Thermodynamic Analysis of Heat Transfer Across the Wall of the Dividing-Wall Column
On-line Number 0145

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ABSTRACT

The dividing-wall column, a compact structure of the fully thermally-coupled distillation or the Petlyuk column, has been known for around half a decade. Typically, it can claim up to 30% savings in terms of both capital and energy costs when compared to the other conventional column arrangements. The dividing wall column is thermodynamically equivalent to the Petlyuk column on the condition that no heat transfer is allowed across the dividing wall. However, better energy efficiency of the column may be obtained if heat transfer occurs within a certain part of the wall. The effects of heat transfer across the dividing wall can be analyzed by using the Column Grand Composite Curve (CGCC) [Lestak, et al., 1994]. The heat transfer potential across the wall can be observed by looking at the CGCC of both column sections alongside the dividing wall. However, the possibility of whether heat should be added or rejected at any stage is not clearly known ahead of the CGCC. Consequently, in this work, the exergy analysis is applied to the dividing wall column in order to determine whether heat should be added or rejected at any particular stage. The heat load targets at any stage, plotted as a T-H profile similar to the CGCC, can then be determined using the Method of Pinto (1998). This method was reported to successfully apply to the column with multiple feeds and products. After having identified the locations and quantities of the feasible heat transfer across the dividing wall, the benefits are discussed via a case study.

KEYWORDS

Fully thermally-coupled distillation column, Dividing-wall column, Column exergy loss.

INTRODUCTION

The complex distillation columns such as column with side rectifier or side stripper are now used widely in the industrial communities due to their lower energy requirement than the equivalent conventional column sequences. Another type of complex column, the fully thermally-coupled column or the Petlyuk column (Figure 1a) which has been known for around 50 years, can also save the energy of about 30% compared to the conventional sequences [Petlyuk, et al., 1965]. Furthermore, the construction of the Petlyuk column may be carried out in a single shell with a dividing wall installed at the middle column section. As a result, the so-called dividing-wall column (DWC, Figure 1b) can save the capital investment by around 30% [Triantafyllou, et al., 1992]. Even though the advantages of DWC in terms of both energy and capital can be realized, not until the recent two decades, has its industrial application become ever more realistic. The world’s first
DWC was established by BASF in 1985. In addition, the understandings of control and operability issues have been much improved [Wolff, et al., 1995; Abdul Mutalib, et al., 1998]. Since then, many more of the dividing-wall columns have been established worldwide, such as in Europe, South Africa and the U.S. [Greene, 2001].

A number of design methods for the DWC were proposed by several researchers [Nikolaides, et al., 1988; Carlberg, et al., 1989; Triantafyllou, et al., 1992]. One common assumption of these methods is that no heat transfer occurs across the wall dividing between the prefractionation section and the middle section of the main column. In the real DWC operation, however, the heat transfer across the wall can occur unless the insulated wall is applied. The study of Lestak et al. (1994) revealed that the heat transfer across the wall may be allowed in certain region of the wall. While, in the other regions, heat transfer across the wall may not be allowed otherwise it could incur the energy penalty to the column. Their analysis was based on the application of Column Grand Composite Curve (CGCC) to identify the possible location of horizontal heat transfer across the wall. However, the generation of CGCC is based on the minimum thermodynamic condition of distillation column, which is just theoretical, thus only approximation. The modeling of the DWC is also approximated by the column with prefractionator, which is not the Petlyuk column or the DWC. Recently, the thermodynamic analysis method was applied as an additional tool in the construction of CGCC. This method was proposed by Pinto (1998). The exergy loss profile of the distillation column is analyzed and used to establish the heat load target for any particular stage in a real column. This heat load target represents the actual amount of heat, which may be added to or removed from that corresponding stage of the column, therefore exhibiting the real target not just the theoretical value. The profile of heat load targets was called the minimum driving force profile (MDFP), which can be used to identify the suitable location for installing side cooler or side heater. In addition, the methodologies for establishing the MDFPs for some types of complex columns such as columns with multiple feeds, multiple products, side rectifiers or side strippers were also proposed. The MDFP can also be applied to identify the possible location of horizontal heat transfer across the wall of the DWC in the same manner as Lestak et al. (1994) used the CGCC in their work. Here, the underlying methodology of thermodynamic analysis of distillation column will be briefly discussed.

