Hydraulic Driven Active Vapor Distributor for Enhancing Operability of a Dividing Wall Column

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ABSTRACT: A novel active vapor distributor (AVD) was proposed to address the need for vapor split control during dividing wall column (DWC) design and operation. A DWC’s energy efficiency can be significantly reduced by a small deviation in the vapor split ratio; therefore, the vapor split ratio needs to be regulated during operation. In the proposed AVD, vapor splitting was implemented by a modified chimney tray with a specially designed cap. The liquid level of the chimney tray on each end side of the dividing wall section could be adjusted to control the vapor flow split. As the proposed AVD adjusts the friction of the vapor flow path efficiently without any mechanical moving parts, it can realize a more reliable operation of a DWC. The performance of the proposed AVD was evaluated, and the results demonstrated its easy implementation and superior ability to regulate vapor flow split during DWC operation.

1. INTRODUCTION

A dividing wall column (DWC) consists of two conventional distillation columns that are integrated into a single column with an internal wall partition to separate multicomponent feed mixtures into high purity product specifications.1,2 In the chemical and petrochemical industries, the distillation process is a representative process that is associated with large energy and capital costs. DWCs have, therefore, received considerable attention from both academia and the industrial sector because of their notable energy and cost saving potential in industrial distillation applications.3–5 Advanced DWC technologies, such as reactive, extractive, and azeotropic DWCs, have been actively considered in recent years.5–9 However, despite its potential applications, DWC technology has had a slow acceptance in the distillation process industry, and only hundreds of DWCs have been installed in industrial applications. The operability and controllability issues associated with the limitation of vapor split control during operation have limited its commercial application.

A DWC has more design variables than a conventional distillation column, such as a liquid and vapor split (Figure S1). Liquid and vapor splits in DWCs are defined as the ratio of each stream flowing into the prefractionation section to that flowing to the main fractionation section. Liquid and vapor splitters are needed to properly distribute the liquid and vapor flows to each section divided by the dividing wall (DW). Several researchers have observed that the liquid and vapor split ratios are the key parameters, and they play an important role in the optimal design and operation of DWCs.10–13 Generally, the energy efficiency of a DWC is sensitive to the optimality of the vapor or the liquid split ratios; therefore, it can be severely reduced by a small deviation in either the vapor or the liquid split ratio from the optimal conditions. The liquid and vapor split ratios could be affected by the uncertain feed composition in the system and its relative volatilities.14 Figure S210 shows the effects of internal flow distribution on the reboiler duty consumption in a DWC for different compositions. As can be seen from the trend plot, the minimum reboiler duty of a DWC is attained at different vapor and liquid flows when the feed composition is changed. The trend plot also indicates that the reboiler duty could quickly deviate far from the minimum if either the liquid or vapor flow tilts to the wrong direction,10 which would increase the total costs required to meet the product specification.

During DWC operation, the operator can simply adjust the liquid split ratio by using an active liquid splitter. Several different forms of commercial liquid splitters are already available and widely used, such as the moving bucket type splitter, the manual reflux splitter, and the in-the-column reflux splitter.16 However, a vapor split arrangement that can optimally manipulate the splits of vapor streams has proved elusive and remains a serious challenge in practical operation of DWC.2,17 Most of the studies related to DWC control and...
operation ignore the use of a vapor splitting device as a degree of freedom because of its practical limitation in industrial implementation.\textsuperscript{19,20} In most existing DWCs, vapor splitting is fixed in the design stage by a specific fixed open area for vapor flow\textsuperscript{14,15} and thus cannot be adjusted during column operation. In such a configuration, the vapor split ratio tends to respond inversely to changes in the liquid split ratio because of the variation in hydrostatic pressure of the liquid in each section.\textsuperscript{6} This tendency can cause an unfavorable loss in separation efficiency and result in higher reboiler duty to compensate for the loss in efficiency.

Vapor splits need to be actively controlled so that the optimal vapor split ratio can be maintained in the occurrence of operation variations. Although the use of a vapor split controller has not yet been reported in industry, several studies have highlighted the importance of a control strategy to adjust vapor splits, as it would result in stable regulatory control against both feed flow rate and composition disturbances.\textsuperscript{20–23} Nevertheless, very few studies have been found on the active vapor splitter. Dwivedi et al.\textsuperscript{15} proposed an adjustable vapor split consisting of two separate vapor valves that were driven by externally placed electrical motors using a rack and pinion assembly. In their vapor splitter, the vapor split ratio is controlled by the degree of opening a cap that sits on a steel valve seat. UOP\textsuperscript{24} patented an external vapor control system that blocked upward vapor flow located below the DW and flowing vapor from below the vapor isolation system to both sections of DWC through external vapor conduits. Recently, Huaqiang et al.\textsuperscript{25} applied the blade-shape structure inside each vapor channel to adjust the vapor split in a DWC by changing the blade angle. In their system, the blade is connected to an axle and operated by an externally placed electrical motor.

