A novel self-heat recuperative dividing wall column to maximize energy efficiency and column throughput in retrofitting and debottlenecking of a side stream column

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HIGHLIGHTS

- Novel hybrid configuration is proposed for debottlenecking of side stream column.
- Significant saving in operating cost could be achieved.
- A DWC can increase the energy efficiency of a heat pump.
- A synergetic advantage of enhancing energy efficiency and reducing capital cost.
- Can be applied to both close-boiling and wide-boiling mixtures.

ABSTRACT

Improving the energy efficiency of distillation columns and reducing the related CO₂ emissions is a part of the global effort towards greater sustainability in chemical processing industries. Furthermore, increasing the capacity, which has been a major focus of the chemical process industry, can cause an entrainment flooding or a bottleneck problem in the distillation column. This paper reports the results of a techno-economic feasibility study to retrofit and debottleneck side stream columns, as one of most popular industrial distillation columns, in order to maximize energy efficiency and column throughput by using a novel hybrid configuration – heat pump assisted dividing wall column. The heat pump technique was used to improve the energy efficiency of a dividing wall column in debottlenecking a side stream column. On the other hand, the dividing wall column was exploited to increase the performance of a heat pump while also to removing bottlenecking problems. Several industrial cases were examined to demonstrate the proposed configuration. A heat pump assisted dividing wall column was optimized using a response surface methodology. The results showed that the proposed heat pump assisted dividing wall column can remove the bottleneck problem effectively and achieve substantial energy saving and CO₂ emission reduction as well. Notably, an 83.7%, 85.9% and 61.3% reduction in operating costs could be achieved in the ethylene dichloride, acetic acid and alkanes separation processes, respectively. The proposed...
configuration can be applied to both close-boiling and wide-boiling mixtures, and also employed to both retrofit and grass-roots designs.

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1. Introduction

Distillation is the most widely used separation technology, accounting for 95% of all separations in chemical process industry worldwide, and also one of the most energy intensive processes, occupying 10% of the US industrial energy consumption [1]. Among distillation types used in the chemical and petroleum industry, side stream distillation columns (SSCs) are popular and increasing continuously because they offer a cost-effective way of producing three products from a single column [2]. SSCs can be attractive either when the middle product dominates the feed and one of the other components occurs only in minor quantities, when the middle boiling components are trace components and columns are used as prefractionators. Thus, SSCs can only be applied to specific feed compositions and product specifications [3]. On the other hand, limited purity of the intermediate component product stream is a problem commonly associated with SSCs. A high-purity side stream might require large reflux ratios and a large number of stages, as well as larger associated energy requirements [4], which produces a larger CO₂ amount in the atmosphere. Therefore, the increasing cost of energy and tightening environment regulations have forced industry to create better SSC process alternatives for reducing operating costs, overall plant footprint and/or enlarging the column capacity.

Many studies have examined the relative advantages of a dividing wall column (DWC), including the huge potential for a reduced consumption of utilities. These studies have shown that DWC systems can achieve energy savings of up to 30% over conventional direct and indirect distillation sequences [5]. DWCs can also be used to conduct azeotropic [6], extractive [7], and reactive distillation [8] without any major change to the internal types of internal used. Furthermore, dividing wall columns have shown similar potential when retrofitted to conventional 2-column systems [9] and SSCs [10]. However, even DWCs are one of the best examples of proven process intensification in distillation; they are expected to be more intensified systems for sustainable development.

Heat pumps, which allow the heat of condensation released at the condenser to be used for evaporation in the reboiler, are mainly applied to conserve energy when the temperature difference between the overhead and bottom of the column is small and the heat load is high [11]. A heat pump on the top of the column does not alter the vapor and liquid traffic inside the column. Nevertheless, a side heat pump can reduce the vapor and liquid traffic on the trays above it, as well as increasing the vapor and liquid traffic below it, which in turn increases the area utilization below the side heat pump [12]. Heat pumps can also be easily retrofitted to existing designs, as they are located externally and require little alteration to existing systems [13,14]. Although there is an additional investment cost associated with the addition of a heat pumps [15–18], their economic benefits will vary, and should be evaluated individually in each case.