**THERMODYNAMIC ANALYSIS OF DISTILLATION COLUMN**

Pinto (1998) proposed a thermodynamic methodology for the analysis of distillation columns. Exergy analysis is used to establish the MDFP, which gives the benefit in identifying the feasible targets for installing side heaters or side coolers. This approach is superior to the previous CGCC approach [Dhole, et al., 1993], as there is no heat load penalty incurred and no temperature shifted due to installing the side exchanger with the target amount of heat load. However, some additional stages have to be installed once adding a side exchanger. The addition of side exchanger to the column will reduce the exergy loss around that stage location, and also alter the vapor-liquid traffic in that region. For side condenser, the vapor-liquid flow above the side condensing stage will be reduced. Accordingly, some stages must be added between the side condenser and the main column.
condenser in order to maintain the same separation work, otherwise the overall energy consumption will increase. For side reboiler, some extra stages have to be added below the side reboiling stage with the similar reason as above. In other words, it may be said that to maintain the amount of energy requirement in the column, the penalty on adding some extra stages has to be sacrificed.

From the Pinto’s methodology, the heat load target at any stage in the column can be determined by using the exergy loss criteria. Once adding some extra stages to the column as explained above, the vapor and liquid flows below side condensing stage or above side reboiling stage, and also the product specifications have to be kept the same as before installing any side exchangers. More stages may be added until the exergy loss value around the side exchanging stage approaches the exergy loss target, the heat duty at this condition will be the heat load target at that particular stage (Figure 2). Generally, the exergy loss target is usually set as the minimum exergy loss value at any stage in the column. For any conventional column, the minimum exergy loss value will appear at or near the feed stage. After having determined the heat load target at each stage, a T-H profile of the column can be generated. This so-called Minimum Driving Force Plot (MDFP) shows the heat load that can be added to or removed from any temperature level in the column.

Furthermore, this methodology was extended to the column with multiple feeds and multiple products. Briefly explained here, for column with multiple feeds, the exergy loss profile also shows the minimum exergy loss value around a certain feed stage. As shown in Figure 3, Feed 1 represents the main feed of the column, and the minimum exergy loss near Feed 1 will be the target value when installing any side exchanger to the column. Above this feed, only side condenser will be allowed. The same rule still applies when adding side reboiler below the main feed stage.

Figure 2: Determination of heat load target by using exergy loss criteria.

Figure 3: The Minimum Driving Force Plot for column with multiple feeds.

Figure 4: The Minimum Driving Force Plot for column with multiple products.
For column with multiple products such as one shown in Figure 4, the minimum exergy loss value is typically found around the feed stage. As in the simple column, side condenser can only be applied to section I above feed, and side reboiling applied to section II and III below the feed. To determine the heat load target for any stage in section I and III, the methodology for simple column can be used as regular. However, the heat load target for any stage in section II will be limited by the maximum heat load determined at the side draw stage, as shown in Figure 4. Also, the sidedraw stage signifies the partition of stripping section into two subsections (section II and III). The heat load target for any stage in section II can be determined by adding some extra stages to section II. However, the vapor and liquid flows in both section II and III will be reduced once installing any side reboiler. For this reason, some extra stages must also be added to section III if the total energy consumption is to be maintained. This methodology is also practical with the column with vapor or liquid sidedraw above feed where only side condenser is allowed.

