

Special theme research article

Improvement of natural gas liquid recovery energy efficiency through thermally coupled distillation arrangements

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ABSTRACT: The depropanizing, debutanizing, and deisobutanizing fractionation steps of processing natural gas liquids were improved through studying complex distillation arrangements, including the double prefractionator arrangement (DPA), the double dividing wall column (DDWC) arrangement, and the Agrawal arrangement. The DPA and DDWC arrangements were obtained from an initial conventional column sequence, and both offer benefits by decreasing reboiler and condenser power consumption. Reducing the number of columns and their diameters in the DDWC arrangement can potentially reduce construction costs. Inter-reboiling of the bottom section of the second dividing wall column improved the performance of the DDWC. © 2011 Curtin University of Technology and John Wiley & Sons, Ltd.

KEYWORDS: thermally coupled distillation; dividing wall column; double dividing wall column; double prefractionator arrangement; natural gas recovery

INTRODUCTION

The uses and processing of natural gas (NG) are still evolving since their early 20th century origins in the United States. Although its primary use is as a fuel, NG is also a source of hydrocarbons for petrochemical feed stocks and a major source of elemental sulfur, an important industrial chemical.^[1] Its clean burning and ability to meet stringent environment requirements ensure demand for NG.^[2] Recovery of NG liquids (NGLs) has become increasingly economically attractive because a number of its components are often isolated and sold separately. Consequently, numerous methods exist to increase NGL recovery from a feed gas, with potential enhancements involving integrated processes.^[2,3]

Distillation is the primary separation process used in industrial chemical processing. Although it has many advantages, the drawback is its large energy requirement,^[4] which can significantly influence overall plant profitability. Increasing energy costs deter energy consumption as do tighter environmental regulations regarding fossil fuel use, leading to research into new and more efficient separation methods.^[5,6]

Ternary separations typically involve either direct or indirect sequences with two conventional columns.

Although the control and operation of conventional columns are simple, their use is inefficient in terms of energy due to the mixing entropy by irreversible split.^[7] Therefore, various methods have been developed to improve the energy efficiency of such distillation systems. Many studies confirm that the fully thermally coupled distillation system or the Petlyuk column can reduce energy consumption.^[8–12] The Petlyuk column allows reversible splits, with no part of the separation being performed twice (Fig. 1), which gives superior separation energy efficiency over other column configurations.^[13]

Instead of having an external prefractionator, the prefractionator can be incorporated into a single shell arrangement by installing an internal wall, which divides the column into the prefractionator and the main section (Fig. 2). This dividing wall column (DWC) is conceptually similar to the Petlyuk column, given their thermodynamically equivalent arrangements,^[14] and is expected to give a similar energy saving. However, the DWC requires less capital expenditure and space. Its single shell feature, single reboiler, and condenser can typically reduce capital expenditure by 30% compared with conventional two column sequences. The design of the DWC is more complex than a simple column because there are more degrees of freedom that need to be specified. Key variables and parameters such as the number of trays of the column, the liquid and vapor splits in each side of the dividing wall, and the feed and side tray locations must be established. These degrees of

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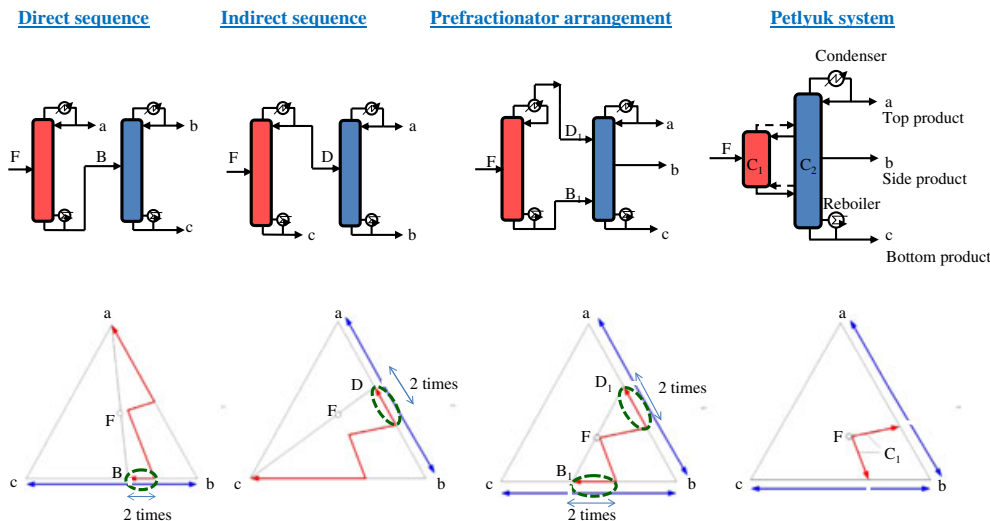


Figure 1. The ternary systems of direct sequence, indirect sequence, prefractionator arrangement, and the Petlyuk system. This figure is available in colour online at www.apjChemEng.com.

