}\} = \{1.1, 1.1, 2.5, 2.5\}$.

^aNote: CTC Figure 6k refers to the configuration of Figure 6k after introducing complete thermal coupling.

HMP is higher than the FTC configuration by <10%. This exciting fact indicates that HMP is capable of providing effective energy savings for a wide window of feed compositions. Note that this HMP configuration also has only 13 column sections and 5 intermediate transfer streams, much less than what the FTC configuration has. Again, for the relative volatility set considered, no other configuration in the search space generated by the SA method^{11,12} with less than 14 column sections gives the same V_{\min}^{tot} as the FTC configuration.

Moreover, we can observe the benefits associated with the HMP configurations in Figures 8b, c compared to the FTC configuration in Figure 8a when drawing some of the many possible operable dividing wall column versions for these configurations following the methodologies of Madenoor Ramapriya et al.^{24,25} From Figure 9, it is clear that the dividing wall column versions of these HMP configurations use fewer partitions and less number of intermediate transfer streams compared to the dividing wall column version of the FTC

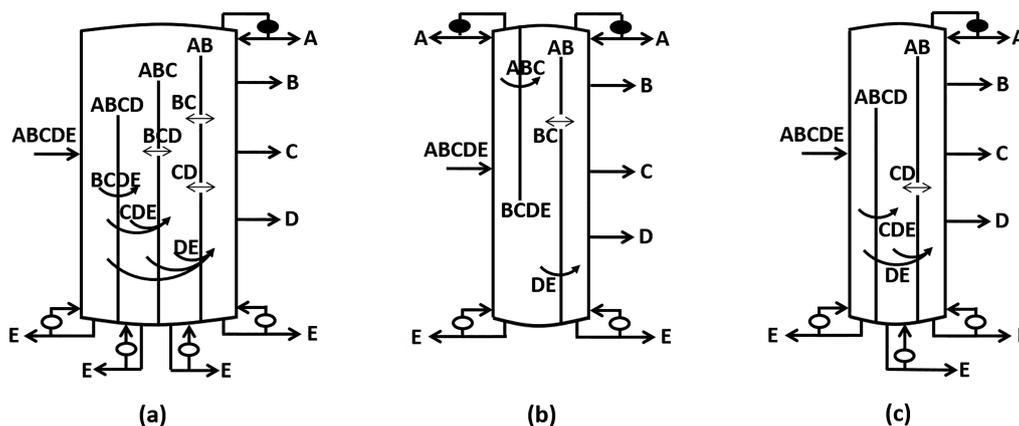


Figure 9. (a) One possible operable dividing wall column drawn from the FTC configuration of Figure 8a using the methodology of Madenoor Ramapriya et al.^{24,25} Notice that this dividing wall column uses three dividing walls and nine intermediate transfer streams; (b) one possible operable dividing wall column version synthesized from the HMP configuration of Figure 8b; (c) one possible operable dividing wall column version synthesized from the HMP configuration of Figure 8c.

Notice that both dividing wall columns of Figures 8b, c use only 2 dividing walls and 5 intermediate transfer streams.

configuration. Additionally, some other interesting observations are made for the HMP configuration of Figure 8c. For the same relative volatility set $\{\alpha_{AB}, \alpha_{BC}, \alpha_{CD}, \alpha_{DE}\} = \{2.5, 2.5, 1.1, 1.1\}$, when we start with this HMP configuration and replace the thermal coupling at AB stream with a condenser, for the new partially thermally coupled configuration drawn in Figure 8d, all the 18 feed compositions described above retain their V_{\min}^{tot} that's equal to the FTC configuration. If we further replace the thermal coupling at stream $ABCD$ with a condenser, a new configuration shown in Figure 8e is derived. Given the same relative volatility set, for 16 out of the 31 feed compositions, this configuration has the same V_{\min}^{tot} as the FTC configuration. In general, with much fewer column sections and intermediate streams, as well as more heat exchangers used in comparison to the FTC configuration, the configurations of Figures 8d, e are expected to be easier to control than the FTC configuration.