For any column with multiple feeds and side products, the methodologies for column with multiple feeds and multiple products can be used in combination. First, the main feed stage, where the stage exergy loss is minimum, has to be identified, hence dividing the column into rectifying and stripping sections. Next, the sidedraw locations will divide the column into more subsections. The heat load target for any stage in the top-end and bottom-end sections can be determined in a similar way as simple column. Finally, the heat load target for any stage in the intermediate sections can be determined in the same manner as the column with sidedraws.

The generation of MDFP for the DWC can also be generated by the methodologies explained above. However, they cannot be applied directly since the prefractionation and the middle sections are connected to each other at both ends, as shown in Figure 5. The modified procedure to create the MDFP for the DWC will be outlined in the next section.

**THERMODYNAMIC ANALYSIS OF THE DIVIDING-WALL COLUMN**

As seen in Figure 5, the condensing load may be shifted from the main condenser to either the prefractionation or the middle sections. This is similar to the reboiling load, which may be shifted into either of these sections. At any particular stage in the column section, either side condensing or side reboiling loads may only be applied. To determine which types of side duties is appropriate for any stage, one needs to consider the exergy loss profile for each column section. Similar to the simple column, the stage with minimum exergy loss value will divide the column into rectifying and stripping sections. Above this stage, only side condensing is possible, while side reboiling is only allowed below that stage. The maximum side condensing load which may be shifted into the prefractionation or middle sections, is determined by the heat load target at the upper connection (UC) or stage above the dividing wall. Likewise, the maximum side reboiling load which may be shifted into those sections alongside the wall is limited by the heat load target at the lower connection stage (LC). Here, the potential of heat transfer across the wall of the DWC can now be identified. In the column sections on both side of the wall, heat transfer between them can occur when a stage with possible side condensing in one
section is at the same vertical height as another stage with possible side reboiling in the other section. The stage location between the couple column sections, which require a similar type of side duty, should be insulated to prevent heat transfer across the wall, hence avoiding any energy penalty to the column. The target heat load, which should be transferred across the wall, can be determined by the MDFP of each column section. Finally, the rigorous simulation of the DWC with heat transfer across the wall can be carried out to evaluate whether any energy saving could be achieved.

This modified procedure for generating the MDFP of the DWC and to analyze the heat transfer across the wall will be illustrated by a case study, as will be explained further.

A CASE STUDY

The separation of Benzene-Toluene-p-Xylene (BTX) mixture using the DWC was studied here. The feed mixture contains 30 %mol Benzene, 40 %mol Toluene, and 30 %mol p-Xylene. The feed is at 1.6 bar(a), and saturated liquid with flowrate of 1,000 kmol/hr. The product specifications are 95% molar recovery of Benzene, Toluene, and p-Xylene in Top, Middle, and Bottom products, respectively. The column design is shown in Figure 6. The simulation of the base case is carried out in HYSYS.Plant version 3.1 without any heat transfer between the column sections on both side of the wall. To determine the potential and scope of heat transfer across the dividing wall, the outlined procedure as explained in the previous section can now be followed. First, the exergy loss profiles of all column sections are determined as shown in Figure 7 and 8. It can be seen that the stage with the minimum exergy loss in the prefractionation section is near the main feed stage, whereas the lowest stage in the middle section shows the minimum exergy loss value. From Figure 7, section I and IV, like the conventional column, can allow for side condensing and side reboiling, respectively. Since the minimum exergy loss appears around the main feed stage, the side condensing load can be shifted from the UC stage into the top section of prefractionation (section V). Similarly, the side reboiling can only be applied to the bottom section of the prefractionation (section VI) by shifting the heat load from the LC stage. In the middle section (II, and III), however, the side condensing can only be used because the lowest stage in the middle section shows the minimum value of exergy loss hence making it the partitioning stage as shown in Figure 8. Only side condensing is allowed above the LC stage. At this
point, the potential heat transfer across the dividing wall could occur between section III and section VI. When considering the feasibility of heat transfer as shown in Figure 9, it becomes obvious that some amount of heat could be transferred from some stages in section III to their corresponding stages in section VI.

