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# Operation of energy efficient divided wall column

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## Abstract

Based upon the nominal design of a divided wall column, one obtains the minimum energy usage to achieve the desired separation. During operation, when the column is actually run, the vapor split ratio $R_v$ is found to be non-optimal. For this and other reasons, it is likely that available energy is actually lower than the energy required for the separation of three products. The objective of this study, is to find how to operate the column under such conditions, such that we minimize the degradation in terms of the product purities. We also want to study how the column should be controlled under such conditions. For this analysis various simulations have been conducted and the effects on product compositions are examined.

**Keywords**: Divided wall column; Thermally coupled distillation columns; Optimal operation; Minimum energy

## 1. Introduction

Divided wall columns have gained increasing application due to their lower energy consumption and investment costs compared with conventional distillation column sequences. A divided wall column (DWC) has a vertical partition that divides the column shell into a pre-fractionator and side draw section. Figure 1 shows a three-product divided wall column with a single reboiler and condenser, along with its thermodynamically equivalent Petlyuk implementation with a pre-fractionator arrangement.
Several studies [1-3] have been conducted to address the DWC structure design. Amminudin et al. [1] developed a semi-rigorous method for the initial design of fully thermally coupled distillation columns based on the concept of equilibrium stage composition. In their study, the system was divided into two separate columns to eliminate interlinking and obtain an optimal initial design that could be confirmed through rigorous simulation. Recently, Lee et al. [2] proposed an efficient design method for determining the optimal design structure of a divided wall column. The internal section of the DWC is divided into four separate sections and matched to the sloppy arrangement with three conventional simple columns. The light and heavy key component mole-fractions are used as the design variables in each column. They found that the structure that gives superior energy efficiency in the shortcut sloppy case also brings superior energy efficiency in the DWC, while the optimal internal flow distribution of the DWC is different from that obtained from the sloppy configuration.
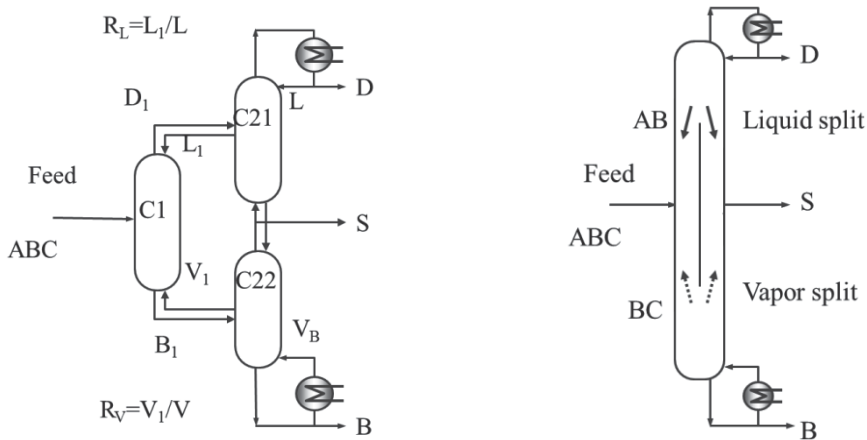
Figure 1: Thermodynamically equivalent implementations of three-product DWC; (a) Implementation of three separate columns (b) DWC implementation

Halvorsen and Skogestad [4,5] presented the idea of the $V_{min}$ diagram for analyzing the energy consumption for separation of feed components in distillation column. The graphical tool $V_{min}$ diagrams can be utilized to design the column and initialize simulations, as well as to check the minimum energy requirement for sharp and non–sharp separations in both the conventional and thermally coupled columns. $V_{min}$ diagrams can be created (see [4,5]) for any mixture assuming a column with a large number of theoretical stages and it is based upon the Underwood equations.

Recently, Dwivedi et al. [6] have studied the three-products Petlyuk (divided-wall) column with an objective to achieve desired product purities with the minimum use of energy ($V_{min}$). They have mainly focused on the control structure selection and considered four alternate control structures with and without the vapor split as a degree of freedom.

Ghadrdan et al. [7] have extended the concept of three products DWC to four products Kaibel distillation column. They worked for two different objectives, first minimizing energy requirement at fixed product purities, and second maximizing product purities with a fixed boilup rate.

It is clear from the literature survey that none of the studies has focused on the operation of the divided wall column at energies lower than the minimum energy ($V_{min}$) needed to achieve sharp separation.

Therefore, this study is focused on the operation of divided wall column at energies lower than minimum energy ($V_{min}$) where sharp separation is not possible. This could be the usual case in the operation of the divided wall column in practice. The results and analysis of this study can be quite useful in the real plant where sometimes the available energy (vapor flow rate) is less than the energy needed for optimal operation. It could also give some insight when the column is operating at non-optimal $R_V$.

## 2. A Case Study

The process parameters with notations of this case study are given in Table 1. Dwivedi et al. [6] have studied this model mainly for the selection of control structure, however present work is limited to the analysis of DWC operation at lower than optimal energy. The process is modeled in Matlab and fmincon solver is used for the optimization. For

simplification, we have assumed constant relative volatility and constant internal molar flows in column sections. The other assumptions are constant pressure, negligible vapor holdup, a total condenser, equilibrium on all stages and the linearized flow dynamics. For the given product purities in Table 1, we have a large number of stages in each sub-column. This implies that the required energy is close to the minimum energy using an infinite number of stages.

