Retrofit and Debottlenecking of Naphtha Splitter Process to Thermally Coupled Distillation Sequence with a Side Reboiler

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The naphtha splitter process is a representative distillation processused in the refinery industry. To improve the fractionation of the naphtha boiling range derived from hydro-treatment, naphtha feedstock is sequentially separated into light naphtha, heavy naphtha, and light kerosene. Conventional naphtha splitting columns can be retrofitted to an advanced configuration requiring less energy consumption with consequently less CO_2 emission. A systematic design for retrofitting naphtha splitting columns for the thermally coupled distillation sequence (TCDS) that addresses the bottleneck phenomenon by integration of existing shells was developed in this study. The results showed that the operating cost could be reduced drastically by novel combination of the TCDS and a side reboiler with minimal process modification.

Introduction

Distillation units are widely utilized inthe refinery and petrochemical industry for fluid separation techniques. The main disadvantage of distillation is its high-energy requirement; distillation can comprise more than 50% of the operating cost of a plant (Kiss and Bildea, 2011). Furthermore, because the huge energy demand of the distillation process is accompanied by significant greenhouse gas emissions, saving energy in this area has become an important issue from the environmental standpoint of CO_2 mitigation. The naphtha splitter process is one of the core distillation processes in the refinery industry, but this process consumes a considerable amount of energy. To improve the fractionation of the naphtha boiling range derived from hydro-treatment, the naphtha feedstock is separated sequentially into light naphtha, heavy naphtha, and light kerosene. In recent years, increasing focus has been placed on increasing the efficiency of existing capital in naphtha splitter processing facilities.

Most retrofitting practices in distillation have emphasized the use of column internals that not only promote separation, but also govern the column hydraulic performance (Amminudin and Smith, 2001a; Amminudin *et al.*, 2001b). Because user companies strive to improve the capacity with minimum investment, retrofitting of existing columns is a frequently employed option in which existing trays are replaced or packed with an effective alternative device. However, the use of better internals in retrofit distillation columns is not the only design option, nor is it always the most cost effective. In several cases, this approach does not improve the energy efficiency of the system and might preclude a large increase in capacity (Manley, 1998).

Process integration is an attractive option for retrofitting that has been successfully employed to reduce the energy requirements compared to processes where all the units are configured with little or no integration (Bravo-Bravo *et al.*, 2010; Van Duc Long *et al.*, 2010). In particular, the use of columns with thermal coupling has attracted considerable interest (Hernández and Jiménez, 1999; Serra *et al.*, 2000; Schultz *et al.*, 2002; Jiménez *et al.*, 2003; Kolbe and Wenzel, 2004; Errico *et al.*, 2009; Asprion and Kaibel, 2010; Dejanović *et al.*, 2010; Kim *et al.*, 2012; Kiss *et al.*, 2012; Van Duc Long and Lee, 2012a, 2012b, 2013a, 2013b). The thermally coupled distillation sequence (TCDS) was developed 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 one reboiler from one of the columns, providing potential cost savings. However, the issue of entrainment flooding may be a constraint in the integration of existing columns.

In this study, the bottleneck in the retrofitting of the naphtha splitting distillation columns to TCDS is identified, and a systematic approach for the design and optimization of the retrofitted TCDS using response surface methodology is presented. To address the issue of entrainment flooding in the retrofitted TCDS, equipment and process modifications utilizing the existing reboiler as a side reboiler are proposed with particular emphasis on the use of existing hardware.

1. Conventional Naphtha Splitter Process

Figure 1 shows a schematic diagram of the conventional naphtha splitter process. The existing column configuration uses two splitter columns: the naphtha splitter unit (NSU)

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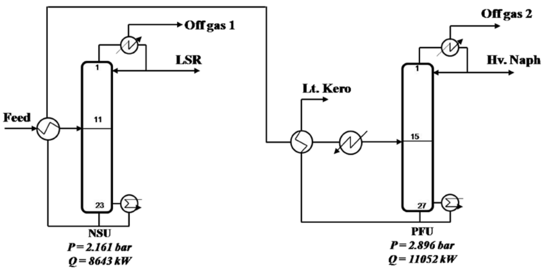

Fig. 1 Schematic diagram of the naphtha splitter process

and the paraffinic fractionation unit (PFU). Typical product streams are the light straight run (LSR), heavy naphtha (Hv. Naph), and light kerosene (Lt. Kero) products. The process details are as follows:

1.1 Naphtha splitter unit (NSU)

The saturated feed stream containing complex mixtures of hydrocarbons is introduced into the process. In the NSU column, the LSR product is separated from the heavy naphtha mixture, which is then collected in the overhead stream (LSR stream). The end-point of the LSR is defined by the hydrocarbon component distribution in the fraction, as determined by ASTM D86, which is the method most widely used to characterize the volatility of light and middle distillates in the refinery industry. Heat recovery by preheating the feed with the bottom product is used to reduce the amount of energy consumed. The bottom stream containing heavy naphtha and light kerosene fractions is sent to the PFU, which is operated under higher pressure, for further separation.

