CHEMICAL ENGINEERING TRANSACTIONS

VOL. 69, 2018

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Elisabetta Brunazzi, Eva Sorensen

ISBN 978-88-95608-66-2; **ISSN** 2283-9216

Solution to Lestak's Heat Transfer Problem for Dividing Wall Columns and Implications for Practical Operation

Christoph Ehlers[a,*], Moritz Schroeder[a], Georg Fieg[b]

[a]Evonik Technology & Infrastructure GmbH, Paul-Baumann-Strasse 1, 45772 Marl, Germany
[b]Hamburg University of Technology, Am Schwarzenberg-Campus 4 (C), 21073 Hamburg, Germany
christoph.ehlers@evonik.com

Dividing wall columns (DWCs) are distillation columns containing a vertical inner wall in the area of the feed and the side product stage. Thereby, three high-purity fractions can be obtained in one single column. For the same task, two conventional distillation columns are needed. In many cases, DWCs thus have the potential to reduce investment costs. At the same time, it is also possible to save energy compared to a sequence of conventional columns. These benefits, however, can only be realized if the column is designed and operated in a sensible manner. If not, small internal changes of heat and material streams often cause a significant increase of energy demand. A famous paper about this topic was published by Lestak et al. (1994). The authors show simulation results indicating that small heat streams across the inner wall might strongly affect the energy demand of the DWC. A detailed explanation for Lestak's observation, however, was missing for many years. Ehlers et al. (2015) showed that the high sensitivity observed by Lestak et al. (1994) was due to resulting changes of the internal component splits in the prefractionator of the column. The authors also showed that such sensitivity can effectively be prevented with an additional temperature control (Ehlers et al., 2015). The first part of this paper shows how these findings help to gain a precise understanding of the internal processes inside dividing wall columns. Based on that, the second part focuses on the practical operation of DWCs. It is shown how a suitable control concept will allow to run the column in an energy-efficient manner even if different input parameters are not known exactly. Such a control concept is very important for industrial processes, especially when high-purity products are required. Combining simulation results with practical issues in industry, this paper aims to give relevant insights into this special type of distillation column.

1. Introduction

Dividing wall columns (DWCs) allow the continuous separation of a multicomponent feed stream into three pure fractions. In contrast to conventional distillation columns, this task can be solved by using one column only. Figure 1 shows the difference between both concepts. Dividing wall columns perform a first separation step inside the so-called prefractionator (feed side of vertical partition wall). The final separation into three pure fractions is performed inside the main column, which comprises the upper and lower parts of the column as well as the product side of the vertical wall. For these different separation steps, only one condenser and one reboiler are used. Intermediate heat exchanger between the separation steps are completely omitted. For conventional distillation columns, however, separate condensers and reboilers are needed for each binary separation step. Thus, by using less equipment for the same separation task, the resulting investment costs for dividing wall columns are typically smaller than for conventional distillation sequences. When it comes to energy demand for a certain separation task, dividing wall columns allow for corresponding savings as well. As shown for example by Agrawal and Fidkowski (1998), compared to a conventional sequence without further heat integration measures, the energy savings can be 30% and higher for a wide range of feed compositions. The thermodynamic advantage of DWCs compared to conventional distillation columns was first described by Petlyuk et al. (1965) more than 50 years ago. Twenty years later, in 1985, the first industrial application of this technology was finally achieved (Asprion and Kaibel, 2010). Since then, dividing wall distillation technology has become more and more popular within chemical industry. Today, it can be described as a well-established technology in the area of thermal separation processes (Kaibel, 2014).