In an existing distillation process with a fixed feed composition, there will be a maximum feed flow rate that can be separated to meet certain fixed product specifications [19]. Nevertheless, an increase in production capacity can cause bottleneck problems. The retrofit projects, which are performed more often than the installation of new equipment, aim to identify and remove these bottlenecks. Due to the minimal cost required, especially when compared with the construction of an additional facility, the debottlenecking of an existing facility is an attractive method [20,21].

2. Problem statement

Although SSCs used to separate ternary mixtures are widely employed, it requires substantial energy. Furthermore, increasing the capacity of SSCs can cause an entrainment flooding or a bottleneck problem. To solve this problem, this paper proposes a novel configuration, combining a heat pump with a DWC, as a mean of debottlenecking the process stream while reducing operating costs remarkably of a SSC. The interactions between a heat pump and DWC are also analyzed and evaluated to emphasize the efficiency of the novel configuration. A techno-economic analysis of proposed configuration was also carried out to demonstrate the feasibility, simplicity and efficiency. A column grand composite curve was used to indicate the thermodynamic feasibility of the heat pump or side heat pump implementation, as well as the energy saving after retrofitting. A hydraulic performance indicator and fractional utilization of the area (FUA) was used to identify a bottleneck in a distillation column when the capacity was increased. The design and optimization procedures using the response surface methodology (RSM) were used to retrofit the SSC to a heat pump assisted dividing wall column (HPDWC), placing particular emphasis on the utilization of existing hardware with minimal investment and construction costs. Several industrial case studies were used to evaluate the proposed HPDWC. Notably, the proposed configuration was shown to remove the bottleneck problem while using less energy and reducing corresponding CO₂ emissions than the existing SSC or the conventional heat pump assisted SSC. This proposed configuration can also be applied to wide-boiling mixtures.

3. Design and optimization of proposed configuration

3.1. Design

This paper is carried out with the following assumptions:

a. The capacity must increase by 10% over the standard operational capacity.

b. The existing column is already operating with the highest performance internals.

c. The recovery of all products is kept constant.

d. The FUA_max of all columns is 1.

e. The lifespan of the system will continue for at least 8 years after retrofitting.

f. New trays are installed in the dividing wall section.

With a production capacity increase of 10%, the new base was simulated using the former process configuration, where all columns were used to obtain their products. Unfortunately, the results showed that it is impossible to use the existing column, as it is bottlenecked when the throughput is increased. Therefore, the HPDWC was utilized to determine the requirements of the product in terms of productivity, recovery and purity.

Fig. 1 shows a number of options for retrofitting an existing SSC to a HPDWC. A heat pump is used to supply heat to the reboiler, the
vessel of which is installed with a dividing wall (shown in Fig. 1b). The latent heat of condensation of the top vapor stream can be utilized to provide partial/total heating of the reboiler. Alternatively, instead of supplying heat to the reboiler, a heat pump can be used to provide side heating (Fig. 1c), reducing the temperature difference and the traffic in the stripping section, and further increasing the capacity. Similarly, a side heat pump dividing wall column (SHPDWC) is implemented to supply heat to the reboiler while reducing the traffic in the rectification section (Fig. 1d). Supplying heat to the side reboiler by a side heat pump can reduce the temperature difference throughout the system and decrease the traffic in the affected sections (above the side heat pump and below the side reboiler, Fig. 1e). Consequently, this system can be applied not only for close-boiling but also for wide-boiling mixtures. In addition, it can be employed both at the time of construction and as a retrofitted design. This study assumes no change in the diameter or the total number of stages of each column to highlight the optimal use of existing columns. Debottlenecking the existing distillation column begins with the development of preliminary designs for complex systems, and maximizes the operating cost saving through the optimization procedures [19]. The HPDWC was designed using a divided-wall and a heat pump. The required modifications for the retrofit include a change in the feed tray and the inclusion of a draw tray for the side stream product.