The MDFP for all column sections can now be generated as shown in Figure 10. It can be seen that the MDFP of the middle section (II, and III) is the heat source while the MDFP of the prefractionation section VI is the sink profile. For better illustration, these profiles are plotted separately as shown in Figure 11. The overlap between the source (section III) and sink (section VI) profiles occur only partially. The maximum amount of heat load that can be added to section VI is 139 kW whereas only about 82 kW can be rejected from section III. Thus, the target amount of heat transfer between these sections is limited by the maximum amount of heat removal from section III.

Also, the corresponding stages between section III and VI cannot be evenly matched when looking at the overlap between their MDFP profiles. However, in actual column, heat transfer can occur only between the stages at the same vertical height on both sides of the wall. The 11th to 21st stages on the prefractionation side are respectively matched with the 16th to 26th stages on the main column side. The matching between the 22nd stage on the prefractionation side and the 27th stage on the main column side is, however, not feasible due to negative temperature driving force. The rigorous simulation of the DWC with heat transfer across the wall between section III and VI can now be carried out to check whether there is any energy saving benefit from this consideration. By assuming that the UA values for any stages with heat transfer are the same, the target amount of heat transfer is distributed to each match of the stages on both sides in proportion to the temperature driving force at each match. The amount of heat transfer across the wall near feed location is therefore larger than the amount at the lower-end of the dividing wall. The simulation results show that the energy savings in condensing and reboiling loads of around 0.6% each can be achieved in relation to the base case without any heat transfer across the wall. Also, the overall exergy loss saving is around 0.5%. The possible reason for such a small energy saving may be the energy
penalty incurred from not adding some extra stages once allowing for heat transfer across the wall. In this case, the extra stages were not added in order to maintain the physical match of the corresponding stages on both sides of the wall.

Figure 10: The MDFP of all column sections of the dividing-wall column for BTX separation.

However, the heat transfer across the wall can be allowed at some stages in the feasible region. For example, between the 11th to 14th stage of the prefractionation and the 16th to 19th stage of the main column, where driving forces are not as tight as in the lower-end of the wall, the energy savings in condensing and reboiling loads of around 2.4% each can be achieved. Also, around 2.4% reduction in the overall exergy loss can be obtained. This partial heat transfer shows that the lower energy penalty could be incurred if the heat transfer across the wall at region with tight driving force is not allowed.

Figure 11: The MDFP of the column sections on both sides of the dividing wall.
CONCLUSIONS

A thermodynamic analysis, based on the methodology developed by Pinto (1998), has been applied to the dividing-wall column in order to determine the region of the wall, at which heat transfer can be allowed to benefit in terms of energy consumption. In addition to the identification of the potential heat transfer region, the target amount of heat transfer was also determined from the application of the Minimum Driving Force Profile (MDFP). The application with the dividing-wall column was successfully illustrated via a case study. Some amount of energy savings could be achieved if the target amount of heat transfer is allowed at the suitable location of the dividing wall. The amount of energy saving was less than the amount of heat transfer across the wall due to the energy penalty incurred from not adding any extra stages. Although the energy savings were small, the insulation cost of the dividing wall in those parts with heat transfer can be saved. Furthermore, in the case of BTX separation by the DWC, it was shown that the heat transfer across the wall only at the feasible locations with adequate driving force could achieve a higher energy saving of the column which was 2.4% saving compared to 0.6% saving when heat transfer at locations with tight driving force were also allowed. The amount of energy savings in this case may be so small due to the narrow scope for exergy loss reduction in column section III. However, for any cases which show high exergy loss in column sections, a larger improvement in energy saving may be achieved. In practical aspect, the heat transfer across the wall of the DWC could only be allowed in tray column with the same tray location and spacing on both sides of the dividing wall. In contrast, it may be difficult to apply this idea to the DWC with packing internal.

REFERENCES


