Energy Recovery in a Naphtha Splitter Process through Debottlenecking of Retrofitted Thermally Coupled and Double-Effect Distillation Sequences

Le Quang Minh, Nguyen Van Duc Long, and Moonyong Lee*

A thermally coupled distillation sequence (TCDS) and a double-effect sequence (DES) were proposed to retrofit an existing naphtha splitter process in the refinery plant for enhanced energy efficiency. This, however, can create a bottleneck in the columns. A side reboiler was proposed to debottleneck the retrofitted columns. The concept of minimum vapor flow rate was used as a preliminary calculation to determine the benefits of these proposed arrangements. A practical optimization using the response surface methodology was applied to the design of TCDS and DES. In addition, a column grand composite curve was used to highlight the thermodynamic feasibility of the implementation of a side reboiler into the retrofitted sequences. As a result, the DES was shown as the best alternative through combination of a side reboiler, and this achieved 32.7% savings on operating costs with a maximum reuse of the existing equipment.

Introduction

The naphtha splitter process is one of core distillation processes in the refinery industry but it consumes a considerable amount of energy in its operation. To improve the fractionation of the naphtha boiling range from the hydro-treating process, the naphtha feed stock is separated sequentially into light naphtha, heavy naphtha, and light kerosene. In recent years, there has been great incentive to improve the efficiency of existing capital in the naphtha splitter processing facilities. For instance, the use of a dividing wall column has a significant impact on energy savings in the process.[1,2]

Process integration is an interesting option for retrofitting that has been successful in reducing the energy requirements compared to processes where all the units are configured with little or no integration.[3] In particular, the use of columns with thermal coupling has attracted considerable interest.[4-7] Thermally coupled distillation sequences (TCDSs) were obtained by implementing interconnecting streams (one in the vapor phase and the other in the liquid phase) between two columns. Each interconnection replaces one condenser or reboiler from one of the columns, providing potential cost savings. Simultaneously, double-effect sequence (DES, also called pressure-staged) operates at column pressures such that the cooling (energy loss) of one column can be used efficiently to heat (energy gain) another column, providing more potential for further energy savings. DES has been considered in the literature by Engeli[5] and Emtit et al.[8] who demonstrated that this arrangement can achieve high energy savings.

Several studies have examined the application of dividing wall columns (DWC) in a retrofit.[10,11] They reported that the dividing wall column can be used to save energy and capital costs. Nevertheless, there can be practical difficulties.[12] In addition to existing column constraints, such as a fixed column diameter, most of these concerns focused on the need to modify the column shells to accommodate the dividing wall, and have another nozzle fitted to withdraw the middle product. Such modifications to install a dividing wall, which might involve the removal of tray support rings and the replacement of existing internals, can be a major undertaking. In addition, the mechanical design aspects of the column, such as mechanical stress, are affected by changing the feed or side-draw locations.

Although the DWC initially might be the best option for retrofit projects, these concerns must be addressed fully during a retrofit design. These modifications often require significant plant downtime, which leads to a loss of production and an interruption of the product supply to the consumers. On the other hand, DWC is not attractive if the plant lifetime is not long because of the lengthy payback period.[13] Instead, TCDS and DES have attracted considerable attention in retrofitting projects due to the lower energy requirements compared to existing column sequences, as well as the small scale of the modification.

Despite its high impact and the importance of the overall energy economics in the refinery plant, there are very few reports to study the retrofitting and design of the naphtha splitter process to energy efficient advanced distillation configurations. The aim of this study was to retrofit a naphtha splitter process by taking into consideration both energy savings and maximum utilization of existing equipment with the concepts of TCDS and DES. To tackle the retrofit problem of the complex naphtha splitter process, a systematic approach was proposed that utilizes several well-proven methodologies.
such as the minimum vapor flow \( (V_{\text{min}}) \) diagram for preliminary evaluation of complex distillation sequences and the response surface methodology (RSM) for optimal design of complex columns. Furthermore, the target is not just to identify the best solution in terms of operating cost but also to find the solution that matches energy savings with a maximum usage of the existing equipment such as trays, exchangers, and columns.