3.2. Optimization

RSM is a general technique which is used for the empirical study of the relationships between measured responses and independent input variables [22]. A response surface is normally polynomial, and its coefficients are extracted by a simple least-square fit to the experimental data [23]. The RSM is quite powerful, as in addition to modeling, it can also be used to optimize the conditions of a process [24]. Normally, a low-order polynomial is used for a number of independent variables [25]. On the other hand, the RSM encounters some difficulties in approximating the sufficient quality on the entire design space when the behavior of the function is highly nonlinear with respect to the variables [26]. The optimum may not be defined if the range of factors is too narrow or too wide. Furthermore, critical factors may not be defined or specified correctly. In the case of many factors, the problem becomes complex and the RSM cannot be predicted well.

In order to minimize the required modifications for a retrofit, the number of column trays (N) accurately represented those used in existing distillation columns. After a preliminary design for the HPDWC system, the main design variables, including the internal vapor (FV) and liquid (FL) flows to the prefractionator, and the number of trays in the top (N1), middle (N2), feed rectifying (N3), and side product (N4) sections, were optimized. The main design variables of the HPDWC system are also depicted in Fig. 1b. RSM was used to examine the effects on operating costs. After determining the preliminary ranges of the variables through single-factor testing, a Box–Behnken design [25] was used to determine how the variables interact, allowing for optimization of the system and maximization of cost savings.

The simulation data was fitted to a second-order polynomial model, and the regression coefficients were obtained. The generalized second-order polynomial model used in the response surface analysis can be expressed as

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j + \varepsilon \]  

where Y is the predicted response (operating cost saving), X_i are the uncoded or coded values of the variables, \( \beta_0 \) is a constant, \( \beta_i \) and \( \beta_{ij} \) are the coefficients of the linear, quadratic and interactive terms, respectively, and \( \varepsilon \) is an error term. MINITAB software was used for response surface fitting to maximize cost savings.

Fig. 1. Schematic diagram of the (a) side stream column; (b) retrofitted HPDWC; (c) retrofitted HPDWC with a side reboiler; (d) retrofitted SHPDWC; and (e) retrofitted SHPDWC with a side reboiler.
3.3. Hydraulic performance – fractional utilization of area

Column hydraulics has to be considered during carrying out the retrofit. The performance indicator for the hydraulic conditions of an existing distillation system, which is related to the area needed to allow for vapor flow, was used [12]. The indicator allows for the identification of bottlenecks, and an evaluation of proposed modifications to overcome these bottlenecks. It is important to determine at which stages the vapor and liquid traffic should be reduced, as well as which stages can accommodate increased flows [19]. A new indicator of the hydraulic performance of an existing distillation column, the FUA, is utilized as follows:

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

where the area required for vapor flow is calculated for a given approach to the flooding conditions (e.g. when the vapor velocity is 85% of the flooding velocity) [19].

4. Case study

4.1. Retrofit of ethylene dichloride separation column (EDC case)

4.1.1. Process description

Vinyl chloride monomer (VCM) for the polyvinyl chloride raw material is normally produced by a thermal reaction of ethylene dichloride (EDC), which is synthesized from ethylene, oxygen and chlorine by oxychlorination and direct chlorination [27,28]. Fig. 2 outlines a schematic representation of a VCM production plant. The EDC routed to the pyrolysis furnace requires a sufficiently high purity in order to prevent side reactions which will lead to fouling in the pyrolysis tubes, and to achieve a high-quality VCM. In the EDC purification process, a SSC is used for the removal of light and heavy impurities which are contained with those components having a lower boiling-point than EDC in the overhead stream, as well as for removing impurities from higher boiling-point components lower down. Fig. 3 presents the existing SSC flow under the systems original operating conditions. The existing 45-valve-tray SSC (diameter 3.8 m) was operated at 1.6 bar. Table 1 lists the feed composition, temperature, pressure and flow rate. The simulation was performed using Aspen HYSYS 8.4, where the NRTL property method was chosen to predict the vapor–liquid equilibrium (VLE) of these simulations. The base case simulation model shows that the energy requirement of this column is 11.37 MW.