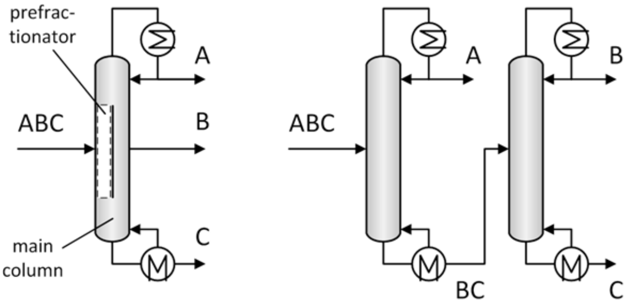

Figure 1: Dividing wall column and direct distillation sequence for the separation of three components A, B, C

A thermodynamic explanation about the actual reasons for the energy saving potential of dividing wall columns is given by Triantafyllou and Smith (1992). For both concepts in Figure 1, the authors show the concentration profile of the middle boiling component. For the first column of the distillation sequence, the profile shows a maximum value within the stripping section. Due to the overall mass balance being set, the concentration of the middle boiling component decreases again below that maximum (backmixing effect). Inside dividing wall columns, however, such backmixing can be omitted by using the prefractionator for a first, non-sharp, separation step between AB/BC. The middle boiling component is, thus, removed at both ends of the prefractionator before the final separation into pure products is carried out. According to Kaibel et al. (2004), this split of the middle boiling component around both ends of the dividing wall is the decisive thermodynamic difference that allows dividing wall columns to use less energy than conventional distillation columns for the same separation task.

2. Understanding Internal Processes inside Dividing Wall Columns

The proper split of middle boiling component B around both ends of the dividing wall is a prerequisite in order to raise the full energy saving potential of this technology. Without a decent understanding of the internal processes inside DWCs, it is, however, easily possible to not reach a perfect split of component B inside the prefractionator. It is actually even quite easy to not split the middle boiling component at all. In those cases, the light boiling or heavy boiling component (or parts of it) leave the prefractionator at the wrong side. In such a situation, the energy demand might rise drastically. As shown by Ehlers et al. (2015), without a proper split of component B in the prefractionator, it might even become impossible to reach desired product purities at all.

2.1 Splitting vapor and liquid streams at the ends of the dividing wall

At the ends of the dividing wall, the internal streams inside dividing wall columns are distributed between prefractionator (feed side) and main column (product side). The liquid stream is split at the upper end of the wall, the vapor stream is split at the lower end of the vertical partition. At first sight, one might gain the impression that the exact split of both phases is not too important, as long as energy input and overall mass balance of the column are kept at sensible values. This, however, is definitely wrong. Varying the split ratios of liquid and vapor directly influences the split of middle boiling component B on the feed side of the dividing wall. And this, as mentioned above, is a decisive quantity determining the overall energy demand of dividing wall columns.

$$CS_B = \frac{(V\, y_B - L\, x_B)_{prefrac,top}}{F_B} \tag{1}$$

In accordance with Fidkowski and Królikowski (1986), the component split of component B inside the prefractionator can be calculated with Eq(1). This equation contains the molar streams of vapor and liquid (V, L) at the top of the prefractionator and the corresponding molar fractions of middle boiling component B (y, x). Divided by the molar stream of B within the feed, one gets the molar fraction of component B leaving the top of the prefractionator. Ehlers et al. (2015) use the same quantity (CS_B) to explain the influence of internal vapor and liquid splits on the energy demand of DWCs. As shown in Eq(1), a variation of the internal vapor or liquid streams inside the prefractionator directly influences the split of B on the feed side of the dividing wall.

If the vapor stream rising on the feed side of the dividing wall is increased, the net amount of component B leaving the prefractionator at its top end typically will increase as well. For the liquid stream, however, it is the other way round. If the liquid stream entering the prefractionator is increased, the net amount of B leaving the prefractionator at its upper end typically will go down. Knowing that, one easily understands why there cannot be a constant optimal value assuring minimum energy demand for either the liquid split at the upper end of the wall or the vapor split at its lower end. In order to assure energy-efficient operation, the values of those quantities cannot be chosen independently. They have to fit together. If the vapor stream going up on the feed side of the wall is increased, the liquid flowing down on that side typically has to be increased as well in order stay at a point with minimum energy consumption. Other situations that can make it necessary to adapt the liquid and/or vapor splits are changes of feed compositions (cf. Table 1) or heat streams across the dividing wall. The effect of heat streams on the energy demand of DWCs was studied by Lestak et al. (1994). The authors simulate the separation of a mixture of methanol, iso-propanol, and butanol into product streams with purities of 95 mole-%. For this example, Lestak et al. (1994) observed a high sensitivity of the resulting energy demand on heat streams across the wall. A detailed explanation for this observation, however, was missing for many years. Ehlers et al. (2015) finally showed that the high sensitivity observed by Lestak et al. (1994) was due to resulting changes of the internal component splits in the prefractionator of the DWC. Heat streams across the dividing wall directly affect the amount of vapor rising on both sides of the wall due to condensation and evaporation effects. Therefore, a combination of vapor and liquid splits assuring minimum energy demand for an adiabatic base case might have to be adapted when heat streams are considered. As shown by Ehlers et al. (2015), keeping the same vapor and liquid split values for the adiabatic base case and the case with heat transfer across the wall directly explains the results observed by Lestak et al. (1994).