**Problem Statement**

Initially, the minimum vapor flow rate was determined as an easy form of comparison for energy requirement for the proposed sequences. Nevertheless, an entrainment flooding problem also occurs upon integrating existing columns. In this study, a hydraulic performance indicator (fractional utilization of area, FUA), was used to identify the bottleneck of a distillation column upon retrofitting to TCDS and DES. Highlighted by the thermodynamic analysis, a side reboiler was recommended to remove the flooding problem.

Additionally, the process was focused to maximize the utilization of existing equipment, while simultaneously making relatively minor modifications, including the adjustment of the operating pressure of each column, number of trays, adding equipment, and rearranging the existing columns to complex advanced distillation sequences, particularly, the TCDS and DES shown in Figure 1.

**Conventional distillation sequence**

The process under analysis is a naphtha “splitter” process, which produces the main components such as, light straight-run product (LSR), heavy naphtha (Hvy. Naph) and light kerosene (Lt. Kero). Figure 2 presents a schematic diagram of the existing naphtha splitter process for this study. The hydrotreating unit provides feed to a naphtha splitter section. This feed is first preheated against the bottom product stream and sent to the splitter column. The existing column configuration uses two splitter columns: the naphtha splitter unit column (NSU), and paraffinic fractionation unit (PFU). Table 1 lists the composition of the feed stream. The feed flow rate introduced to the first column is 4586 m³ per day.

In this study, the simulation was performed using commercial software, Aspen HYSYS 8.0 with an “oil environment” that allows a calculation of the different fractions in the distillation of complex mixtures of organic compounds. Therefore, it can generate a hypothetical hydrocarbon mixture from the distillation data and simulate the performance of different process equipment. Figure 3 shows the compositional complexity of the three fractions to display the ASTM D86 distillation curves for the specific distillates from the proposed process.

The Peng–Robinson equation of state, which has gained wide acceptance in hydrocarbon process modeling to support the wide range of operating conditions and the great variety

**Figure 1.** Schematic diagram of a) thermally coupled direct sequence with side rectifier (TCDS); b) double-effect sequence (DES).

**Figure 2.** Schematic diagram of the existing naphtha splitter process.
of hydrocarbon mixtures, was selected to predict the vapor–liquid equilibrium of this simulation study. Table 2 lists the parameters necessary to define the existing hydraulic features and product specifications of the columns.

### Table 1. Composition of the starting point stream.

<table>
<thead>
<tr>
<th>Non-condensable Compound</th>
<th>Volume [%]</th>
<th>Condensable Compound</th>
<th>Volume [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>0</td>
<td>NBP[0]90*</td>
<td>0.0140</td>
</tr>
<tr>
<td>propane</td>
<td>0.0008</td>
<td>NBP[0]20*</td>
<td>0.0171</td>
</tr>
<tr>
<td>i-butane</td>
<td>0.0010</td>
<td>NBP[0]75*</td>
<td>0.0292</td>
</tr>
<tr>
<td>n-butane</td>
<td>0.0043</td>
<td>NBP[0]50*</td>
<td>0.0618</td>
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<td>i-pentane</td>
<td>0.0070</td>
<td>NBP[0]63*</td>
<td>0.1185</td>
</tr>
<tr>
<td>n-pentane</td>
<td>0.0097</td>
<td>NBP[0]78*</td>
<td>0.1156</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]90*</td>
<td>0.1363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]106*</td>
<td>0.1017</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]120*</td>
<td>0.1041</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]134*</td>
<td>0.1052</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]149*</td>
<td>0.0816</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]162*</td>
<td>0.0424</td>
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<tr>
<td></td>
<td></td>
<td>NBP[0]175*</td>
<td>0.0221</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]191*</td>
<td>0.0131</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]206*</td>
<td>0.0062</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NBP[0]219*</td>
<td>0.0078</td>
</tr>
</tbody>
</table>

#### Proposed Arrangements

**Minimum vapor flow rate using Underwood equations**

Engelien and Skogestad[15] developed an application of the minimum vapor flow (V_{min}) diagram, considering the sharp separation of a ternary mixture. After defining the feed composition and the relative volatility of the components being separated, the diagram can be drawn by simply plotting several remarkable points. Additionally, the V_{min} diagram can be used as an excellent tool for the identification of energy savings potential and fast screening of alternative configurations for implementation of a double-effect structure in a given case. In this study, the diagram was used to find the minimum vapor flow rate for the DES.