4.1.2. Proposed configuration

The purity of the component fractions produced is often proportional to energy usage, and in some instances, the temperature difference between the top and bottom sections of a SSC (ΔT = 11 °C) may not be great enough to warrant the installation of an additional heat pump. The factors and levels used in this case study are listed in Table 2. A four-run $2^4$ simulation was created in each of six two-factor interactions while the remaining two were held at their zero levels. This means that the design contains $6 \times 2^4 = 24$ runs plus three center runs (0, 0, 0, 0) to resolve the quadratic terms. Thus, twenty-seven simulations were run in order to optimize 4 parameters of the HPDWC structure. For each run, the internal vapor and liquid flow to the prefractionator were altered in order to minimize operating costs while still achieving the required degree of product purity. Fig. 4 shows as contour plot of the interactions between the main design variables $N_1$, $N_2$, $N_3$, and $N_4$ for the EDC case. Two parameters of each model were plotted on each set of $X$ and $Y$ axes. The remaining parameters were automatically set at their center point values by the software while constructing the plots. The resulting second-order polynomial model was as follows:

$$Y = 57.6632 + 1.5669N_1 + 0.9389N_2 + 0.6162N_3 + 0.2304N_4 - 0.0281N_1^2 - 0.0244N_2^2 - 0.0373N_3^2 - 0.0198N_4^2 - 0.0221N_1N_2 - 0.0076N_1N_3 - 0.0083N_1N_4 + 0.0027N_2N_3 + 0.0245N_2N_4 - 0.0016N_3N_4$$

The quality of the polynomial model was expressed as the coefficient of determination ($R^2$). Based on an analysis of the results generated through MINITAB, the model showed a high $R^2$ value of 0.99, indicating a very strong correlation between the simulated and predicted values. The relationship between the independent variables and the response is well explained by the regression
As a result, the maximum cost savings were observed at the top ($N_1$), middle ($N_2$), feed rectifying ($N_3$), and side product ($N_4$) tray sections of 18, 18, 7, and 13, respectively (Fig. 5). The maximum savings of operation costs achievable from the retrofitted HPDWC were predicted to be 85.1%. Note that the vapor from the top of the distillation column is compressed to a certain pressure (pressure ratio = 1.84) and condensed in the column’s reboiler through indirect contact with the liquid in the column [29]. The adiabatic efficiency of compressor was assumed to be 75% [30–33]. This allows the heat of the condensing vapor to assist in vaporization at the bottom of the column via a heat exchanger (minimum approach temperature $\Delta T = 10^\circ$C). The top outlet stream must be cooled further prior to its recycling to the column as a reflux, and a heat pump will condense the vapor phase and recycle it as a liquid phase. There was no alteration in the composition of the produced products. Fig. 6 shows a simplified flow chart, illustrating the proposed HPDWC. Compared to the existing SSC, the use of a HPDWC can significantly reduce condenser duty, reboiler duty and operational costs of 48.3%, 100%, and 83.7%, respectively, as shown in Table 3. The operating cost savings were in good agreement with the results predicted by the RSM. The utility cost data is listed in Table 4 [29]. These cost savings can be further increased when the electricity/steam cost ratio decreases [34]. Note that the existing SSC and the configuration of the existing SSC with a heat pump cannot operate when the capacity is increased by 10% due to their flooding conditions. The results in Table 3 are aimed to show the relative saving of the proposed sequence.

Remarkably, compared to the SSC with a heat pump, the proposed configuration reduced the electricity cost and operating cost up to 49.4% and 45.8% savings, respectively. This indicates that the installation of a dividing wall into a SSC can dramatically reduce power requirements, in addition to an apparent saving in compressor capital cost. Through the installation of the proposed configuration, operating costs can be reduced by 72.6%, as compared to the DWC without a heat pump.

Fig. 7 shows the FUA curve, as a graphical display of hydraulic performance. The FUA is different at each stage, with stages in the top being limited by area (FUA > 1). This indicates that flooding occurs in the top of the column when capacity is increased. This bottleneck problem can be alleviated through the installation of a side heat pump, which can alter the vapor traffic in the top of the column. Such bottlenecking problems can be further improved.