In practice, the vapor splitter should operate for at least 8400 h/year without mechanical problems. In developing an ideal internal flow-splitting device for DWC application, the following technical requirements should be considered: (1) the device should not include a pump and moving unit, (2) the additional volume contributed by the device should be small, (3) the device should be able to manipulate and control the split ratio in a stable and accurate manner, and (4) the device should be simple, durable, and reliable.\textsuperscript{16} The moving elements of the vapor splitter can be damaged by continuous movement of the mechanical parts. Therefore, any vapor splitting equipment requiring an inserted axle and mechanical/electrical moving unit could have potential mechanical trouble and leaking and quaking problems, which would increase the capital and maintenance costs. The concerns associated with these potential problems might limit the real implementation of this type of vapor splitter in DWC.

In this paper, a hydraulic driven active vapor distributor (AVD) was proposed to address the potential problems associated with a mechanically driven vapor splitter. In the proposed AVD, the friction of a vapor flow path is hydraulically adjusted by changing the liquid level of a modified chimney tray, rather than directly changing the angle or the opening position of a mechanical element inside the column. The proposed AVD was evaluated under different operating conditions to demonstrate its performance. The proposed AVD can be simply implemented by a minimum modification of a popular chimney tray and requires minimum or no mechanical unit. Furthermore, it is expected to offer a more reliable and robust vapor split during DWC operation.

### 2. STRUCTURE OF THE PROPOSED ACTIVE VAPOR DISTRIBUTOR

Figure 1 shows the 3D drawing of the proposed active vapor distributor (AVD).\textsuperscript{26} It consists of two valves for the liquid level controller and several chimneys (the number can be varied according to the design) which are surrounded by a cap that has windows as vapor channels. The top side of the caps is closed to circumvent the liquid flowing into the vapor channels. As visualized in Figure 2, the vapor leaves the cap through the windows. The quantity of vapor flow is controlled by adjusting the liquid level in each section. The chimney tray, the column wall and weir collect liquid flowing from the upper tray. To adjust the liquid level, liquid flow from the chimney tray is conveyed to the tray below through a control valve that is similar to the one used in conventional distillation columns. The height of the liquid overflow weir is designed to secure a minimum area for the vapor flow path and to prevent downward liquid flow through the openings of chimneys. When the liquid level in the chimney tray is above the weir height, the liquid automatically flows over the weir and down to the liquid collector tray below before it floods into the vapor channels of inner chimneys (i.e., 9 in Figure 2).

### 3. EXPERIMENTAL APPARATUS

Figures 3 and 4 show the schematic and photograph of the experimental apparatus for evaluating the proposed AVD, respectively. This laboratory setup which consists of two columns is equivalent to the DW section of a DWC for demonstrating the proposed AVD. Table 1 lists the dimensions of the column, tray, and caps in the apparatus. Different shapes and types of windows can be designed for the proposed AVD depending on the design and operating condition of the DWC. In this study, a single H-cap with several discontinuous horizontal slit open holes (or windows) was used. The type-I cap with straight vertical slit open windows on the cap shown in Figure 2 can also be used but was not tested in this study.

The column was made of acrylic sheet, and the experiment was done using acrylic sheet, and the experiment was done using water/air systems under ambient conditions. The air was obtained from the environment and supplied by an air compressor. Prior to entering the column, the air was cooled by an air cooler. The total inlet gas flow was controlled manually by a valve, and the gas flow rate of each section (inlet, A, and B) was measured by a volume flow meter. Water was
supplied by a metering pump attached to a water tank. Then, it was divided into two flows to distribute the liquid to the two sections, which corresponded to the prefractionator and main fractionation section or vice versa. The water flowed into the chimney tray through a dual-flow sieve tray and finally returned to the water tank located at the bottom of the equipment. The two partitioned sections were designed symmetrically. The liquid flow rate for each section was also measured by a metering pump. With the valve and metering pump to supply liquid and vapor streams, the inlet liquid and vapor flow rates could be kept constant for all experiment sets. The specifications of the measuring apparatus are listed in Table 2.

4. RESULTS AND DISCUSSION

For the experimental results and discussion, the liquid and vapor split ratios are defined as

\[ R_L = \frac{L_A}{L_B} \] (1)

\[ R_V = \frac{V_A}{V_B} \] (2)

where \( R_L \) and \( R_V \) are the liquid and vapor split ratios, respectively. \( L_A \) and \( V_A \) are the liquid and vapor flow into section (a) (the left section in Figure 3), respectively, and \( L_B \) and \( V_B \) are the liquid and vapor flow into section (b) (the right section in Figure 3), respectively.