For a detailed analysis about the maximum impact of heat streams across the wall on energy demand of DWCs, the reader is referred to Ehlers et al. (2015). The present paper rather focuses on the way how temperature profiles are affected by improper split ratios and gives additional insight on that topic (cf. Figures 2 and 3).

2.2 Energy-Efficient Operation of Dividing Wall Columns

Instead of keeping the vapor and liquid split ratios at the end of the dividing wall constant for all situations, it is rather recommended to always assure a certain split of middle boiling component B inside the prefractionator. A famous paper providing insights about optimal operation of DWCs with respect to energy demand was published more than 30 years ago by Fidkowski and Królikowski (1986). Using a classical modeling approach for the description of distillation columns derived by Underwood (1948), the authors provide an analytical solution for the task to minimize the energy consumption of DWCs with an infinite number of theoretical stages.

Table 1: Optimal operation (minimum energy demand) for dividing wall columns with infinite number of stages and relative volatilities of 2.5 (original values from Fidkowski and Królikowski (1986) in columns 1 to 5, own calculation results for corresponding split ratios in columns 6 and 7)

Feed composition			Internal distribution / split ratios			
A (kmol/s)	B (kmol/s)	C (kmol/s)	$L_{prefrac,top}$ (kmol/s)	CS_B (-)	Liquid split (-)	Vapor split (-)
0.1	0.1	0.8	0.1905	0.29	0.30	0.43
0.1	0.8	0.1	0.1905	0.29	0.13	0.34
0.8	0.1	0.1	0.1905	0.29	0.32	0.73
0.33	0.33	0.34	0.1905	0.29	0.24	0.55

Calculation results from Fidkowski and Królikowski (1986) in Table 1 show that by keeping both the molar liquid stream to the top of the prefractionator and the internal component split of middle boiling component B inside the prefractionator constant at their optimal values, it is possible to stay at a point with minimum energy demand for all kinds of feed compositions. Concerning vapor and liquid splits, it is, however, important to notice that these values are not constant between the different scenarios in Table 1. The definition of liquid split (LS) and vapor split (VS) used in this paper is shown in Eq(2) and Eq(3). It is the molar fraction of the overall liquid or vapor stream inside the main column going to the feed side of the dividing wall. For the liquid stream, this value is calculated at the top end of the dividing wall (DW). For the vapor stream, it is calculated at the lower end.

$$LS = \frac{L_{prefrac,top}}{L_{main\ colum,above\ DW}} \tag{2}$$

$$VS = \frac{V_{prefrac,bottom}}{V_{main\ colum,below\ DW}} \qquad (3)$$

3. Energy-Efficient Operation of Dividing Wall Columns in Industrial Practice

The results of Table 1 verify that it is a good idea to keep the split of middle boiling component (CS_B) at a constant value. The question, however, is how this can be achieved in industrial practice. Staying close to a point with minimum energy demand is, of course, more challenging in an actual distillation column than in a simulation model. This part of the paper explains why and it also shows how a suitable control concept will allow to run the column in an energy-efficient manner even if different input parameters are not known exactly.