### Table 1
Feed conditions for EDC case.

<table>
<thead>
<tr>
<th>Feed conditions</th>
<th>Liquid stream (wt.%)</th>
<th>Vapor stream (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.06</td>
<td>0.59</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>0.28</td>
<td>0.58</td>
</tr>
<tr>
<td>1,1-dichloroethane</td>
<td>0.29</td>
<td>0.01</td>
</tr>
<tr>
<td>1,2-dichloroethane</td>
<td>98.74</td>
<td>98.32</td>
</tr>
<tr>
<td>Trichloroethylene</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>1,1,2-trichloroethane</td>
<td>0.06</td>
<td>0.32</td>
</tr>
<tr>
<td>3,4-dichloro-1-butene</td>
<td>0.32</td>
<td>0.06</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>80</td>
<td>115</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Mass flow (kg/h)</td>
<td>67,636</td>
<td>116,655</td>
</tr>
</tbody>
</table>

### Table 2
Coded factor levels for three cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Factor</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDC</td>
<td>Top section ($N_1$)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Middle section ($N_2$)</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Feed rectifying location ($N_3$)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Side product location ($N_4$)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>AA</td>
<td>Top section ($N_1$)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Middle section ($N_2$)</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Feed rectifying location ($N_3$)</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Side product location ($N_4$)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>AK</td>
<td>Top section ($N_1$)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Middle section ($N_2$)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Feed rectifying location ($N_3$)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Side product location ($N_4$)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Side heat pump location ($N_5$)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Side reboiler location ($N_6$)</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 4. Contour plot of interactions between $N_1$, $N_2$, $N_3$ and $N_4$ for EDC case.
through the use of a DWC, which can improve the performance of a heat pump. However, the installation of a side heat pump requires a relatively large degree of modification compared to the installation of a heat pump at the top of the column. In this case, the vapor and liquid traffic inside the column is redistributed using a heat pump assisted DWC, which can accommodate significantly higher flows while reducing the energy requirement.

The estimated savings in cost by the proposed configuration was USD 32.3 m USD after 8 years. The payback period for the installation of the system was calculated to be 10.7 months, with much reduced additional costs thereafter.

4.2. Acetic acid purification column (AA case)

4.2.1. Process description

Acetic acid (AA) is an important industrial chemical with many industrial uses and an annual worldwide demand of almost six million tonnes [35]. An industrial method based on the carbonylation of methanol (MeOH) is widely preferred for its manufacture, accounting for approximately 60% of the global manufacturing capacity [36]. Fig. 8 outlines the AA production process by MeOH carbonylation. The process consists of three main units: a catalyst preparation/regeneration unit, a MeOH carbonylation unit and an AA purification unit. In the purification unit, a mixture containing the crude AA, as well as contaminants from the carbonylation unit, is separated in a series of conventional distillation column with the final column as a SSC. This column produces the final AA product from the side draw, once lighter and heavier components have been isolated in the top and bottom of the column, respectively.

To predict the vapor–liquid equilibrium (VLE) of this column simulation, the NRTL-HOC property model, which uses the Hayden–O’Connell equation of state as the vapor phase model, and the NRTL for the liquid phase, was used [21,37]. The existing SSC, which is 3.7 m in diameter with 65 valve-trays, requires 20.45 MW at the reboiler (Fig. 9a).

4.2.2. Proposed configuration

A retrofit the SSC in the AA purification unit to a HPDWC was studied, with the aim of removing bottlenecks problems, as well as reducing the energy requirement when capacity is increased. Fig. 10 shows the column grand composite curve (CGCC) profiles for the existing SSC. The distance between the points on the curve and the vertical axis indicates the heat load required for each stage (Fig. 10a). An inspection of the CGCCs confirmed that the column energy requirements can be met by the operation of a heat pump.
between the stages when there is a reasonably small differences in temperature ($\Delta T = 17^\circ C$) (shown in Fig. 10b). Some preliminary simulations were carried out in order to determine the main optimizing variables and their levels. The response values (operating cost saving), corresponding to changes in the factor value, were also recorded. The presence of curvature suggests that the simulation region is close to optimal. The factors and levels used in this case study are listed in Table 2. Based on the analysis of results generated using MINITAB, the model showed a high $R^2$ value of 0.93, which indicates a strong correlation between the simulated and predicted values. It is worth to note that using the RSM may result a non-integer solution, which needs to be truncated the fractional parts to obtain a new integer solution. Fig. 9b shows the simplified flow sheet of the retrofitted HPDWC. A heat pump with a 2.0 pressure ratio will condense the vapor phase and recycle it within the column as a liquid phase. Fig. 10 also shows the CGCC profile of the retrofitted HPDWC when capacity is increased by up to 10%, and indicates that reboiler duty can be dramatically reduced through the installation of the proposed system. In particular, the reduction of reboiler duty and associated cost savings from this system were 94.3% and 85.9%, respectively, which were comparable to the performance of the existing column, as shown in Table 5. Note that the operating cost of the resulting DWC without a heat pump was estimated to be 25.1% that of the original SSC.