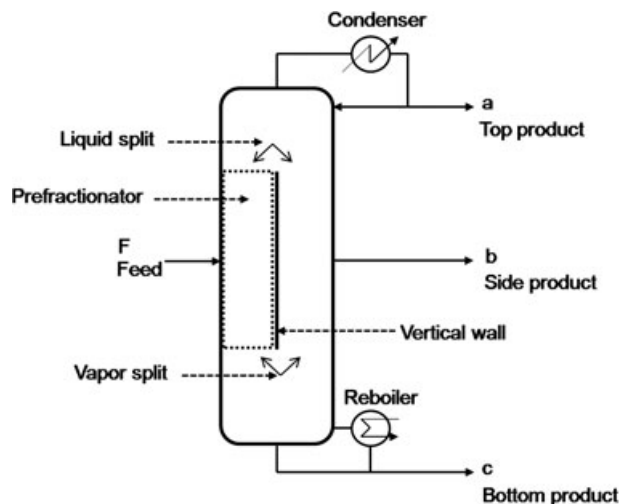


Figure 2. A dividing wall column.

freedom all interact with each other and need to be simultaneously optimized to obtain the best design. Because the number of stages is an integer variable, column

optimization falls into a class of mixed integer nonlinear programming problems,^[15] which cannot be solved by commercially available rigorous process simulators.

More than three components in the feed stream ($n > 3$) lead to many possible arrangements of distillation columns that can produce n product streams, each enriched in one of the components. A large number of reboilers and condensers are often associated with these arrangements—expensive apparatus both to acquire and to operate that significantly contributes to the cost of the overall arrangement. One method to reduce the number of reboilers and condensers is to use thermally linked columns. Literature on the separation of mixtures with more than three components is relatively scarce. Fig. 3 shows dividing wall implementations of the Kaibel, Sargent, and Agrawal arrangements. These configurations permit multicomponent separation within a single shell using only one reboiler and one condenser.^[16–20]

However, integrating three columns, whose operating pressures are so different, in such ways is impractical. At least two columns are needed. This work aims to find a configuration suitable for improving the performance

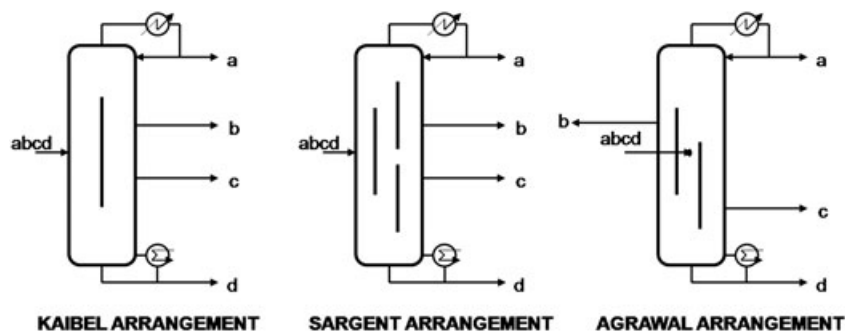


Figure 3. Kaibel, Sargent, and Agrawal arrangements.

of the depropanizing, debutanizing, and deisobutanizing fractionation steps of NGL processing. Furthermore, inter-reboiling of the bottom section of the second DWC was also studied to improve the performance of the DDWC arrangement.

CONVENTIONAL DISTILLATION SEQUENCE

Liquid hydrocarbons recovered from NGL are typically separated into relatively pure ethane (C_2), propane (C_3), isobutane (iC_4), normal butane (nC_4), and gasoline products (C_{5+}). This is conventionally done by distilling C_2 , C_3 , and C_4 from gasoline in sequence and then distilling iC_4 from nC_4 . Because of the large energy consumption, there are numerous configurations and methods known to increase NGL recovery from a feed gas. The difference of operating pressures complicates the columns' integration and directly affects energy consumptions and the use of refrigeration. The high-pressure demethanizer and deethanizer columns should not be integrated with other columns (depropanizer, debutanizer, and deisobutanizer).