3.1 Differences between Simulation Model and "Real Columns"

When comparing the optimization of simulated distillation columns with the optimization of real columns in industrial practice, there are mainly two differences. First, in industrial practice, there are many different quantities that are not known exactly. Examples are the local heat loss including the heat transfer across the dividing wall, exact compositions on each stage, internal vapor streams on each side of the dividing wall and many more. And even for the quantities that can be measured (e.g. mass flows, temperatures, pressure drops) certain tolerances apply. Second, in contrast to simulation models, not every quantity can easily be changed in real life. When it comes to DWCs, an important quantity in this respect is the distribution of the vapor stream on both sides of the dividing wall. This split ratio is mainly determined by geometrical issues (free-cross sectional area, packing type/height or tray type/number) and it is also influenced by other topics like countercurrent liquid flow or heat loss issues. Therefore, even if the simulation model provided a perfect prediction for the actual plant (concerning physical property data, pressure drop models, models for separation efficiency, etc.), keeping the column at its energy minimum might still be a challenging task. The following part of the paper gives suggestions about how an energy-efficient operation of dividing wall columns can be achieved in industrial practice.

3.2 Energy-Efficient Operation of DWCs using Temperature Control

As mentioned above, the chosen values of vapor and liquid split can have a huge influence on the energy demand of dividing wall columns. This can be seen in Figure 2a, which was first published in AIChE Journal by Ehlers et al. (2015). The diagram shows the relative energy demand of a DWC separating a three-component feed stream into fractions with purities of ≥ 99.9 mole-% each. For these calculations, a common equilibrium stage model is used with an idealized chemical system showing constant relative volatilities of 1.5 for which the assumption of constant molar overflow is perfectly fulfilled. Relative energy demand θ is defined as the energy demand of the DWC compared to the energy demand of a distillation sequence with no additional measure of heat integration and an infinite number of stages. The feed stream contains equal molar amounts of each component. Figure 2a shows a broad area of operation (vapor splits between 36 % and 84 %) for which it is possible to save energy compared to a sequence of distillation columns with infinite number of stages. In order to get a fair comparison, the DWC was set up with a high number of stages as well. The operation point with minimum energy demand is shown at a vapor split of 0.65. There, with a split of middle boiling component B quite close to 0.5, it is possible to save 38 % of energy. The corresponding temperature profile, which strongly resembles the one shown by Halvorsen and Skogestad (1999), is shown in Figure 2b.

In order to save energy, it is important to choose sensible values for liquid and vapor splits. Arbitrarily choosing values of 0.5 each would typically not be a good idea. In this case, as can be seen in Figures 2a and 3a, such values would strongly increase the energy demand of the column. Compared to the optimal point shown in Figure 2b, the energy input would have to be raised by a factor of more than 2.3 in order to still reach desired product purities. This is because the resulting value of middle boiling component split CS_B within the prefractionator (-0.49 for Figure 3a) is far from having a sensible value in this case (cf. Figure 2a). $CS_B < 0$ means that the middle boiling component is not split within the prefractionator at all. It rather "flows in a circle" around the dividing wall leaving the prefractionator at its lower end. Luckily, the temperature profile for this (thermodynamically nonsensical) mode of operation looks quite different than the one for optimal operation (cf. Figures 2b and 3a). Especially in the upper part of the prefractionator, these differences are quite evident.

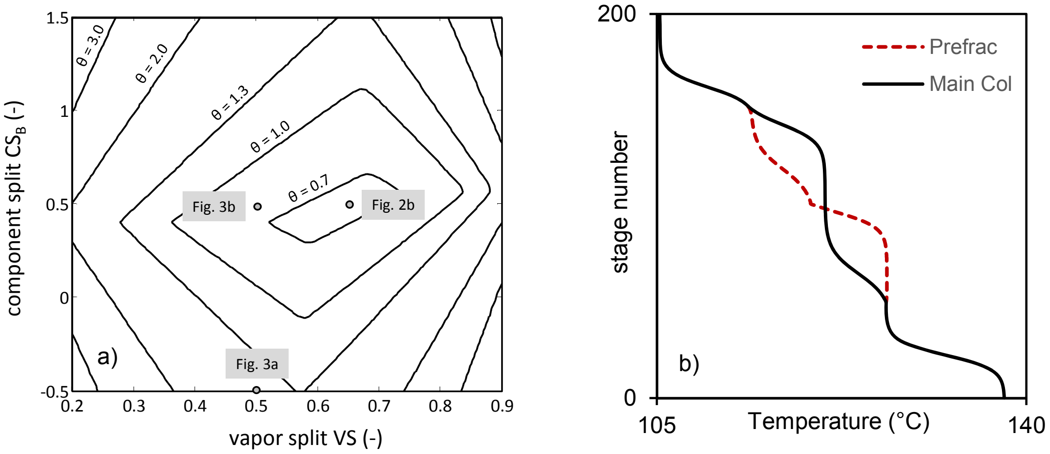

Figure 2: a) Relative energy demand θ of DWC as a function of CS_B and vapor split (Ehlers et al., 2015), b) Temperature profile of operation point with minimum energy demand (θ = 0.62)