The operation is considered optimal for a given product specifications when the column is operated at energy as close to minimum energy. It should be noted that energy term referred here is only the vapor flow rate V (kmol/min). Following in Eq. (1) product specifications are active constraints at the optimal energy solution. The input data, parameters and product compositions for optimal operation are listed in Table 1. The subscripts are used for the components and superscripts for the product streams.

Impurity in distillate stream D  :  $\qquad x_B^D \leq 0.5\%$  (1-a)

Light impurity in side stream S :  $\qquad x_A^S \leq 0.5\%$  (1-b)

Heavy impurity in side stream S:  $\qquad x_C^S \leq 0.5\%$  (1-c)

Impurity in bottom stream B     :  $\qquad x_B^B \leq 0.5\%$  (1-d)

**Table 1:** Process parameters and specifications for the case study of the Petlyuk column

| | |
|---|---|
| Relative volatilities [A (lightest), B, C] | [4.2 2.1 1] |
| Number of stages in C1, C21 and C22 | 20+20 (each sections) |
| Nominal feed flow rate (F) | 1 kmol/min |
| Nominal feed composition [A, B, C] | [33.3 33.3 33.3](mol %) |
| Nominal purity of distillate ($x_A^D$) | 99.5 (mol %) |
| Nominal purity of side-product ($x_B^S$) | 99.00 (mol %) |
| Nominal light impurity of side-product ($x_A^S$) | 0.5 (mol %) |
| Nominal heavy impurity of side-product ($x_C^S$) | 0.5 (mol %) |
| Nominal purity of bottom product ($x_C^B$) | 99.5 (mol %) |

For the sake of analysis, the proposed study is categorized in two different modes which are given below

## Mode 1: Minimum energy consumption for fixed product specifications

The objective function in this case is to minimize the required energy with fixed product specifications (Ghadrdan et al. [7]). The cost function for distillation column is given by:

$$J = cost\,feed + cost\,energy - value\,products \qquad (2)$$

For fixed product specifications the cost function can be deduced to minimizing energy which is written below:

$$J = V \qquad (3)$$

There are total 5 degrees of freedom i.e., liquid split ($R_L$), vapor split ($R_V$), flow rates of boilup (V), side stream(S) and reflux (L). Distillate (D) and bottom (B) flow rates are used to control the holdup in condenser and reboiler respectively and have no steady state effects. Since we have fixed product specifications, therefore $R_L$ and $R_V$ could be

used as degrees of freedom to control vapor flow rate V. The remaining degrees of freedom L, S and V can be used to control product specifications or achieve the purity constraints of three products.

The optimal composition profiles of components A, B and C for both the pre-fractionator and the main column are shown in Figure 2. The values of optimal conditions are given in Table 2. The value of minimum energy $V_{min}$ is 1.3322 (kmol/min) and the total sum of impurities in the three products (eq. 4), is 0.0067 (kmol/min).
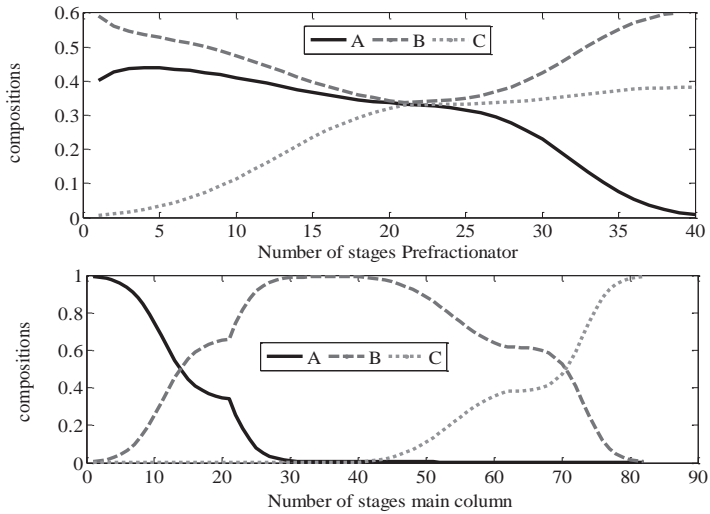


Figure 2: Optimal composition profiles of components A, B and C in Divided wall (Petlyuk) column.