Simultaneously, the V_{min} for the TCDS system can be calculated using the shortcut equation proposed by Fidkowski.[16,17] From these preliminary calculations, further rigorous simulations were performed to compare the energy requirement and operating costs with that of the existing distillation sequence. Finally, a candidate for integration was identified for the retrofit.

The calculations of V_{min} for this mixture can be performed under the assumptions of liquid feeds, sharp splits and constant relative volatility. For the sake of convenience, the pseudo-components mixture was taken as a ternary mixture for shortcut calculations. Therefore, the LSR fraction, heavy naphtha fraction, and light kerosene fraction were assumed to be pseudo-component NBP 90*, NBP 120*, and NBP 162*, respectively. The ternary feeds are marked in Table 3 as A, B, and C, respectively. From the K-value of each component in the simulation, the relative volatility was derived for each component, and pseudo-component NBP 162* was considered to be the heaviest component. The V_{min} diagram (Figure 4) was plotted for this case using the relative volatility data and the simplified feed compositions in Table 3.

The calculation shown in Table 4 was used to compare the energy requirements of the integrated and non-integrated

### Table 2. Column hydraulics and product specifications of the existing sequence.

<table>
<thead>
<tr>
<th>Tag</th>
<th>Component</th>
<th>Mole fraction</th>
<th>Relative volatility</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>NBP 90*</td>
<td>0.5159</td>
<td>8.4</td>
<td>LSR</td>
</tr>
<tr>
<td>B</td>
<td>NBP 120*</td>
<td>0.3926</td>
<td>3.6</td>
<td>Hvy. Naph</td>
</tr>
<tr>
<td>C</td>
<td>NBP 162*</td>
<td>0.0916</td>
<td>1.0</td>
<td>Lt. Kero</td>
</tr>
</tbody>
</table>

### Table 3. Representatives used to construct the V_{min} diagram.

<table>
<thead>
<tr>
<th>Tag</th>
<th>Component</th>
<th>Mole fraction</th>
<th>Relative volatility</th>
<th>Product</th>
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<td>1.0</td>
<td>Lt. Kero</td>
</tr>
</tbody>
</table>

### Table 4. Minimum vapor flow rate and percentage improvement for different arrangements.

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>V_{min}/F</th>
<th>Savings [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct split</td>
<td>1.78</td>
<td>0</td>
</tr>
<tr>
<td>TCDS</td>
<td>1.49</td>
<td>16.4</td>
</tr>
<tr>
<td>DES</td>
<td>1.20</td>
<td>32.5</td>
</tr>
</tbody>
</table>
schemes. From an energy savings point of view, the integrated structures including the TCDS and DES are better than the non-integrated one (direct sequence). However, the DES gives the highest energy savings under an infinite number of trays. This preliminary comparison with the results from Emtir or Engelien highlighted their feasibility. In addition, the information shown in the $V_{\text{min}}$ diagram was also used to find out the column sections that receive excessive vapor in the DES arrangement. In this case, the lower section in the main column received excessive vapor. Therefore, the information is necessary to consider using the side reboiler to balance the main column.

Thermally Coupled Distillation Sequence

The TCDS was designed by integrating two columns, which eliminates the reboiler in the direct scheme or the condenser in the indirect scheme. A modification for retrofitting involves a change in the draw trays for the vapor and liquid streams. Retrofitting the existing distillation sequence begins with the development of preliminary designs for complex systems and minimizes the heat duty supplied to the reboilers through the optimization procedures. After a preliminary design of the TCDS structure was fixed, the main design variables were then optimized to including the internal vapor flow ($F_V$) to the side rectifier, feed ($N_1$) and vapor ($N_2$) stream locations. In this study, the RSM-based optimization approach was used to examine the effects on the reboiler.