1.2 Paraffinic fractionation unit (PFU)

The bottom stream from the NSU columnis preheated by the bottom product from the PFU and is finally fed into the PFU column after passing through the trim heater. The PFU column is operated at higher pressure. Accordingly, the heavy naphtha is effectively fractionated from the light kerosene fraction. The heavy naphtha stream can boil between 80°C and 150°C. The PFU may provide a concentrated light kerosene stream from the bottom section. This heavy naphtha product can be introduced into the catalytic cracker unit to produce liquid fuel and/or petrochemical feedstock. In parallel, the light kerosene product is blended with other fuel sources based on the specific purpose. Similarly, the end-point of the heavy naphtha fraction is adjusted to an ASTM D86 of 142°C (95% cut point).

Table 1 Composition of the starting point stream

Noncondensable		Condensable	
Compound	vol%	Compound	vol%
H_2O	0	NBP[0]6*	0.0140
Propane	0.0008	NBP[0]20*	0.0171
i-Butane	0.0010	NBP[0]35*	0.0292
n-Butane	0.0048	NBP[0]50*	0.0618
i-Pentane	0.0070	NBP[0]63*	0.1185
n-Pentane	0.0097	NBP[0]78*	0.1156
		NBP[0]90*	0.1363
		NBP[0]106*	0.1017
		NBP[0]120*	0.1041
		NBP[0]134*	0.1052
		NBP[0]149*	0.0816
		NBP[0]162*	0.0424
		NBP[0]175*	0.0221
		NBP[0]191*	0.0131
		NBP[0]206*	0.0062
		NBP[0]219*	0.0078

In this study, rigorous simulation was performed using the commercial software-Aspen HYSYS 8.0. This software also provides an "oil environment" that allows calculationof the different fractions in the distillation of complex mixtures of organic compounds by generating a hypothetical hydrocarbon mixture from distillation data (Murillo *et al.*, 2006).The Peng–Robinson equation of state was selected for prediction of the vapor–liquid equilibrium of the mixture. **Table 1** presents the composition of the feed stream. **Table 2** summarizes the feed conditions and product specifications of each column in the existing distillation sequence. **Figure 2** shows the ASTM D86 distillate curves for the specific distillates from the naphtha splitting columns. **Table 3** presents the hydraulics and energy performances of the existing columns. The base case simulation model revealed the energy consumption of the NSU and PFU to be 8643 and 11052 kW, respectively.

To retrofit the conventional distillation sequences to the TCDS, the main design parameters of the existing columns were evaluated. The maximum flooding, which is the ratio of the actual vapor velocity to the maximum flooding vapor

Table 2 Feed conditions and specifications of the naphtha splitter process

		Feed	Products		
			LSR	Hv. Naphtha	Lt. Kerosene
Temperature [°C]		32.0	55.1	128.8	210.7
Pressure [bar]		2.05	1.5	2.3	2.9
Volume flow rate [m^3/d]		4,586	892	3,000	669
Column spec. ASTM D86	LSR 95% [°C]	—	90.4	—	—
	Hvy. Naph 95% [°C]	—	—	142.3	—
	Lt. Kero 5% [°C]	—	—	—	152