**Table 2:** Resulting optimal conditions and minimum energy ($V_{min}$) obtained for fixed product specifications for three products Petlyuk (divided-wall) column

| | |
|---|---|
| Liquid reflux (L) | 0.9989 kmol/min |
| Boilup (V) | 1.3322 kmol/min |
| Distillate flow rate (D) | 0.3333 kmol/min |
| Bottom product flow rate (B) | 0.3333 kmol/min |
| Side-product (S) | 0.3333 kmol/min |
| Liquid split ($R_L$) | 0.3189 |
| Vapor split ($R_V$) | 0.57045 |
| Heavy impurity of prefractionator top ($x_C^{D1}$) | 0.0055 (mol %) |
| Nominal light impurity of pre-fractionator bottom ($x_A^{B1}$) | 0.00832 (mol %) |

## Mode 2: Minimize product impurities at energies lower than minimum energy ($V_{min}$)

Although the column was designed to operate for fixed product specifications with optimal vapor flow rate (close to minimum energy). Nevertheless, during the operation (most likely to happen in real practice) we may have a situation where the available

energy V (vapor flow rate) is even lower than the minimum energy to achieve the desired sharp separation. Due to this reason, we are analyzing the various ways to minimize impurities in products streams for different values of lower vapor flow rates. This situation is very important for the operation where product purity affects the profit. The objective function is derived from Eq. (2) and is given as:

$$-J = x_B^D D + (x_A^S + x_C^S)S + x_B^B B \qquad (4)$$

The optimization has been conducted to minimize impurities in all three products streams. Starting with the base value for the optimal energy point of $V_0=1.3322$ ($V_0=V_{min}$), we did simulation to minimize the impurities for various lower values of V like 100%, 98%, 96%, and so on.

Two different cases were considered here:

*Case I: Given energy and remaining degree of freedoms L, S, $R_L$ and $R_v$ varying*

With variable Rv, the optimal impurity sum (-J in kmol/min) was found to 0.0047 for V=100%, 0.0069 for V=98%, 0.0113 for 96%, 0.033 for 90%, 0.050 for 85% and 0.078 for 80%. Note that the optimal impurity sum Eq. (4) for V=100% is 0.0047 which is less than the nominal value of 0.0067 in mode 1. This may seem strange, but it is because we in mode 2 allow for a redistribution of the impurities in order to minimize the impurity sum.
The degradation in purity as we reduce V is mainly due to increased mole fraction of heavy component (C) in the side stream, from 0.007 (V=100%) to 0.16 (V=80%). This is also illustrated in Fig. 3(a) which shows the product purities (main component) in the three products as a function of V. The impurities mainly increased in side product S and there was not much effect on distillate and bottom product.

*Case II: Given energy and remaining degree of freedoms L, S and $R_L$ ($R_V$ fixed)*

In case I, the optimal value of Rv was found to change from 0.57 (V=100%) to 0.70 (V=80%). However, with the present technology, we cannot adjust Rv during operation. Therefore, we redid the optimization with Rv fixed at its nominal value of 0.57 obtained for mode 1 (Table 2). With fixed Rv, the optimal impurity sum (-J in kmol/min) was found to 0.0047 for V=100%, 0.0081 for V=98%, 0.0129 for 96%, 0.044 for 90%, 0.059 for 85% and 0.079 for 82%. The resulting product purities are shown in Figure 3b. We note that there is an increase in impurity compared to case I (Figure 3a), but not as large as one might have expected.
Of course, the simulations in Case II are also optimistic because we cannot in practice expect to obtain a desired value of Rv, even nominally. We are therefore performing simulations of cases where the fixed value is changed from 0.57 to 0.50 and to 0.70. The results indicate that with operation in mode II, the degradation is relatively small when the side stream product is impure.

## 3. Conclusion

The study has been conducted for the sensitivity analysis of given energy on product compositions. When we decrease the vapor flow rate (energy), we can no longer stick to the desired product specifications. The optimal in terms of minimizing the impurities sum of all three products tends to increase the impurities in the side stream. The side stream mainly consists the heavy component impurity C. The top and bottom products

purities did not drift much from the optimal values. The results obtained are useful when product specifications are not given and we are paid for the purity in all three products. The other case could be that the side stream has no value and we get paid for the purity in both top and bottom product.
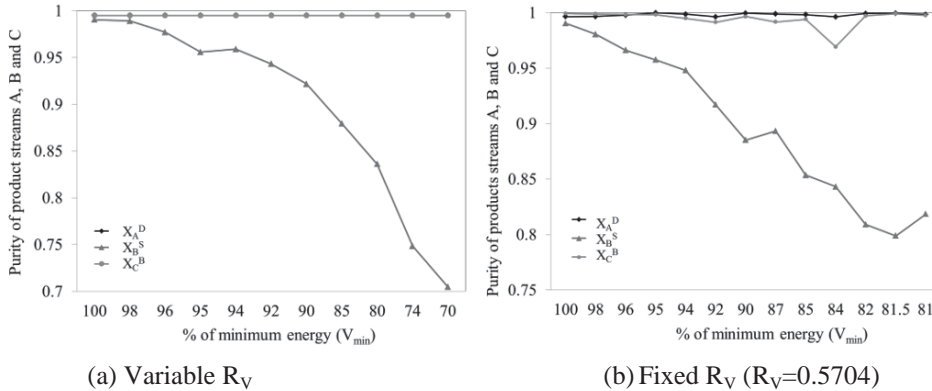


(a) Variable $R_V$                                    (b) Fixed $R_V$ ($R_V$=0.5704)

Figure 3: Purity of product streams (Mode 2) for various values of energies lower than minimum energy ($V_{min}$).

## Acknowledgement

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