The depropanizer, possessing 34 theoretical trays, is operated at 17.50 bar as commercial propane can be condensed with cooling water at this pressure, as seen in Fig. 4. The debutanizer and deisobutanizer columns, with 40 and 92 trays, respectively, are operated at 3.50 and 4.40 bar, respectively.^[21,22] The final distillation of iC_4 from nC_4 is energy and capital intensive because of these compounds' small relative volatility.^[23] The feed composition, temperature, and pressure are listed in Table 1. Simulations were performed using the simulator Aspen HYSYS V7.1. The Peng–Robinson equation of state that supports the widest range of operating conditions and the greatest variety of systems were used to predict the vapor–liquid equilibria of these

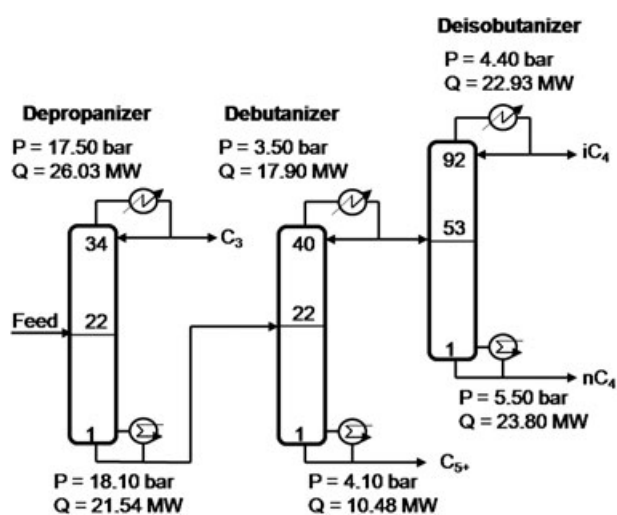


Figure 4. Simplified flow sheet illustrating the separation train of three conventional columns.

simulations.^[24] Table 2 lists the conditions and product specifications of each column. The base case simulation shows that the energy consumptions of the depropanizer, debutanizer, and deisobutanizer are 21.54, 10.48, and 23.80 MW, respectively.

All columns were designed for use with a load near 85% of the flooding point load to prevent their flooding. To determine the maximum flooding of a particular column, we simulated a rating mode with each column's internal specifications, such as the type of trays, column diameter, tray spacing, and number of passes. Table 2 lists the parameters defining the hydraulic features of the columns.

In this study, the Guthrie modular method^[25] was applied to the estimation of investment cost. The investment cost for conventional distillation is the total cost of the

Table 1. Feed mixture conditions.

Component	Feed conditions	
	Mass flow (kg/h)	Liquid volume fractions (%)
Methane	0.00	0.00
Ethane	4736.72	3.18
Propane	82 944.01	39.09
<i>i</i> -Butane	26 781.79	11.38
<i>n</i> -Butane	57 177.26	23.41
<i>i</i> -Pentane	20 651.89	7.91
<i>n</i> -Pentane	14 610.02	5.54
<i>n</i> -Hexane	17 566.46	6.33
<i>n</i> -Heptane	9088.96	3.16
Temperature (°C)	111.6	
Pressure (bar)	31.47	

Table 2. Column hydraulics, energy performance, and product specifications of the conventional column sequence.

	Depropanizer	Debutanizer	Deisobutanizer
Number of trays	34	40	92
Tray type	Sieve	Sieve	Sieve
Column diameter (m)	4.9	3.6	4.5
Number of flow paths	1	1	1
Tray spacing (mm)	609.6	609.6	609.6
Max flooding (%)	83.51	84.22	84.48
Condenser duty (MW)	26.03	17.90	22.93
Reboiler duty (MW)	21.54	10.48	23.80
Purity (liquid volume fractions, %)			
C_3	90.14		
<i>i</i> C_4	97.00		
<i>n</i> C_4	95.00		
C_{5+}	99.06		

column and the auxiliary equipment, such as reboiler and condenser, whereas for the DWC, it entails the additional dividing wall cost. For cost updating, the Chemical Engineering Plant Cost Index of 575.4 was used.