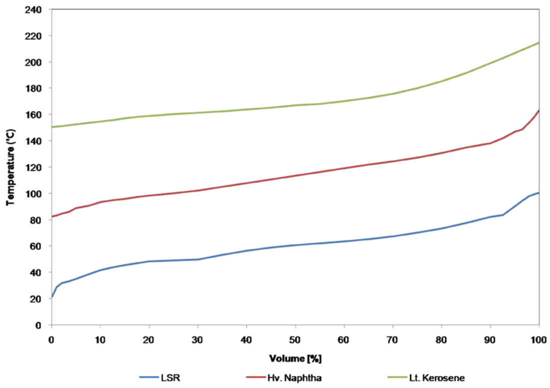

Fig. 2 Naphtha splitting column—ASTM D86 curves of the distillates

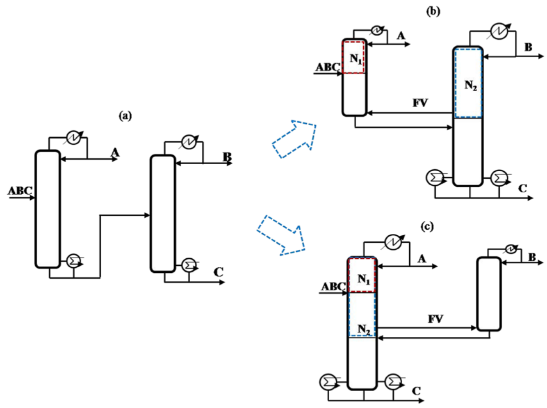

Fig. 3 Schematic diagram of the (a) Existing direct sequence; (b) Thermally coupled direct sequence with side rectifier and (c) Equivalent side rectifier arrangement

Table 3 Column hydraulics and energy performance of the existing columns sequence

	NSU	PFU
Number of trays	23	27
Tray type	Valve	Valve
Column diameter [m]	2.8	3.1
Number of flow paths	1	1
Tray spacing [mm]	609.6	609.6
Max flooding [%]	81.42	82.24
Condenser duty [kW]	3,797	9,403
Reboiler duty [kW]	8,643	11,052

velocity, was in the acceptable range. The reusability of the existing reboilers and condensers with minimal modifications is another area of concern for evaluation. To determine the maximum flooding of a particular column, the rating mode was simulated using the internal specifications. All columns were designed with a load of 85% of the flooding point load to prevent flooding in the column (Premkumar and Rangaiah, 2009; Van Duc Long and Lee, 2011).

2. Selection of Retrofitted TCD Structure

At the preliminary design stage in industrial practice, the selection of the TCDS is normally based on heuristics, which have been proposed to formulate alternatives for the direct and indirect sequence. Because the fraction of an intermediate component is less than 30% in the feed of the naphtha splitter process, the thermally coupled configurations with a side rectifier should be considered as an alternative (Tedder and Rudd, 1978a, 1978b, 1978c; Glinos *et al.*, 1986) (**Figure 3**). In this study, the focus of the process design is to maximize the utilization of existing equipment, while simultaneously making relatively minor modifications, including adjusting the operating pressure of each column, number of trays, adding equipment, and rearranging the existing columns to a complex sequence. The thermally coupled direct sequence shown in Figure 3(b) was thus selected for the retrofitted TCD structure. To achieve optimal use of the existing columns, no change in the diameter or the total number of stages of each column was considered in this study.

3. Optimization of TCDS

The first stage of retrofitting the existing distillation sequence is the development of preliminary designs for complex systems, and minimizing the heat duty supplied to the reboilers through the optimization procedures. After fixing the preliminary design of the TCDS structure, the main design variables were then optimized, including the internal vapor flow (F_V) to the side rectifier, feed (N_1), and vapor (N_2) stream locations. In this study, the response surface methodology (RSM)-based optimization approach (Van Duc Long and Lee, 2012c) was used to examine the effects of the feed and vapor stream locations on the reboiler. After determining the preliminary ranges of the variables through single-factor testing, central composite design was used to determine how the variables interact, as well as to optimize the system in terms of the reboiler duty. **Table 4** lists the factors and levels used in this case study. Thirteen simulations were run to optimize two parameters of the TCDS structure: the feed (N_1) and vapor (N_2) stream location. For each run, vapor flow to the side rectifier was varied to minimize the

Table 4 Factors' coded levels for the RSM

Factor	Levels		
	−1	0	1
Feed stream location in the side rectifier (N_1)	3	6	9
Vapor stream location in the main column (N_2)	16	18	20