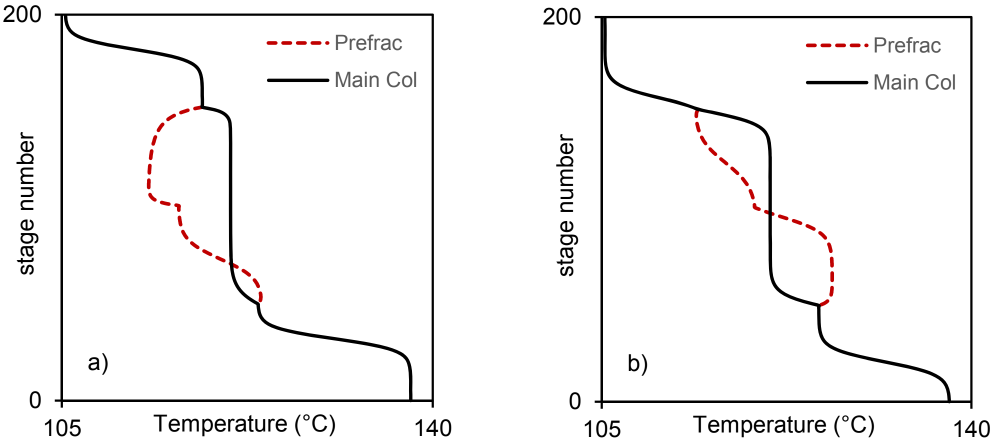

Figure 3: Temperature profiles for two points shown in Figure 2a, a) operation with vapor split and liquid split at 0.5 (energy demand θ = 1.46), b) operation with vapor split = 0.5, liquid split changed to keep temperature on third stage above feed on same value (119.4 °C) as in Figure 2b (energy demand θ = 0.79)

As mentioned above, for real columns, there are some uncertainties especially about the exact value of vapor streams entering and leaving the prefractionator. A direct and precise measurement of these streams is hardly feasible. And the prediction of these values is also only possible with a certain error. This is mainly due to uncertainties of pressure drop correlations and it might also be affected by heat streams across the dividing wall. Therefore, at first sight, assuring energy-efficient operation of dividing wall columns might look like a very challenging task. An exact determination of the vapor streams inside the prefractionator is hardly possible. At the same time, varying this value in small ranges can have a huge effect on the energy demand of the column. So, how to solve this problem? There will always be uncertainties about vapor streams flowing inside the prefractionator. There will also always be uncertainties about the heat streams crossing the dividing wall. As shown by Ehlers et al. (2015), however, by using a suitable temperature control concept, energy-efficient operation of DWCs is possible despite those uncertainties. One does not have to know the exact vapor streams, one does not have to know the exact heat streams crossing the wall, and one does not even have to prevent those heat streams by insulating the wall. The only thing one has to make sure is that the liquid split at the upper end of the dividing wall will fit to the respective situation. Thus, it is possible to reach sensible values for the split of middle boiling component B, which will result in a clear reduction of energy demand.

The following paragraph provides a short summary about how such temperature control could be applied. If, for the case study shown in Figures 2 and 3, one tried to operate the dividing wall with minimum energy input, one should try to design the column in such a way that 65% of the vapor stream will flow to the feed side of the dividing wall. Using a temperature control loop, the liquid split should be used to keep the temperature on the third stage above the feed inside the prefractionator at 119.4 °C. The resulting temperature profile of this optimal point ($\theta = 0.62$) is shown in Figure 2b. If the real vapor split was 50% instead, without temperature control, the resulting energy demand that would be needed to keep product purities ≥ 99.9 mole-% would rise drastically ($\theta = 1.46$). The corresponding temperature profile for this case is shown in Figure 3a. With temperature control of the liquid split, however, an unexpected vapor split of 50 % would be far less problematic. By using the liquid split to keep the temperature three stages above the feed at 119.4 °C again, sensible values for the split of component B inside the prefractionator could be reached (cf. Figure 2a). The temperature profile for this case (Figure 3b) looks quite similar to the optimal case in Figure 2b. The resulting energy demand would go down from $\theta = 1.46$ to $\theta = 0.79$ still allowing energy savings of 21 % compared to a sequence of conventional columns.