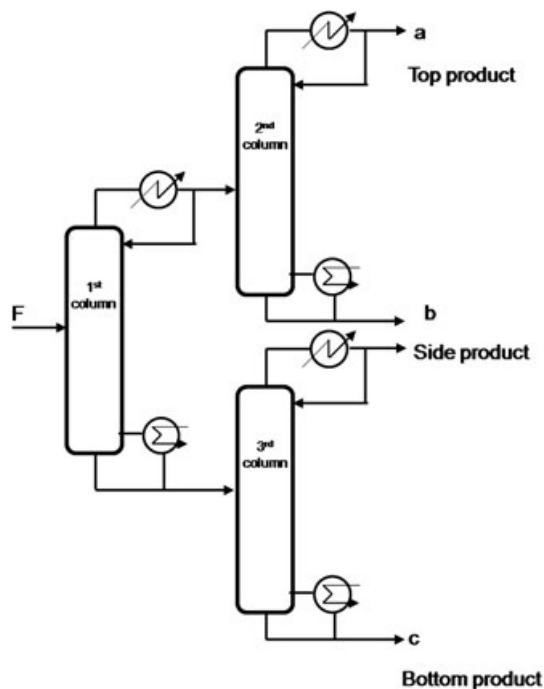


Figure 5. The three-column distillation system used for the initial design of the DWC structure.

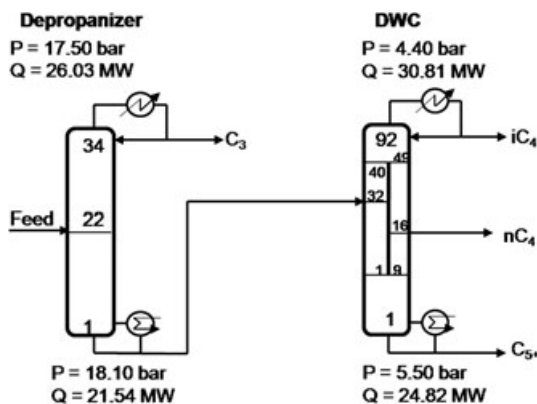


Figure 6. Simplified flow sheet illustrating the separation train of a one conventional column and one DWC system.

PROPOSED ARRANGEMENTS

Integrating debutanizer and deisobutanizer using a dividing wall column

The integration of the debutanizer and deisobutanizer using a DWC was studied to evaluate the performance of the DDWC.

The DWC structure was initially designed with a shortcut design procedure based on the conventional column configuration shown in Fig. 5.^[14,26–28] In this conventional configuration, the first column corresponds to the prefractionator section in the DWC. The rectifying section of the second column and the stripping section of the third column represent the top and bottom sections of the DWC, respectively. Both the stripping section of the second column and the rectifying section of the third column are equivalent to the divided wall section of the DWC.

Furthermore, both the bottom stream from the second column and the top stream from the third column refer to the side stream of the DWC.^[27] Consequently, the structure of the DWC can be divided into four sections: the prefractionator section for the feed mixture, the top and bottom sections above and below the divided wall, and the divided wall section.

After the initial structure of the DWC was fixed by the shortcut methods, the internal recycle flows to the prefractionator were optimized using case study. Then, the total number of trays, feed tray location, side tray location, as well as dividing wall section, were also investigated to establish an optimal DWC structure. For each chosen structure, the internal vapor and liquid flow to the prefractionator were varied to minimize energy consumption, which bears significant influence on overall plant profitability.

Consequently, a new DWC was designed with 92 trays. Its feed tray was the 32nd. The dividing wall was located from the 10th to the 49th trays, and the side stream was drawn from the 16th tray (Fig. 6). The power consumptions of the condenser and reboiler were 30.81 and 24.82 MW, respectively. Based on the total energy consumption of the debutanizer and deisobutanizer, this DWC can save up to 27.62%, i.e. an overall energy saving of 16.96%.

The cross-sectional area of the middle section of this DWC is the sum of the prefractionator section area and the middle section area of the main fractionator. The diameter of the middle section can be calculated from

Table 3. Specifications of dividing wall column.

	Prefractionator	Main fractionator (middle)	DWC (middle)	DWC (top)	DWC (bottom)	DWC
Diameter (m)	3.4	4.6	5.7	5.1	4.7	5.7
Max flooding (%)	82.41	87.71		84.19	83.57	
Position of section		10th tray to 49th tray		50th tray to 92nd tray	1st tray to 9th tray	

its cross-sectional area. Table 3 lists the diameters of the top, middle, and bottom sections of the DWC. Based on these results, the DWC was chosen to have a diameter of 5.7 m.