Three sets of experiments were done: (a) the AVD was inactive (i.e., no adjustment of liquid level), (b) the AVD was operated in one section only, and (c) the AVD was active in both sections. Note that in all experiment runs, the total inlet liquid and vapor flow rates were maintained at 15 L/h and 16 N m\(^3\)/h, respectively. The detailed experiment sets of the experimental DWC and the obtained results are provided in the Supporting Information.

a. Effect of the Liquid Split on the Vapor Split When the AVD Is Inactive. The effect of the liquid split on the vapor split was examined where no active vapor splitting was applied. In this experiment, the liquid split ratio was varied by increasing

Figure 2. Visualization of the adjustment of the liquid level of each section of DWC using the proposed AVD and the inset showing the vapor flow inside of the cap: 1. liquid level; 2. modified chimney tray; 3. liquid drain channel; 4. control valve; 5. liquid collector; 6. type-I cap; 7. hole or windows for vapor flowing; 8. liquid overflow weir; 9. vapor channel; 10. vapor flowing.

Figure 3. Schematic of laboratory setup for the performance evaluation of AVD: 1. air compressor; 2. air cooler; 3. valve; 4. air flow meter; 5. water storage; 6. metering pump; 7. receiver tank; 8. dual-flow tray; 9. type-H cap; 10. vapor channel; 11. hole; 12. vapor flowing; 13. liquid drain channel; 14. chimney tray; 15. liquid level; 16. control valve; and 17. manometer.
because of the increase in hydrostatic friction of the upper trays due to increased liquid flow results in increased resistance of the vapor flow path in that section and vice versa. Therefore, the vapor split ratio is reduced accordingly as the liquid split ratio increases, as shown in Figure 5(ii). Without an active vapor splitting action, the vapor split ratio cannot be maintained, and it responds inversely to changes in the liquid split ratio, which results in unfavorable efficiency loss during the operation of DWC.

**b. Assessment of the Proposed AVD by Altering the Liquid Level in One Section.** The effect of the open hole area on the vapor split ratio was examined in the second set of experiments. In these experiments, the liquid level of section (a) was maintained at the same level with 4 holes open above the liquid level. However, the liquid level of section (b) was varied for several different liquid split ratios. The number of open holes above the liquid level in section (b) was varied from 2 to 8. Therefore, the ratio of the number of holes above the liquid level \( \left( \frac{N_a}{N_b} \right) \) or equivalently the ratio of the open hole area to the vapor flow was varied from 0.5 to 2. As can be seen in Figure 6, the vapor split ratio decreased linearly with the ratio of the open hole area for a given liquid split ratio, which showed that the proposed AVD could adjust a required vapor split ratio with good linearity by simply changing the liquid level in one section. Figure 6 also shows that, when changes in the liquid split ratio occur, one can adjust the ratio of the number of open holes to fulfill a desired vapor split ratio.

**c. Active Vapor Distribution by Regulating Both Sections.** In order to control the vapor split ratio, the liquid levels in both sections could be manipulated simultaneously to meet the desired vapor split ratio more precisely and to keep the pressure drop throughout the DW section constant. This task can be attained by adjusting the liquid levels of both sections simultaneously: the liquid level of one section is decreased and that of the other section is increased while keeping the total open hole area above both liquid levels constant.

The vapor split ratio in the proposed AVD depends on the liquid split ratio and the open area ratio \( \left( \frac{A_a}{A_b} \right) \). In the third experiment set, all possible open area ratios of the single type-H cap on each section of DWC were evaluated for different liquid split ratios. The open area ratio could be calculated by varying the number of holes above the liquid level in each section. Figure 7 shows the resulting map for the effect of the liquid split ratio and the open area ratio on the vapor split ratio of the experimental DWC. The map also shows the proposed AVD can handle vapor split control efficiently for a wide range of liquid split ratio variations by adjusting the open hole area ratio of the chimney tray. For example, suppose that \( R_v \) is increased. \( R_v \) reduces with this \( R_v \) increase if the AVD is inactive, as shown by the red line (i) of Figure 7. To increase \( R_v \) accordingly, the AVD needs to be activated in a direction to the open area ratio being increased properly, as represented by the white line (ii) in Figure 7. This kind of operating window map can be utilized to

The liquid flow to one section and decreasing the liquid flow to the other section, while the liquid levels of the chimney tray were kept constant in both sections for a fixed total open hole area of the H-cap. This situation usually occurs during the operation of DWC under the constant reflux condition: when the liquid load increases in a partitioned section, the liquid load in the other section decreases. As shown in Figure 5(i), as the liquid flow rate into section (a) increased and that into section (b) decreased, the vapor flow into section (a) decreased and that into section (b) increased. This observation is expected to

