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Multi-Product Dividing Wall Columns: A Simple and Effective Assessment and Conceptual Design Procedure

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The objective of this paper is to further exploit and demonstrate the potential benefits of a V-min diagram based analysis, using a fifteen component feed mixture as base case. Detailed explanations are given on how to interpret properly a V-min diagram and use it for DWC assessment. Emphasis is on how to set the component or fraction splits to maximize potential gains as well as how to handle some variations in the feed with the same purpose. Interestingly, it appeared that depending on the choice and specification of interesting products (components or fractions), a simplified four-product DWC and even five-product DWC could be an interesting option for aromatics processing plants.

1. Introduction

Proven energy and capital saving potential of dividing wall columns (DWC) could be substantially increased if this technology would be applied to obtaining four or even more products. A comprehensive review of the contributions from 115 important DWC-publications is given by (Dejanović et al., 2010). The design of a four-product DWC has been addressed and encouraging advancements made in a previous effort indicating that utilizing non-welded partition walls a packed DWC can be implemented either as a practical, single partition wall column, or a thermodynamically optimal, but complex, three-partition walls column, in an industrially viable way in an aromatics processing plant as encountered in complex refineries (Dejanović et al., 2011). The key to success in this respect was efficient utilization of so called V-min diagram method, as a simple but very effective means to identify and quantify accordingly internal configuration of a complex DWC, providing at the same time reliable data for initialization of detailed calculations using an appropriate rigorous simulator. In this paper a step further has been made, by using V-min diagram to demonstrate an alternative, simplified configuration for a four-product DWC and a five-product DWC.

2. The V-min diagram

We will here describe the V-min diagram, or minimum energy diagram, and how it can be used for assessment of multicomponent separations (Halvorsen and Skogestad,

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2003a). We first consider a single two-product column with a multicomponent feed (*F*). The minimum energy requirement for a given product specification is determined by the minimum vapour flow through the feed stage with infinite number of stages. We consider constant pressure. Then we have at steady state two degrees of freedom in operation. We choose to use the vapour flow rate above the feed (V/F) and the net flow of product to the top (D/F) per unit feed. For a given pair (D/F, V/F) all column properties are determined. The thermal feed condition is given by the liquid fraction (q).

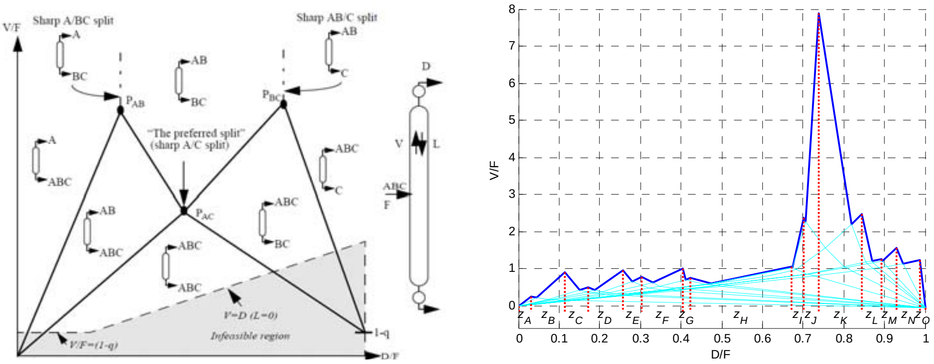


Figure 1: V-min diagram for a ternary mixture (a) for a 15-component feed (b, right)