FUA profiles in Fig. 11 demonstrate that bottlenecking occurs in the SSC when the capacity is increased. This bottleneck problem can be removed efficiently after retrofitting of the HPDWC system. In addition, after 8 years, the cost savings by the retrofitted HPDWC was estimated to be 65.2 million USD. The simple payback period was estimated to be 6.4 months. Accordingly, the proposed configuration can save energy and remove the bottlenecking problems.
4.3. Alkanes separation column (AK case)

4.3.1. Process description

In this example, the separation of n-pentane, n-hexane and n-heptane in a single column is considered [38,39]. The side stream, possessing 41 theoretical trays, was designed and operated at 5 bar (Fig. 12a). The Peng–Robinson equation of state, supporting the widest range of operating conditions and the greatest variety of systems, was used to predict the simulations’ vapor–liquid equilibriums [34,37]. The base case simulation model showed that the energy consumption of the existing SSC was 1.77 MW.

4.3.2. Proposed configuration

Fig. 13 shows the CGCC profiles for the existing SSC, and indicates that there is a relatively large difference in temperature ($\Delta T = 66^\circ$C). This requires the retrofitting of a large compressor in order for the top vapor stream to be compressed and the generated heat transferred to the reboiler. To achieve this with minimal compressor size and operating costs, a SHPDWC with a side reboiler was employed. In this configuration, a side heat pump was used to provide side heating. Debottlenecking the existing SSC begins with the development of preliminary designs for a complex system and the minimization of operating costs. The factors and levels used in this case study are listed in Table 2. Fifty-four simulations were run in order to optimize 6 parameters of the HPDWC structure [40]. A CGCC of the retrofitted SHPDWC system with a side reboiler is shown in Fig. 13, and indicates that the duty in the reboiler and condenser is reduced dramatically, which results in a reduction of operating costs of up to 61.3% as compared to the existing SSC (Table 6). The simple payback period was calculated to be 17.8 months.

Fig. 14 shows the composition profiles of n-pentane, n-hexane and n-heptane in the existing side distillation column, prefractionator and the main column in the proposed configuration for AK case. In the top section, a portion of the vapor stream is condensed to the liquid phase, which causes a decrease in the composition profile of the intermediate component (n-hexane) and an increase in the composition profile of the light component (n-pentane). The same phenomenon occurs in the bottom section: a decrease in the composition profile of the intermediate component (n-hexane) and an increase in the composition profile of the heavy component.

### Table 5

Summary of relative performance for various arrangements for AA case.

<table>
<thead>
<tr>
<th>Structure alternatives</th>
<th>SSC</th>
<th>Heat pump</th>
<th>DWC</th>
<th>HPDWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser duty (MW)</td>
<td>23.26</td>
<td>9.86</td>
<td>17.76</td>
<td>3.76</td>
</tr>
<tr>
<td>Reboiler duty (MW)</td>
<td>22.50</td>
<td>6.79</td>
<td>16.84</td>
<td>1.28</td>
</tr>
<tr>
<td>Compressor duty (MW)</td>
<td>0.00</td>
<td>2.07</td>
<td>0.00</td>
<td>1.60</td>
</tr>
<tr>
<td>Annual operating cost (USD)</td>
<td>10,177,200</td>
<td>4,182,295</td>
<td>7,620,000</td>
<td>1,438,858</td>
</tr>
<tr>
<td>Energy requirement saving in condenser (%)</td>
<td>0.0</td>
<td>57.6</td>
<td>23.7</td>
<td>83.8</td>
</tr>
<tr>
<td>Energy requirement saving in reboiler (%)</td>
<td>0.0</td>
<td>69.8</td>
<td>25.2</td>
<td>94.3</td>
</tr>
<tr>
<td>Operating cost savings (%)</td>
<td>0.0</td>
<td>58.9</td>
<td>25.1</td>
<td>85.9</td>
</tr>
<tr>
<td>CO2 emission reductions (%)</td>
<td>0.0</td>
<td>51.0</td>
<td>25.2</td>
<td>79.8</td>
</tr>
</tbody>
</table>
(n-heptane). As a result, the temperature profile was reduced in the top section and increased in the bottom section compared to that in existing SSC (Fig. 15). It implies DWC does not offer preferential profile structurally for side heat pump configuration generally. Nevertheless, DWC can reduce reboiler duty, i.e. the compressor duty, which needs to supply, is reduced. Fortunately, this effect is dominant compared to the effect on compressor duty due to temperature profile change in this case. This brings a saving in compressor duty and operating cost up to 15.0% and 53.1% as compared to the SSC with a side heat pump and a side reboiler.