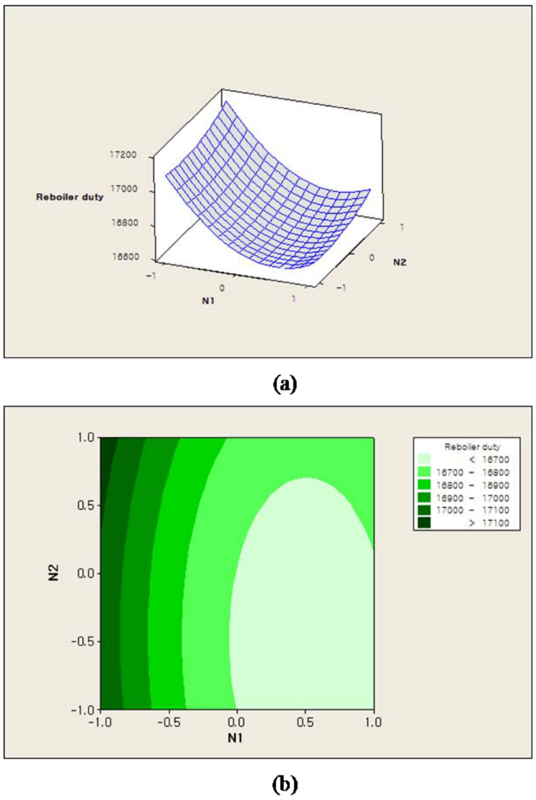

Fig. 4 N_1, N_2 are the coded values of number of feed and vapor stream stage location, respectively: (a) Three-dimensional response surface plot and (b) Contour plot of interaction between N_1 and N_2

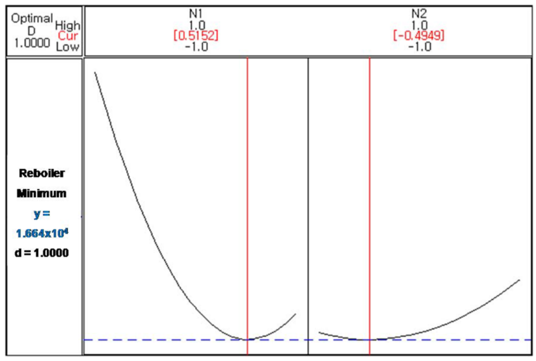

Fig. 5 Optimization plot by the RSM

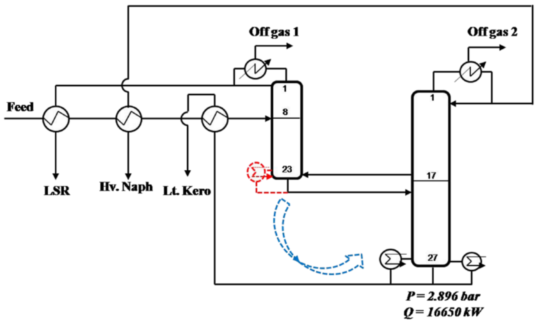

Fig. 6 Simplified flow sheet illustrating the retrofitted TCDS

reboiler duty while still achieving the required 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:

$$Y = 16696.70 - 195.64X_1 + 42.61X_2 + 189.76X_1^2 + 44.78X_2^2 + 2.91X_1X_2 \quad (1)$$

where Y is the predicted response (reboiler duty), and X_1 and X_2 are the coded values of the vapor and feed stream locations, respectively.

Figure 4 shows the three-dimensional response surface plot and contour plot of the interaction between the main design variables, N_1 and N_2. Two parameters were plotted on each set of X and Y axes. The reboiler duty was plotted on the Z axis. The smallest reboiler duty was observed at the code level of 0.5151 for the number of trays for the vapor stream location and −0.4949 for the feed rectifying section (**Figure 5**). Under these conditions, the minimum reboiler duty using the retrofitted TCDS was predicted to be 16,636 kW (equivalent to 17.3% energy saving). **Figure 6** shows a simplified flow sheet illustrating the resulting retrofitted TCDS. Note that the retrofitted TCDS allows preheating of the feed with the product streams only, which should result in a decline in the reboiler duty, whereas the existing conventional sequence requires external heat to preheat the feed. The natural values of the variables can be derived from the coded levels. The flow of vapor to the side rectifier was then optimized using rigorous simulation to minimize the reboiler duty, whilst maintaining satisfactory product purity. The simulation result also showed that the energy consumption of the TCDS was 16,650 kW (equivalent to 17.2% energy saving), which is in good agreement with the results predicted by the RSM.