Also, it is worthwhile to comment on the change in column diameter when two columns are consolidated in an HMP configuration. The diameter of a distillation column is roughly proportional to the vapor traffic inside the column. One might have the suspicion that, after HMP, the diameter of the consolidated column could increase significantly due to large increase in vapor traffic. However, this is true only if, before HMP, one column has significantly more vapor traffic than the other column. However, it turns out that the HMP configurations that achieve the maximum energy savings are always the ones in which two columns to be consolidated have similar vapor duty requirements. To understand this, consider two distillation columns that are capable of HMP. For simplicity, we assume that the feed streams entering both columns are saturated liquids. Let V_1 denote the vapor duty requirement of the column associated with the lighter pure product reboiler and V_2 denote the vapor duty requirement of the column associated with the heavier pure product condenser. Then, after HMP, the vapor traffic inside the consolidated column is given by $V = \max\{V_1, V_2\}$. Thus, the relative energy savings due to HMP is given by $\Delta V/V = (V_1 + V_2 - V)/V = (V_1 + V_2)/\max\{V_1, V_2\} - 1$. As a result, the maximum relative energy savings (100%) is achieved when $V_1 = V_2$. Conversely, if V_1 and V_2 are very different, say $V_1 \gg V_2$, then $\Delta V/V \ll 1$. The key message here is that distillation columns with distinct vapor traffics are generally not good candidates for HMP anyway. Therefore, attractive HMP configurations that give significant energy savings are unlikely to result in large increase in column diameter.

Finally, after performing exhaustive calculations, we identify that none of the six sharp-split HMP configurations have the same V_{\min}^{tot} as the FTC configuration for any of the 31 representative feed compositions under the two relative volatility sets considered. This result is in accordance with our previous observations that configurations allowing nonsharp splits generally have lower heat duty than those with only sharp splits.²⁹

Conclusion

Overall, thermal coupling and simultaneous HMA can help reduce heat duty requirement of a distillation configuration significantly. However, we demonstrate that when the configuration is completely thermally coupled, HMA at the submixture level is not required. Instead, delaying HMA until the final product ends can lead to energy efficient HMP configurations which are, for certain feed conditions, comparable with the FTC configuration in terms of total reboiler vapor duty.

These configurations also require much less number of column sections and intermediate streams, making them very attractive to build and operate. Finally, for the first time, a stepwise method is suggested to systematically synthesize all possible sharp and nonsharp HMP configurations.

Acknowledgment

The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0005768.