The V-min diagram in Figure 1a shows how the feed components for a typical ternary feed (ABC) are distributed to the top and bottom products in a simple two-product "infinite stage" distillation column as a function of the operating point (D/F,V/F). For values of V/F above the upper "mountain-like" boundary in the diagram ([0,0]-P_{AB}-P_{AC}-P_{BC}-[1,1-q]), the column is over-fractionated, that is, we are wasting energy. The values at the peaks give vapour flow Vmin for the corresponding sharp neighbour component splits. As the vapour flow V is reduced below the line for a given D, one more component will become distributed as we cross boundary lines. The point P_{AC} is the "preferred split" (Stichlmair, 2000) which is the minimum energy operating point for a sharp separation between the heavy and light keys while the intermediate distribute to both column ends. With the ternary feed, we only need thee points: P_{AB}: sharp A/B, P_{BC}: sharp B/C and P_{AC}: sharp A/C. To find the diagram for n components in the feed, we need to solve for sharp split between each possible pair of key components (ij) to find the n(n-1)/2 points P_{ij}. The V-min diagram for a 15 component aromatics feed (Dejanović et al., 2011) is shown in Figure 1b. Each of the 14 peaks represents Vmin and D for sharp component split. We will in the following use this feed and assess alternatives for separating it into four fractions (A: 5 most volatile components, B: two components, C: one, and D: the six heaviest). Then we only need the six points related to the four product splits 4(4-1)/2=6 as opposed to 15(15-1)/2=105. The highest peak in Figure 1b then need not to be considered since it is within the heavy group (D). We observe that V/F<1 for most of the remaining sharp splits. For real mixtures the diagram can be made by using a commercial simulator. For ideal mixtures with constant relative volatility and constant molar flows the Vmin diagram can be calculated in milliseconds by use of the classical Underwood equations. This is applied in this paper.

3. Minimum energy of generalized DWC from the V-min diagram

The real power of the V-min diagram is that it contains all necessary information to calculate the overall minimum energy requirement and all the internal flow rates for an optimally operated extended Petlyuk arrangement for an arbitrary multicomponent feed and any number of products (Halvorsen and Skogestad, 2003b).

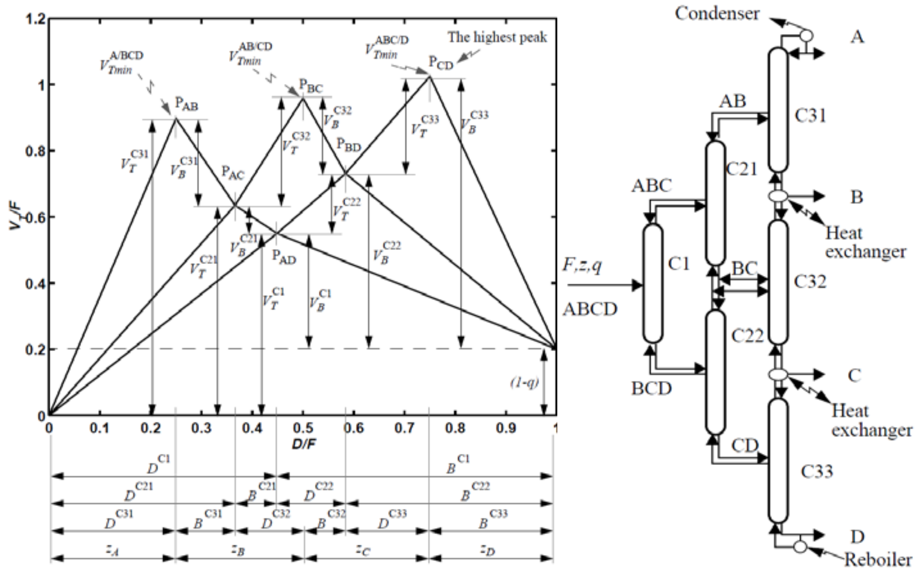


Figure 2: V-min diagram for 4-component feed, also showing how the internal flows in the complex extended four product Petlyuk arrangement are found.

The overall minimum energy is simply given by the highest peak. This peak represents the most difficult product split in a two-product column. It may be a bit surprising that by supplying this vapour rate to an extended four product Petlyuk arrangement as shown in Figure 2 we get all the other products separated for “free”. The key is that in an optimally operated arrangement, each sub-column must be operated at its local “preferred split”. Generally we would need to calculate the minimum energy for each succeeding column, but at minimum energy operation all the information can be obtained from the V-min diagram which is based on feed data only. Each section’s vapour flow and net top product flow can be found as a difference between the peaks and knots in the V-min diagram as illustrated in Figure 2. (Superscripts denote sub-columns, and the subscripts T and B denote the top or bottom section in that sub-column). The liquid flow rates and bottom net flows are uniquely determined from simple mass balances.