4. Retrofit to TCDS

4.1 Fractional utilization of area (FUA)—A hydraulic performance indicator

Ascertaining the extent of use of the available area for vapor flow at each stage during column operation at maximum throughput is essential for determining the stages at which 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 that would be needed if the flows on that stage represent the maximum flows that could be tolerated can be calculated. 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. The following indicator of the hydraulic

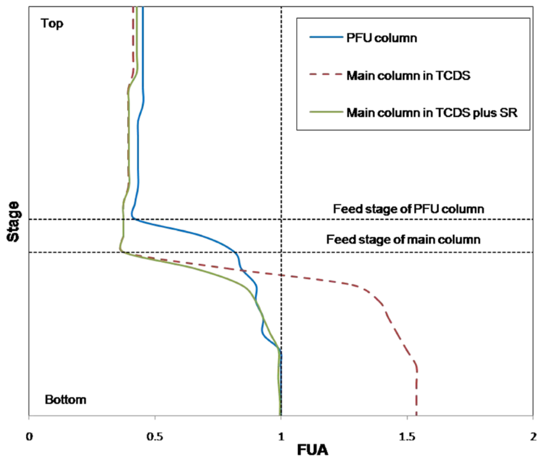

Fig. 7 *FUA* profiles of existing PFU and main column in TCDS

performance of an existing distillation column, the fractional utilization of area (*FUA*), was used as proposed by Liu and Jobson (2004a):

$$FUA = \frac{\text{Area required on stage } i \text{ for vapor flow}}{\text{Area available on stage } i \text{ for vapor flow}} \quad (2)$$

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).

As seen from **Figure 7**, the *FUA* of the existing PFU varies from stage to stage, i.e., the *FUA* began to increase from the feed stage, with some stages requiring all of the available area (i.e., $FUA = 1$), whereas the stages in the rectifying section could accommodate significantly higher flows. When the existing PFU column is retrofitted to the main column of the TCDS, the bottom section that must cover all the vapor flows that are shared by the main column and side rectifier of the PFU is likely to be bottlenecked. Figure 7 shows that the *FUA* in the main column of the TCDS (i.e., the retrofitted PFU) increases drastically from the vapor stream location (17th stage), and creates a bottleneck in the stripping section.

4.2 Debottlenecking retrofitted TCDS with a side reboiler

The side reboilers can be used to modify the vapor and liquid flows within a column section for more uniform utilization of the available area (Liu and Jobson, 2004b). This modification will reduce the vapor and liquid traffic below the tray, where the side reboiler is placed, and increase the vapor and liquid traffic above the tray. Therefore, the liquid and vapor traffic in the bottom-most section of the column can be reduced by using a side reboiler, i.e., the bottleneck problem can be resolved. Van Duc Long and Lee (2013c) proposed a strategy utilizing the side reboiler for retrofitting a conventional distillation sequence to the TCDS.

Figure 8 shows the simplified flow sheet outlining the retrofitted TCDS with a side reboiler. The maximum area utilization (in the stripping section) decreases to 1 when the side reboiler is adopted, as can be seen in the *FUA* plot in Figure

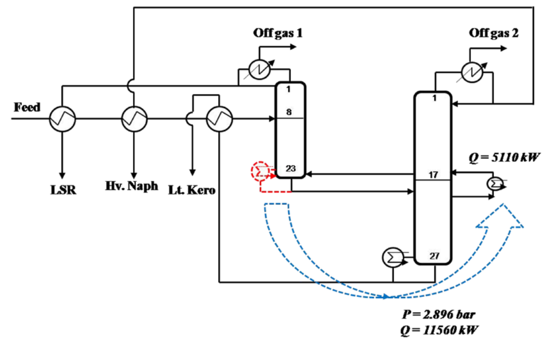

Fig. 8 Simplified flow sheet illustrating the retrofitted TCDS with side reboiler