Integration by the double prefractionator arrangement

The integration of debutanizer and deisobutanizer using the prefractionator arrangement has been reported elsewhere.^[22] Fig. 7 illustrates the double prefractionator arrangement (DPA). In the first prefractionator arrangement, the second column is considered the main fractionator as well as the prefractionator in the second arrangement. Simulation of this arrangement was performed with respect to the flow of the distillate and reflux streams of the first and second columns, side tray location and the feed tray location in each column, to minimize the size of the column and total energy consumption. The energy savings of this arrangement were 18.50% compared with the conventional column sequence. Note that the side draw stream from the debutanizer in the DPA is vaporous. Moreover, the DPA saves investment cost up to 6.14% over the conventional sequence.

Integration by double dividing wall column

In this sequence (Fig. 8), energy saving relies on the first column splitting the components well. The sequence contains two DWCs. The first column isolates C_3 from the mixture and also partly splits the remaining components. The second DWC completes the separation.

Simulation based on the equilibrium stage model was performed for this arrangement with respect to the flow of iC_4 in the side stream and in the first DWC, as well as the feed and side tray locations in the two new DWCs to minimize the size and total energy consumption of the system. The DDWC arrangement showed a 28.74% improvement in energy

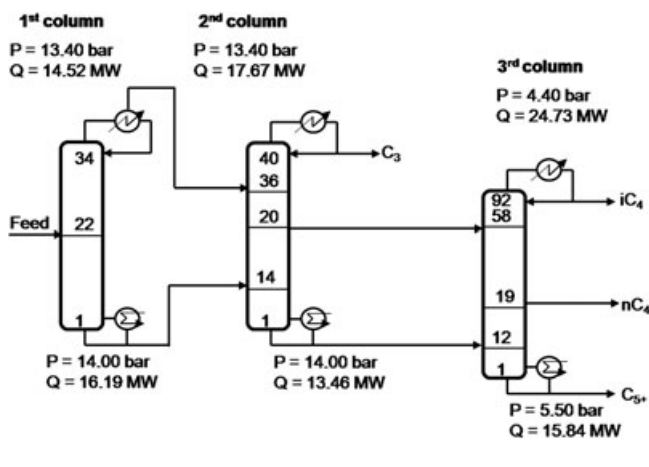


Figure 7. Simplified flow sheet illustrating the DPA system.

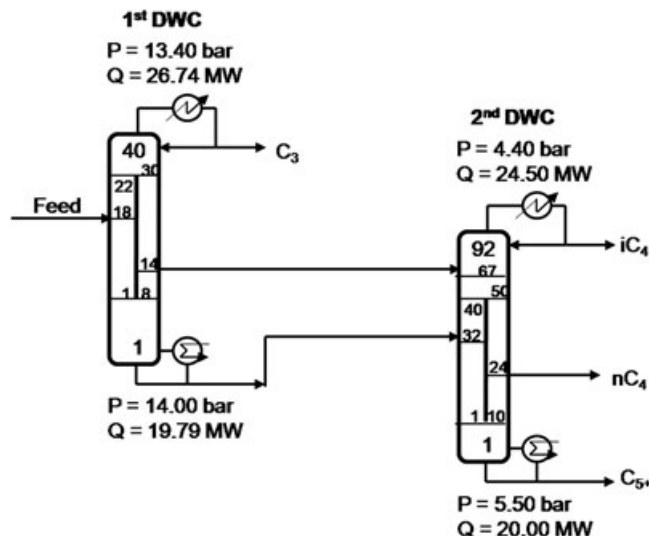


Figure 8. Simplified flow sheet illustrating the DDWC system.

consumption compared with the conventional column sequence.

Table 4 shows the product specifications, as well as the column hydraulics, and energy performance of the DDWC arrangement. Compared with using three conventional columns of diameters 4.9, 3.6, and 4.5 m, using two DWCs of 5.2- and 4.9-m diameter could bring the saving up 8.71% in investment cost.

To minimize energy consumption, the bottom liquid product can be subcooled while inter-reboiling the bottom section of the second DWC (Fig. 9).^[21] This can save 0.99 MW compared with DDWC, i.e. this system reduced energy consumption by 30.50% compared with the conventional column sequence.

Integration by the Agrawal arrangement

Reports on separating mixtures with more than three components are relatively scarce. The energy efficiencies

Table 4. Column hydraulics, energy performance, and product specifications of the double dividing wall column arrangement.