The RSM was successfully implemented to optimize the structure of DWC in previous studies. The main advantage of RSM is its ability to gain understanding of the main factors and interactions that affect the studied response, which is used for the generation of the reduced process model. Furthermore, the RSM can be used as an alternative optimization methodology to reach the pseudo-optimal solutions with a high statistical confidence in its results. After determining the preliminary ranges of the variables through single-factor testing, a central composite design was used to determine how the variables interact as well as to optimize the system in terms of the reboiler duty. Thirteen simulations were run to optimize 2 parameters of the TCDS structure: the feed ($N_1$) and vapor ($N_2$) stream location. For each run, the vapor flows to the side rectifier were then optimized using rigorous simulation to minimize the reboiler duty, while maintaining satisfactory product purity. The simulation data was fitted to a second-order polynomial model and the regression coefficients were obtained. MINITAB software was used for both response surface fitting and to optimize the reboiler duty. The generalized second-order polynomial model was obtained as:

$$Y = 21.119 - 0.3269N_1 - 0.3819N_2 + 0.0211N_1^2 + 0.0111N_2^2 + 0.0005N_1N_2$$

in which $Y$ is the predicted response of reboiler duty (MW), and $N_1$ and $N_2$ are the values of the feed and vapor stream locations, respectively.

Figure 5 shows the contour plot of the interaction between the main design variables, $N_1$ and $N_2$. The smallest reboiler duty was observed at the number of trays for the feed rectifying section, and the vapor stream locations of 7.5455, and 17.0101, respectively (Figure 6). Under these conditions, the minimum reboiler duty using the retrofitted TCDS was predicted to be 16.64 MW (equivalent to 17.2% energy savings).

Figure 7 shows a simplified flow sheet illustrating the resulting retrofitted TCDS. Note that the retrofitted TCDS allows preheating the feed with the product streams only, which would provide a decrease in reboiler duty, whereas the existing conventional sequence requires external heat to preheat the feed. In addition, a set of simulations were performed around this minimum obtained with the reduced model to be sure that the minimum found was a “realistic minimum”. The energy consumption is significantly reduced in comparison to the base case, due to the considerable re-

Figure 4. $V_{\text{min}}$ diagram used to compare the energy saving of DES arrangement.

Figure 5. Contour plot of interaction between feed stream location in the side rectifier ($N_1$) and vapor stream location in the main column ($N_2$) in the TCS case.
The basic concept of heat integration is the utilization of the heat content of the overhead vapor of one column to supply the heat required in the reboiler of another. The DES can be achieved by raising the pressure of column 2 high enough to make its condenser temperature higher than the bottom temperature of column 1; thus, the second column will boil up the first column. During the interactive and intuitive optimization of the heat-integrated columns the following principles are used:[21]

- Control the operating pressure of the second column to keep the heat exchanger minimum approach temperature at 8.0°C.
- Keep the first column at the original pressure.
- Pressure drops across heat exchanger are ignored.
- Pumping was not considered in the cost calculations.

As derived from the \( V_{\text{min}} \) diagram, the DES configuration is capable of achieving higher efficiency than the non-integrated sequence (32.5% energy savings). From the preliminary analysis, the rigorous optimization using the RSM was performed to compare the energy requirements with those of the existing distillation arrangement. Figure 8 shows the contour plot of the interaction between the main design variables, that is, the feed stream location in the first column (N1) and the bottom stream location in the main column (N2). After the design and optimization procedure, the minimum reboiler duty was found at the feed and bottom stream locations of 11.8788 and 19.8687, respectively (Figure 9). At these optimal conditions, the reboiler duty of the retrofitted DES was predicted to be 13.09 MW (which is equivalent to 34.4% less than the conventional sequence).

Figure 10 shows a simplified flow sheet, illustrating the DES.
In which the feed stream was preheated using the heat supplied by the product stream for the efficiency improvement. The rigorous simulation also showed that the reboiler duty from the DES was 13.10 MW, which shows a good agreement with the results predicted by the RSM.

Retrofitted TCDS, and DES with side reboiler

Knowing to what extent the area available for vapor flow on each stage is used for a column operating at its maximum throughput is very important. This knowledge is essential for determining at which stages the vapor and liquid traffic should be reduced, and which stages can accommodate the increased flow. For a given feed flow rate and for each stage, the column diameter can be calculated, which would be required if the flows on that stage represent the maximum flows that could be tolerated. For example, the vapor velocity could be assumed to correspond to 85% of the flooding velocity. The minimum diameter required for satisfactory hydraulic performance can then be compared with the diameter of the existing column to determine if, and to what extent, the flows to that stage can be increased. As proposed by Liu,\textsuperscript{23,24} the following indicator of the hydraulic performance of an existing distillation column, the fractional utilization of area (FUA), can be calculated using the following equation:

$$FUA = \frac{\text{Area required on stage } i \text{ for vapor flow}}{\text{Area available on stage } i \text{ for vapor flow}}$$

for which the area required for vapor flow is calculated for a given approach to flooding conditions (e.g., for a vapor velocity reaching 85% of the flooding velocity).