Literature Cited

- Humphrey JL, Siebert AF. Separation technologies: an opportunity for energy savings. *Chem Eng Prog.* 1992;88(3):32–41.
- Shenvi AA, Shah VH, Zeller JA, Agrawal R. A synthesis method for multicomponent distillation sequences with fewer columns. *AIChE J.* 2012;58(8):2479–2494.
- Agrawal R. Synthesis of multicomponent distillation column configurations. *AIChE J.* 2003;49(2):379–401.
- Petlyuk FB, Platonov VM, Slavinskii DM. Thermodynamically optimal method for separating multicomponent mixtures. *Int Chem Eng.* 1965;5(3):555–561.
- Brugma AJ. Process and Device for Fractional Distillation of Liquid Mixtures, More Particularly Petroleum. US Patent 2,295,256, 1942.
- Cahn RP, Di Micelli E, Di Micelli AG. Separation of Multicomponent Mixture in Single Tower. U.S. Patent 3,058,893, 1962.
- Kaibel G. Distillation columns with vertical partitions. *Chem Eng Technol.* 1987;10(1):92–98.
- Shenvi AA, Shah VH, Agrawal R. New multicomponent distillation configurations with simultaneous heat and mass integration. *AIChE J.* 2013;59(1):272–282.
- Madenoor Ramapriya G, Shenvi AA, Tawarmalani M, Agrawal R. A new framework for combining a condenser and reboiler in a configuration to consolidate distillation columns. *Ind Eng Chem Res.* 2015; 54(42):10449–10464.
- Madenoor Ramapriya G, Tawarmalani M, Agrawal R. Modified basic distillation configurations with intermediate sections for energy savings. *AIChE J.* 2014;60(3):1091–1097.
- Shah VH, Agrawal R. A matrix method for multicomponent distillation sequences. *AIChE J.* 2009;56(7):1759–1775.
- Shah VH, Agrawal R. Conceptual design of zeotropic distillation processes. In: Gorak A, Sorensen E, editors. *Distillation: Fundamentals and Principles*. Cambridge, MA: Academic Press, 2014:271–300.
- Shah VH, Agrawal R. Are all thermal coupling links between multicomponent distillation columns useful from an energy perspective? *Ind Eng Chem Res.* 2011;50(3):1770–1777.
- Agrawal R, Fidkowski ZT. More operable arrangements of fully thermally coupled distillation columns. *AIChE J.* 1998;44(11):2565–2568.
- Agrawal R. More operable fully thermally coupled distillation column configurations for multicomponent distillation. *Trans IChemE.* 1999;77(6):543–553.
- Agrawal R. Thermally coupled distillation with reduced number of intercolumn vapor transfers. *AIChE J.* 2000;46(11):2198–2210.
- Rong B, Kraslawski A, Turunen I. Synthesis of heat-integrated thermally coupled distillation systems for multicomponent separations. *Ind Eng Chem Res.* 2003;42(19):4329–4339.
- Caballero JA, Grossmann IE. Structural considerations and modeling in the synthesis of heat-integrated-thermally coupled distillation sequences. *Ind Eng Chem Res.* 2006;45(25):8454–8474.
- Blancarte-Palacios JL, Bautista-Valdés MN, Hernández S, Rico-Ramírez V, Jiménez A. Energy-efficient designs of thermally coupled distillation sequences for four-component mixtures. *Ind Eng Chem Res.* 2003;42(21):5157–5164.
- Calzon-McConville CJ, Rosales-Zamora MB, Segovia-Hernández JG, Hernández S, Rico-Ramírez V. Design and optimization of thermally coupled distillation schemes for the separation of multicomponent mixtures. *Ind Eng Chem Res.* 2006;45(2):724–732.
- Fidkowski ZT, Krolikowski L. Thermally coupled system of distillation columns: optimization procedure. *AIChE J.* 1986;32(4):537–546.

22. Fidkowski ZT, Agrawal R. Multicomponent thermally coupled systems of distillation columns at minimum reflux. *AIChE J.* 2001; 47(12):2713–2724.
23. Halvorsen IJ, Skogestad S. Minimum energy consumption in multicomponent distillation. 3. More than three products and generalized Petlyuk arrangements. *Ind Eng Chem Res.* 2003;42(3):616–629.
24. Madenoor Ramapriya G, Tawarmalani M, Agrawal R. A systematic method to synthesize all dividing wall columns for n -component separation - Part II. *AIChE J.* 2018;64(2):649–659.
25. Madenoor Ramapriya G, Tawarmalani M, Agrawal R. A systematic method to synthesize all dividing wall columns for n -component separation - Part I. *AIChE J.* 2018;64(2):660–672.
26. Nallasivam U, Shah VH, Shenvi AA, Huff J, Tawarmalani M, Agrawal R. Global optimization of multicomponent distillation configurations: 2. Enumeration based global minimization algorithm. *AIChE J.* 2016;62(6):2071–2086.
27. Tawarmalani M, Sahinidis NV. *Convexification and Global Optimization in Continuous and Mixed-Integer Nonlinear Programming.* Boston, MA: Kluwer Academic Publishers, 2002.
28. Nallasivam U, Shah VH, Shenvi AA, Tawarmalani M, Agrawal R. Global optimization of multicomponent distillation configurations: 1. Need for a global minimization algorithm. *AIChE J.* 2013;59(3): 971–981.
29. Giridhar AV, Agrawal R. Synthesis of distillation configurations: I. Characteristics of a good search space. *Comput Chem Eng.* 2010; 34(1):73–83.

Manuscript received Nov. 15, 2017, and revision received Mar. 24, 2018.