The CO₂ emission reduction associated to the less energy requirement is another important benefit from using the proposed sequence in retrofit of a SSC. The method by Gadalla et al. [41] was used to calculate the CO₂ emissions. Tables 3, 5, and 6 show the CO₂ emission reduction of all considered configurations in the EDC, AA and AK purification processes, respectively. The study result shows that CO₂ emission can be reduced dramatically when

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**Table 6**

<table>
<thead>
<tr>
<th>Structure alternatives</th>
<th>SSC</th>
<th>SHP with a side reboiler</th>
<th>DWC</th>
<th>SHPDWC with a side reboiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser duty (MW)</td>
<td>1.89</td>
<td>1.53</td>
<td>0.91</td>
<td>0.66</td>
</tr>
<tr>
<td>Reboiler duty (MW)</td>
<td>1.95</td>
<td>1.43</td>
<td>0.98</td>
<td>0.56</td>
</tr>
<tr>
<td>Compressor duty (MW)</td>
<td>0.00</td>
<td>0.20</td>
<td>0.00</td>
<td>0.17</td>
</tr>
<tr>
<td>Annual operating cost (USD)</td>
<td>880,255</td>
<td>725,147</td>
<td>440,210</td>
<td>340,271</td>
</tr>
<tr>
<td>Energy requirement saving in condenser (%)</td>
<td>0.0</td>
<td>20.1</td>
<td>51.9</td>
<td>65.1</td>
</tr>
<tr>
<td>Energy requirement saving in reboiler (%)</td>
<td>0.0</td>
<td>29.7</td>
<td>49.7</td>
<td>71.3</td>
</tr>
<tr>
<td>Operating cost savings (%)</td>
<td>0.0</td>
<td>17.6</td>
<td>50.0</td>
<td>61.3</td>
</tr>
<tr>
<td>CO₂ emission reductions (%)</td>
<td>0.0</td>
<td>5.3</td>
<td>49.7</td>
<td>53.5</td>
</tr>
</tbody>
</table>

---

![Fig. 12. Simplified flow sheet illustrating (a) existing SSC and (b) proposed configuration for AK case.](image)

![Fig. 13. CGCC profiles of SSC and proposed HPDWC when capacity is increased by up to 10% for AK case.](image)
distillations are intensified by thermal coupling technique and part of the process heat is recovered to use instead of primary steam. It is worth to note that the configurations including a heat pump utilized to improve energy efficiency of a SSC, the CO₂ emission reduction is smaller than the operating cost saving.