The indicator allows one to identify bottlenecks and evaluate the modifications proposed to overcome these bottlenecks. It is likely to be bottlenecked if two columns are integrated to construct the integrated arrangement. In the FUA profile of the exiting PFU column, the value of FUA began to increase from the feed stage, with some stages requiring all of the available area (Figure 11). A bottleneck problem occurs in the stripping section. The FUA profile indicates that there is an opportunity to reduce the area utilization in the stripping section of the column by increasing the flows in the rectifying section of the main column.

Additionally, the column grand composite curves (CGCC) of the optimal TCDS and DES sequences (shown in
Figure 12) were drawn to facilitate determining the placement of the inter-reboiler. A large shift in the stripping section demonstrates that there is a large amount of heat transfer from the vapor phase to liquid phase. Thus, there is a real opportunity for providing heat input at a temperature lower than the bottom reboiler temperature (Figure 12b). A side reboiler was therefore added to these sequences to remove the bottleneck problems in the proposed sequences. Figure 7 and Figure 10 also show the simplified flow sheets outlining the TCDS and DES with a side reboiler, respectively. With the aim of reducing the operating cost, the side reboiler duties were selected at 5.06, and 1.80 MW for the retrofitted TCDS and DES, respectively.

For the retrofit alternatives with significant energy savings, it is worthwhile to search the optimal sequence that maximizes the utilization of the existing equipment. Table 5 provides a comparative summary of the key results. The relative savings of the proposed configurations are expressed with respect to the existing conventional sequence. The results of the economic analysis showed that the DES is the best alternative in this retrofitting study (which reduced 32.7% operating cost), and the energy consumption is reduced up to 34.3% compared to the existing process. Note that the details of the economics for each configuration largely depend on the utility costs, which fluctuate in accordance to country and company. Furthermore, Table 5 reports that the required heat exchanger areas of the side reboiler for all modified configurations were less than those of the reboiler of the first column. Note that the eliminated reboiler of the first column can be utilized as a side reboiler of the main column in the retrofitted alternatives.

### Conclusions

This study reports a novel and efficient approach for retrofit design to debottleneck the retrofitted TCDS and DES in a petroleum process. The RSM approach has been proven to be reliable and practical to achieve the optimal solutions within a reasonable timescale. From the theoretical consideration and economic analysis, the DES turned out to be the best alternative for the retrofit of a naphtha splitter process (32.7% operating cost reduction). Finally, utilizing a reboiler of the first column as a side reboiler of the second column could debottleneck the second column and also maximize the reuse of heat exchangers in the existing plant. These configurations and approach can be applied not only to the retrofit of naphtha splitter process but also extended to other industrial processes with similar conditions.

### Appendix

Sizing the column: The column diameter was determined under a column flooding condition that fixed the upper limit of the vapor velocity. The operating velocity is normally 70–90% of the flooding velocity. In this study, 85% of the flooding velocity was used.

Area of heat exchanger

\[
A = \frac{Q}{U \Delta T}
\]
in which $Q$ is the heat duty; $A$ is the required area; $\Delta T$ is the logarithmic mean temperature; and $U$ is the overall heat transfer coefficient. For the operating cost:

$$\text{Operating cost (Op)} : \text{Op} = C_{\text{steam}} + C_{CW} \quad (4)$$

in which $C_{\text{steam}}$ is the cost of the steam; and $C_{CW}$ is the cost of cooling water. In this study, the utility cost data listed in Table 6 were taken from Turton et al.[27]

**Table 6. Utility cost data.**

<table>
<thead>
<tr>
<th>Utility</th>
<th>$T ;[^{\circ}\text{C}]$</th>
<th>Price ([$$/GJ]$$</th>
</tr>
</thead>
<tbody>
<tr>
<td>cooling water</td>
<td>20–40</td>
<td>0.35</td>
</tr>
<tr>
<td>low-pressure steam</td>
<td>160</td>
<td>13.28</td>
</tr>
<tr>
<td>medium-pressure steam</td>
<td>184</td>
<td>14.19</td>
</tr>
<tr>
<td>high-pressure steam</td>
<td>254</td>
<td>17.70</td>
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