4. Interpretation of the V-min diagram

The V-min diagram gives important information about the load in each section of a DWC. The peaks are normally of different heights, indicating that the vapour loads for the different product separations also are different.

4.1 Increased 2nd law thermodynamic efficiency

One may in order to improve the thermodynamic (2nd law) efficiency apply heat exchange at each side-stream stage as illustrated in Figure 2 and condense or vaporize an amount of vapour/liquid representing the difference in the height of the peaks. For limited heat removal and differences less than the total side stream, an alternative is to extract a part of the side stream product as vapour. However, use of external heat exchangers is not practised in conjunction with DWC columns. Nevertheless, for certain cases with large differences it might be a good idea to do it, and also reduce diameter in the upper part of the column.

4.2 A practical four product (4p) DWC

The vapour flow corresponding to the highest peak is normally supplied in the reboiler and passes through the whole arrangement. The DWC shown in Figure 4a is equivalent to the extended Petlyuk arrangement in Figure 2 without heat exchangers. The splits corresponding to the other peaks will then be done with higher vapour rate than actually required. This gives a certain tolerance in the operation which may be beneficial, since each sub-column does not have to be operated exactly at its local preferred split. This gives us more flexibility in both design and operation. In our 4p example the peak P_{CD} representing the C/D split sets the overall minimum vapour flow rate requirement. However, the parts of the arrangement leading up to the other products are in a way “over-refluxed”. This gives us the possibility to alter operation of the internal sub-columns, as long as this is done in a way that does not affect the “highest peak”. When we choose an operating point above the local preferred split for a sub-column we get a new V-min diagram for the succeeding part of the arrangement where the peaks now are somewhat lifted as illustrated in Figure 3.

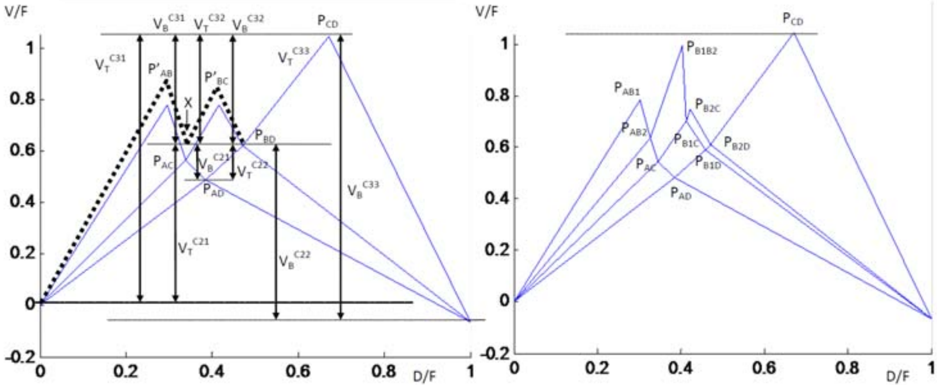
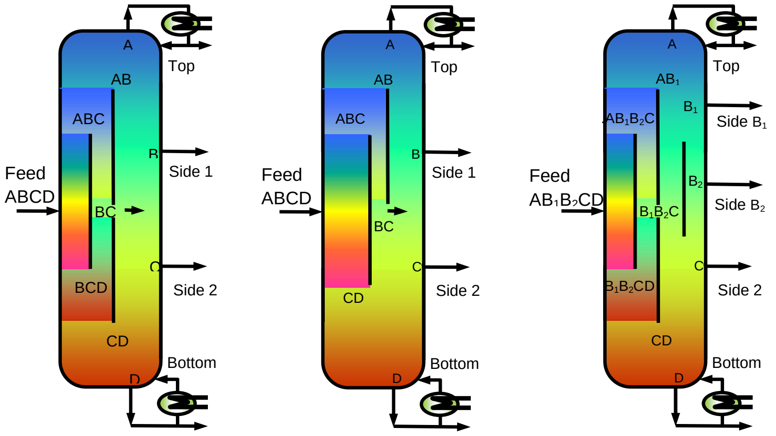


Figure 3: V-min diagram for 4p feed (left) also showing how peaks P'_{AB} and P'_{BC} are lifted when the flow in C21 are set to make vapour flow in top of C22 equal to bottom of C21.V-min diagram for 5p feed where we split B into two components B1 and B2.