5. Conclusions

In this paper, an energy efficient hybrid technology which combines a heat pump and dividing wall column was proposed as a retrofit for the effective debottlenecking of an existing SSC operating under increased capacity. The ability of the heat pump technique to improve the energy efficiency of a DWC in a retrofitted SSC was successfully demonstrated. In addition, the DWC is shown to increase the energy efficiency of a heat pump while also to removing bottlenecking problems. A CGCC was used effectively to indicate the thermodynamic feasibility of the implementation of a heat pump or side heat pump, as well as the potential energy savings which can be achieved through their installation. The FUA curve shows suitable locations for the redistribution of flows within the column. The retrofitted HPDWC structure was designed and optimized efficiently with little computational effort. The results predicted by the RSM were in good agreement with those of the simulation. The simulation indicated a large reduction in operating costs compared to the existing SSC, while removing the bottleneck problem in the column. In particular, an 83.7%, 85.9% and 61.3% reduction in operating costs could be achieved in EDC, AA and AK purification processes, respectively. The study shows that a heat pump can improve the performance of a DWC, and also shows that a DWC can increase the energy efficiency of a heat pump and reduce its capital cost significantly. In addition, this system, which can be applied for close-boiling and wide-boiling mixtures, is suitable for application at both grass-roots and retrofit designs. Furthermore, an existing SSC can be easily retrofitted to a HPDWC by the addition of a dividing wall, or by exchanging or adding the middle section of an existing SSC with a new dividing wall section and installing a heat pump. The short payback periods and reduced CO₂ emissions make the proposed configuration an attractive option for industrial implementation.

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Appendix A. Cost correlations

a. Capital cost: Guthrie’s modular method was applied [30]. In this study, a Chemical Engineering Plant Cost Index of 585.7 (2011) was used for cost updating.

\[ \text{Updated bare module cost (BMC)} = \text{UF} \times \text{BC} \times (\text{MPF} + \text{MF} - 1) \]

(4)

where UF is the update factor:

\[ \text{UF} = \frac{\text{present cost index}}{\text{base cost index}} \]

(5)

\[ \text{BC} \] is the bare cost of the heat exchanger:

\[ \text{BC} = \text{BC}_0 \times \left( \frac{A}{A_0} \right)^{0.8} \]

(6)
for the compressor: \( BC = BC_0 \times \left( \frac{S}{S_0} \right)^x \) \( (7) \)

where MPF is the material and pressure factor; MF is the module factor (typical value), which is affected by the base cost. \( A \) and \( S \) are the area and brake horsepower, respectively.

Area of the heat exchanger, \( A = \frac{Q}{\Delta T} \) \( (8) \)

The material and pressure factor: \( MPF = F_m + F_t + F_m \) \( (9) \)

b. Operating cost (Op):
\[ Op = C_{\text{steam}} + C_{\text{cw}} + C_{\text{electricity}} \] \( (10) \)

where \( C_{\text{steam}} \) is the cost of the steam; \( C_{\text{cw}} \) is the cost of cooling water; and \( C_{\text{electricity}} \) is the cost of electricity.

c. Cost of modification = Cost of new hardware
* modification factor \( [3] \) \( (11) \)

In this study, modification factors of removal of trays to install new trays, installation of new trays, and installation of new dividing wall are 0.1, 1.4, and 1.4, respectively.

d. Cost saving = Operating cost saving – modification cost \( (12) \)

e. Payback period = cost of project/saving per year \( (13) \)

f. Estimation of \( \text{CO}_2 \) Emission Reduction \([41]\)

In the combustion of fuels, air is assumed to be in excess to ensure complete combustion, so that no carbon monoxide is formed. The amount of \( \text{CO}_2 \) emitted, \( [\text{CO}_2]_{\text{emissions}} \) (kg/s), is related to the amount of fuel burnt, \( Q_{\text{fuel}} \) (kW), in the heating device, as follows:

\[ [\text{CO}_2]_{\text{emissions}} = \frac{Q_{\text{fuel}}}{\text{NVH}} \times \left( \frac{C_{\%}}{100} \right) x \] \( (14) \)

where \( x = 3.67 \) is the ratio of the molar masses of \( \text{CO}_2 \) and \( C \), while NVH, which is equal to 47.141 (kg/kj), represents the net heating value of natural gas with a carbon content of 75%.

The amount of fuel burnt can be calculated from:

\[ Q_{\text{fuel}} = \frac{Q_{\text{proc}} \times (h_{\text{proc}} - 419)}{A_{\text{proc}}} \times T_{\text{th}} - T_{\text{th}} \times T_{\text{th}} \] \( (15) \)

where \( h_{\text{proc}} \) (kJ/kg) and \( Q_{\text{proc}} \) (kJ/kg) are the latent heat and enthalpy of steam delivered to the process, respectively, while \( T_{\text{th}} \) (°C) and \( T_{\text{th}} \) (°C) are the flame and stack temperature, respectively.

References