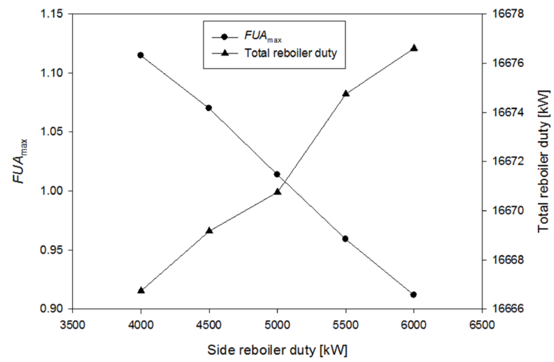

Fig. 9 Influence of side reboiler duty on the total reboiler duty, FUA_{max}

7, and this value may be decreased even further. When the maximum area utilization is less than 1, the feed flow to the column can be increased until the maximum area utilization in the stripping section becomes 1, which corresponds to an increase in throughput (Van Duc Long and Lee, 2013c). The heat duty in the reboiler decreased with increasing heat duty in the side reboiler. Note that in this retrofit case, the reboiler of the existing NSU can be utilized as the side reboiler of the retrofitted TCD, as shown in Figure 8. The FUA_{max} decreased with increasing heat duty in the side reboiler, whereas the total duty increased with increasing duty in the side reboiler, as seen from **Figure 9**. Thus, there is a trade-off between FUA_{max} and the operating cost that must be considered. Based on the overarching objective to reduce the energy requirements, the selected side reboiler duty was 5110 kW, which provides 17.1% savings in terms of the reboiler duty.

Conclusion

The benefit of retrofitting the conventional process to the TCDS sequence, particularly in the oil refining industry, was reported herein. A systematic design approach utilizing RSM to maximize the *FUA* was applied to retrofitting the conventional naphtha splitter process to the more energy efficient TCDS. The predicted RSM results showed good agreement with those from rigorous simulation. The *FUA* curve provides foresight for removing the bottlenecks in the retrofitted TCDS. The need for an external heat source for preheating the feed was precluded in the proposed TCDS. Use of a side reboiler was emphasized in order to change the vapor and liquid flows within a column section to utilize the available area. Furthermore, retrofitting of the TCDS with a side reboiler facilitates utilization of the existing columns, and also increases the process capacity. The proposed retrofitted naphtha splitter process provided significant savings (17.1%) in the reboiler duty withminimal process modification. The results showed that the proposed TCDS with the systematic retrofit design approach is a prospectively attractive option for increasing both the separation efficiency and capacity, and thus to mitigate CO_2 emissions in the existing conventional naphtha splitter process in a cost effective way.

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Literature Cited

Amminudin, K. A. and R. Smith; "Design and Optimization of Fully Thermally Coupled Distillation Columns. Part 2: Application of Dividing Wall Columns in Retrofit," *Chem. Eng. Res. Des.*, **79**, 716–724 (2001a)

Amminudin, K. A., R. Smith, D. Y. C. Thong and G. P. Towler; "Design and Optimization of Fully Thermally Coupled Distillation Columns: Part 1: Preliminary Design and Optimization Methodology," *Chem. Eng. Res. Des.*, **79**, 701–715 (2001b)

Asprion, N. and G. Kaibel; "Dividing Wall Columns: Fundamentals and Recent Advances," *Chem. Eng. Process.*, **49**, 139–146 (2010)

Bravo-Bravo, C., J. Segovia-Hernandez, C. Gutierrez-Antonio, A. Duran, A. Bonilla-Petriciolet and A. Briones-Ramirez; "Extractive Dividing Wall Column: Design and Optimization," *Ind. Eng. Chem. Res.*, **49**, 3672–3688 (2010)

Dejanović, I., L. J. Matijašević and Ž. Olujić; "Dividing Wall Column-A Breakthrough towards Sustainable Distilling," *Chem. Eng. Process.*, **49**, 559–580 (2010)

Errico, M., G. Tola, B. G. Rong, D. Demurtas and I. Turunen; "Energy Saving and Capital Cost Evaluation in Distillation Column Sequences with a Divided Wall Column," *Chem. Eng. Res. Des.*, **87**, 1649–1657 (2009)

Glinos, K., I. Nikolaides and F. Malone; "New Complex Column Arrangements for Ideal Distillation," *Ind. Eng. Chem. Process Des. Dev.*, **25**, 694–699 (1986)

Hernández, S. and A. Jiménez; "Design of Energy-Efficient Petlyuk Systems," *Comput. Chem. Eng.*, **23**, 1005–1010 (1999)

Jiménez, A., N. Ramírez, A. Castro and S. Hernández; "Design and Energy Performance of Alternative Schemes to the Petlyuk Distillation System," *Chem. Eng. Res. Des.*, **81**, 518–524 (2003)

Kim, K., M. Y. Lee and S. Park; "Two-Point Temperature Control Structure Selection for Dividing-Wall Distillation Columns," *Ind. Eng. Chem. Res.*, **51**, 15683–15695 (2012)

Kiss, A. A. and C. S. Bildea; "A Control Perspective on Process Intensification in Dividing Wall Columns," *Chem. Eng. Process.*, **50**, 281–292 (2011)