4. Conclusions

Dividing wall columns are a good alternative to sequences of conventional distillation columns. If operated in a sensible manner, DWCs are thermodynamically more typically more efficient than conventional sequences without additional measures for heat integration. In order to find energy-efficient operating points, one should calculate the split of the middle boiling component inside the prefractionator. Thermodynamic details on this topic were published in an earlier paper by Ehlers et al. (2015). The current paper extends those results by providing additional practical information like temperatures profiles of the overall column for different cases of middle component split (cf. Figure 2 and Figure 3). Those temperature profiles contain valuable information. This is because in real columns, the split of the middle boiling component inside the prefractionator cannot be measured directly. The temperatures inside the prefractionator, however, provide valuable hints about whether the column is operated in a sensible manner or not. Therefore, one can set up a temperature control loop with the liquid split as manipulated variable that makes sure that the liquid split at the upper end of the dividing wall will fit to the current situation. Uncertainties about vapor streams and heat streams in the prefractionator being present in real columns will, thus, just have slight effects on the overall energy demand. With such a control strategy, one does not have to insulate the dividing wall (as suggested by Lestak et al. (1994)) to ensure energy-efficient operation. At this point, of course, one has to keep in mind that the calculation results presented in this paper do not account for any maldistribution effects (like increased wall flow of liquid) due to heat transfer across the wall. Potential mechanical issues due to high temperature differences across the dividing wall are neglected as well. If these topics might become problematic for certain special cases, insulating (parts of) the dividing wall might still be an option.

References

Agrawal R., Fidkowski Z., 1998, Are Thermally Coupled Distillation Columns always thermodynamically more efficient for ternary distillations?, Industrial & Engineering Chemistry Research, 37, 3444-3454.

Asprion N., Kaibel G., 2010, Dividing Wall Columns: Fundamentals and recent advances, Chemical Engineering and Processing: Process Intensification, 49, 139-146.

Ehlers C., Schröder M., Fieg G., 2015, Influence of Heat Transfer across the Wall of Dividing Wall Columns on Energy Demand, AIChE Journal, 61, 1648-1662.

Fidkowski Z., Królikowski L., 1986, Thermally Coupled System of Distillation Columns: Optimization procedure, AIChE Journal, 32, 537-546.

Halvorsen I.J., Skogestad S., 1999, Optimal Operation of Petlyuk Distillation: Steady-State Behavior. Journal of Process Control, 9, 407–424.

Kaibel G., Miller C., Stroezel M., v. Watzdorf R., Jansen H., 2004, Industrieller Einsatz von Trennwandkolonnen und thermisch gekoppelten Destillationskolonnen, Chemie Ingenieur Technik, 76, 258-263.

Kaibel B., 2014, Dividing-wall columns, Chapter In: A Górak and Z Olujić (Eds.), Distillation: Equipment and Processes, Academic Press, London, UK, 183-199.

Lestak F., Smith R., Dhole V.R., 1994, Heat-Transfer across the Wall of Dividing Wall Columns, Chemical Engineering Research & Design, 72, 639-644.

Petlyuk F.B., Platonov V.M., Slavinskii D.M., 1965, Thermodynamically Optimal Method for Separating Multicomponent Mixtures, International Chemical Engineering, 5, 555-561.

Triantafyllou C., Smith R., 1992, The Design and Optimization of Fully Thermally Coupled Distillation Columns, Chemical Engineering Research & Design, 70, 118-132.

Underwood A., 1948, Fractional Distillation of Multicomponent Mixtures, Chemical Engineering Progress, 44, 603-614.