### Table 1. Details of the Caps and Internal Column Dimensions

<table>
<thead>
<tr>
<th>variable</th>
<th>value</th>
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</thead>
<tbody>
<tr>
<td>diameter of dual-flow tray hole</td>
<td>12 mm</td>
</tr>
<tr>
<td>dual-flow tray % hole area</td>
<td>23%</td>
</tr>
<tr>
<td>height of type-H cap</td>
<td>280 mm</td>
</tr>
<tr>
<td>inside diameter of cap</td>
<td>54 mm</td>
</tr>
<tr>
<td>inside diameter of vapor channel</td>
<td>27.8 mm</td>
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<tr>
<td>number of hole (or window) in the cap</td>
<td>8</td>
</tr>
<tr>
<td>area of each hole (or window) in the cap</td>
<td>83.7 mm²</td>
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### Table 2. Specification of the Measuring Apparatus

<table>
<thead>
<tr>
<th>apparatus</th>
<th>specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow meter</td>
<td>Korea Flowmeter, Type PA-601, 4–40 N m⁻³/h (for the total inlet) and 1–10 N m⁻³/h (for each section of DWC)</td>
</tr>
<tr>
<td>metering pump</td>
<td>Prominent, GMXa 0245, Max. 45 L/h, Head 2 bar</td>
</tr>
<tr>
<td>manometer</td>
<td>Dwyer, U-Tube, Type 1221, Range M600</td>
</tr>
</tbody>
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provide both qualitative and quantitative guidelines for the operation of AVD.

Since the proposed active vapor distributor requires the liquid level in the chimney tray at the desired level for accurate vapor split control, the use of PI controller is recommended for an automatic level control. In addition, the implementation of an automatic level control for the AVD could be considered using the cascade control strategy if a higher liquid level in one section needs to be achieved, while, at the same time, the liquid level in the other section needs to be decreased.

5. CONCLUSIONS

Owing to design and operation uncertainties and variations, active vapor splitters have become more important for the efficient and stable operation of DWCs. Without an active vapor splitter, the vapor split ratio cannot be maintained for variations in the liquid split ratio and even tends to deviate unfavorably from its optimal value, causing a significant reduction in the separation efficiency of DWCs. Active vapor splitting issues also pose a significant barrier to the adoption of more complicated and sophisticated DWC configurations with multiple vapor splits.

This work proposed and evaluated a novel active vapor splitter that distributes the vapor flow to each DW section efficiently. As the proposed AVD consists of few parts, i.e., a modified chimney tray and two liquid transfer lines, it can be easily implemented with minimum capital and operating cost. Furthermore, as the AVD is hydraulically driven by simply adjusting the liquid level, there is no need for an external motor, a mechanical moving part, or an axle to be inserted in the column; therefore, it can provide a more robust and reliable operation with less maintenance and a simpler structure. The revamping of existing DWCs could be done by replacing the conventional chimney tray with the proposed chimney tray as an AVD; thus, an additional external device would not be required. The evaluation test results showed the proposed AVD was able to successfully split the vapor flow during operation. Detailed geometry, such as the shape, size, and the number of vapor flow paths in the cap of the chimney tray, could be designed and calculated optimally in the design step prior to the AVD installation. The proposed AVD is expected to provide a promising solution to active vapor splitting, which

Figure 5. Effect of liquid split ratio variation on (i) the vapor flow rate in each section and (ii) the vapor split ratio at the fixed open area of the vapor flow path.

Figure 6. Effect of the ratio of the number of holes above the liquid level to the vapor split ratio for the different liquid split ratios.

Figure 7. Effect of the liquid split ratio and the open area ratio on the vapor split ratio of the experimental AVD.
was a big challenge and concern for real application and extension of DWC technology in the process industry.

Moreover, the proposed AVD can be applied to conventional distillation columns for another purpose, i.e., proper vapor distribution at turn-down operation: when the vapor rate decreases at turn-down operation, the conventional vapor distributor with a fixed vapor flow path area often has difficulties in uniform vapor distribution due to a large vapor flow path area designed based on normal operation. However, the proposed hydraulic driven AVD can handle such a low vapor flow simply by adjusting the liquid level in the chimney tray at a higher level.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.iecr.7b01023.

Figure of dividing wall column and its design parameters and specifications; figure of the effect of internal flow distribution on the reboiler duty consumption in DWC; detailed value of each experimental set (PDF)

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Notes

The authors declare no competing financial interest.

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