Kiss, A. A., S. J. Flores Landaeta and C. A. Infante Ferreira; "Towards Energy Efficient Distillation Technologies—Making the Right Choice," *Energy*, **47**, 531–542 (2012)

Kolbe, B. and S. Wenzel; "Novel Distillation Concepts Using One-Shell Columns," *Chem. Eng. Process.*, **43**, 339–346 (2004)

Liu, Z. Y. and M. Jobson; "Retrofit Design for Increasing the Processing Capacity of Distillation Columns: 1. A Hydraulic Performance Indicator," *Chem. Eng. Res. Des.*, **82**, 3–9 (2004a)

Liu, Z. Y. and M. Jobson; "Retrofit Design for Increasing the Processing Capacity of Distillation Columns: 2. Proposing and Evaluating Design Options," *Chem. Eng. Res. Des.*, **82**, 10–17 (2004b)

Manley, D. B.; Capacity Expansion Options for NGL Fractionation, Proc. 77th GPA Annual Convention, pp. 114–119, Gas Processors Association, Texas, USA (1998)

Murillo, R., A. Aranda, E. Aylon, M. S. Callen and A. M. Mastral; "Process for the Separation of Gas Products from Waste Tire Pyrolysis," *Ind. Eng. Chem. Res.*, **45**, 1734–1738 (2006)

Premkumar, R. and G. P. Rangaiah; "Retrofitting Conventional Column Systems to Dividing Wall Columns," *Chem. Eng. Res. Des.*, **87**, 47–60 (2009)

Schultz, M. A., D. G. Stewart, J. M. Harris, S. P. Rosenblum, M. S. Shakur and D. E. O'Brien; "Reduce Costs with Dividing-Wall Columns," *Chem. Eng. Prog.*, **98**, 64–71 (2002)

Serra, M., M. Perrier, A. Espuna and L. Puigjaner; "A. Espuna andL. Puigjaner; "Study of the Divided Wall Column Controllability: Influence of Design and Operation," *Comput. Chem. Eng.*, **24**, 901–907 (2000)

Tedder, D. W. and D. F. Rudd; "Parametric Studies in Industrial Distillation: Part I. Design Comparisons," *AIChE J.*, **24**, 303–315 (1978a)

Tedder, D. W. and D. F. Rudd; "Parametric Studies in Industrial Distillation: Part II. Heuristic Optimization," *AIChE J.*, **24**, 316–323 (1978b)

Tedder, D. W. and D. F. Rudd; "Parametric Studies in Industrial Distillation: Part III. Design Methods and Their Evaluation," *AIChE J.*, **24**, 323–334 (1978c)

Van Duc Long, N., S. H. Lee and M. Y. Lee; "Design and Optimization of a Dividing Wall Column for Debottlenecking of the Acetic Acid Purification," *Chem. Eng. Process.*, **49**, 825–835 (2010)

Van Duc Long, N. and M. Y. Lee; "Improved Energy Efficiency in Debottlenecking Using a Fully Thermally Coupled Distillation Column," *Asia-Pac. J. Chem. Eng.*, **6**, 338–348 (2011)

Van Duc Long, N. and M. Y. Lee; "Improvement of the Deethanizing and Depropanizing Fractionation Steps in NGL Recovery Process Using Dividing Wall Column," *J. Chem. Eng. Japan*, **45**, 285–294 (2012a)

Van Duc Long, N. and M. Y. Lee; "Improvement of Natural Gas Liquid Recovery Energy Efficiency through Thermally Coupled Distillation Arrangements," *Asia-Pac. J. Chem. Eng.*, **7**, S71–S77 (2012b)

Van Duc Long, N. and M. Y. Lee; "Dividing Wall Column Structure Design Using Response Surface Methodology," *Comput. Chem. Eng.*, **37**, 119–124 (2012c)

Van Duc Long, N. and M. Y. Lee; "Design and Optimization of Heat Integrated Dividing Wall Columns for Improved Debutanizing and Deisobutanizing Fractionation of NGL," *Korean J. Chem. Eng.*, **30**, 286–294 (2013a)

Van Duc Long, N. and M. Y. Lee; "Optimal Retrofit Design of Extractive Distillation to Energy Efficient Thermally Coupled Distillation Scheme," *AIChE J.*, **59**, 1175–1182 (2013b)

Van Duc Long, N. and M. Y. Lee; "Debottlenecking the Retrofitted Thermally Coupled Distillation Sequence," *Ind. Eng. Chem. Res.*, **52**, 12635–12645 (2013c)