This can be done by accurate calculations, but we will only discuss it qualitatively here. When we consider the practical 4p DWC we may choose to have pure liquid connection into the feed junction of sub-column C32. This calls for equal vapour flow in top of C22 and bottom of C21. To obtain this, the vapour through C21 must be increased in a way that the point P_{AC} representing the A/C split (which is carried out in C21) is aligned with the point P_{BD}, representing the B/D split (which is carried out in C22). This will lift either peak P_{AB} or P_{BC} or both. In the illustrated case we find a solution where the lifted peaks still are below the highest peak. Thus the proposed practical arrangement with no vapour crossing into C32 is feasible, and there is also a certain tolerance in selection of operating point (X in Figure 3). We then continue and look closer at operation of the prefractionator (C1). If we move the operating point along the boundary line from the preferred split at P_{AC} towards P_{BC} this will not lift the highest peak P_{CD}, only P'_{AB}, and the point P'_{AC}. As long as the lifted P'_{AB} is below P_{CD} we do not increase the overall vapour flow demand. Due to the different height of peaks we obtain some tolerance in operation that can be used for handling of feed property variations and uncertainties without increasing energy requirement. It is common to keep the vapour splits fixed by design, but the liquid splits should be adjustable.



a) Practical 4p DWC *b) Simplified 4p-DWC* *c) Special 5p-DWC*

Figure 4: Multiple partition wall DWC configurations considered.

4.3 Simplified four product column

In this particular case we actually may move the prefractionator operating point all the way to P_{BD}. As we approach operation at P_{BD} the net distillate product from sub-column C22 diminish, thus, C22 (in Figure 2) becomes superfluous and can be removed. At the bottom of C1 we only have components CD and these can be passed directly to sub-column C33. Sub-column C32 gets its feed from the bottom of C21 only. In a DWC the equivalent of this is removal of the lower right partition wall as shown in Figure 4b. The prefractionator (C1) has to take an increased load, so the partition wall must be shifted closer to the centre of the column. But, the overall vapour flow rate and thereby the diameter of the DWC can remain unchanged. This solution is possible without increase in energy because the peaks P_{AB} and P_{BC} are considerably lower than P_{CD}.

4.4 Five product DWC

The general five product (5p) DWC would require another set of partition walls. In the general Petlyuk system we would need another set of sub-columns C41, C42, C43 and C44. However, we have some tolerance due to the different height of the peaks, so there may exist some simple solutions. And there is. Assume now that we separate our previous B-product consisting of two components into B_1 and B_2. From the V-min diagram we observe that the peak representing the B_1/B_2 split is also below the peak for C/D. Thus, separating B_1 and B_2 is in theory possible without adding more energy, and with the same column diameter. We would have to add more stages, though, so the column height will have to be increased accordingly. Figure 4c illustrates how we can do this by adding an extra partition wall only in front of the new outlet for B_2. This is equivalent to replacing sub-column C32 with a three-product DWC, fully thermally coupled to C31 and C33. To obtain this, the columns C21 and C22 are operated as in the 4p-arrangement namely to separate A/B_1 and B_2/D, while they rather should have been operated to separate A/B_2 and B_1/D if the full 5p procedure should be followed which implies to run each internal sub-column at its local preferred split and by that remove only one by one component from each end.

5. Conclusion

The V-min diagram can be used for both qualitative assessment of multicomponent separations and for the detailed calculation of internal flow rates in complex dividing wall columns. The highest peak sets the overall energy requirement for sharp product splits while the height and position of the other peaks and knots gives information about internal loads and also the possibilities for variation in operating conditions. This is important in order to be able to handle inevitable variations in feed properties and column performance and still obtain the potential energy savings in practice.

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