	First DWC	Second DWC
Number of trays	40	92
Tray type	Sieve	Sieve
Column diameter (m)	5.2	4.9
Number of flow paths	1	1
Tray spacing (mm)	609.6	609.6
Max flooding (%)	87.22	87.71
Condenser duty (MW)	26.74	24.50
Reboiler duty (MW)	19.79	20.00
Purity (liquid volume fractions, %)		
C_3		90.14
iC_4		97.00
nC_4		95.00
C_{5+}		99.06

of different Petlyuk arrangements, including the Kaibel, Sargent, and Agrawal arrangements, have been confirmed.^[20] An Agrawal arrangement with 12 sections has been found best and was therefore used in this work to integrate three columns at approximately 14 bar. This caused an increase of energy consumption. Feed should enter the DWC from the middle partition (Fig. 10). Because of high pressure required to condense C_3 using cooling water, the power consumptions of the condenser and reboiler were 72.62 and 66.68 MW, respectively (a 19.45% increase of reboiler power compared with the conventional column sequence).

A comparative summary of the key results is listed in Table 5. The results indicate that the DDWC can efficiently integrate the depropanizer, debutanizer and

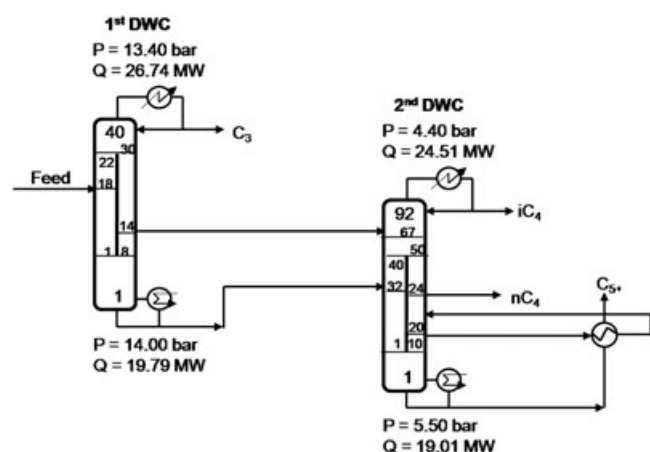


Figure 9. Simplified flow sheet illustrating the DDWC system with inter-reboiling the bottom section of the second DWC.

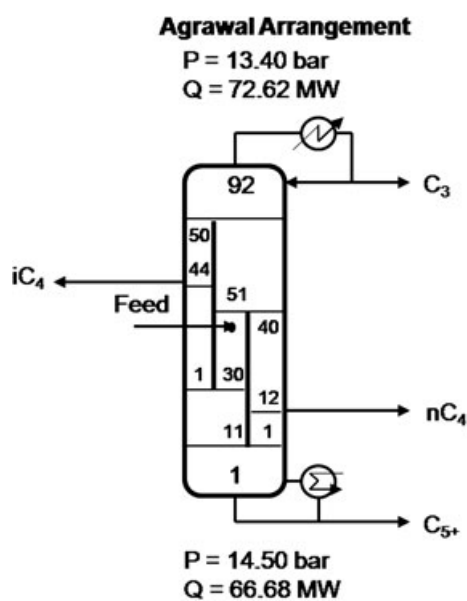


Figure 10. Simplified flow sheet illustrating the Agrawal arrangement.

Table 5. Comparison of different structural alternatives for improving the performance of depropanizer, debutanizer, and deisobutanizer.

Structural alternative	(a) Conventional sequence	(b) Integrating using DWC	(c) Integrating using DPA	(d) Integrating using DDWC	(e) Integrating using Agrawal arrangement
Number of trays	34	34	34	40	92
Column no. 1	40	92	40	92	92
Column no. 2	92	92	92	92	92
Column no. 3	92	92	92	92	92
Total of condenser duty (MW)	66.86	56.86	56.92	51.24	72.62
Total of reboiler duty (MW)	55.82	46.36	45.49	39.79	66.68
Relative energy saving (%)	0.00	16.96	18.50	28.74	-19.45

DWC, dividing wall column; DPA, double prefractionator arrangement; DDWC, double dividing wall column.

deisobutanizer to improve energy consumption. Furthermore, reducing the columns' diameters can lower investment costs.

CONCLUSIONS

Complex distillation sequences were studied to improve the performance of the depropanizing, debutanizing, and deisobutanizing fractionation steps of NGL processing. The DPA and DDWC arrangements significantly reduced energy consumption compared with conventional distillation. Furthermore, the double DWC, with a decreased number of smaller columns, could reduce investment costs. Further energy savings occurred by inter-reboiling the bottom section of the second DWC. Integrating columns of largely different operating pressures were found impractical.

Acknowledgements

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