Malaysian Journal of Chemical Engineering & Technology

Journal Homepage: http://myjms.mohe.gov.my/index.php/mjcet

Natural gas liquid (NGL) distillation process using driving force and thermal pinch analysis methods: Energy and economic assessment

[a,b]Munawar Zaman Shahruddin*, [a]Mohamad Hamidi Asri, [a]Rohani Mohd Zin, [b]Ahmad Nafais Rahimi, [b]Muhammad Afiq Zubir, [b]Muhammad Fakhrul Islam Zahran, [b]Norazana Ibrahim, [b]Mohd Kamaruddin Abd Hamid

[a]Faculty of Chemical Engineering, Universiti Teknologi MARA, Selangor, Malaysia
[b]School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

*Corresponding email: munawar_zaman@uitm.edu.my

Abstract

Distillation column is one of the effective unit operations that is commonly used to separate chemical mixtures. The only drawback of this separation process is its huge energy consumption especially for a multicomponent separation process which involves a series of distillation columns. Therefore, an optimal sequence must be determined to address the issue. This research proposes the methodology to determine the optimal sequence of distillation columns by using driving force method. Then, thermal pinch analysis is applied to obtain further energy saving in the process. The case study selected is a distillation process to recover 5-component of natural gas liquid (NGL) mixture. Based on the input data, the driving force sequence is determined first and simulated together with a conventional sequence (direct sequence). Then, the extracted data from the simulation will be used for thermal pinch analysis via problem table algorithm (PTA). From the results of PTA, energy consumption between both sequences were compared including the energy consumption before and after the thermal pinch analysis. In addition, economic analysis has been performed as well to indicate which sequence has lower capital and operating costs based on the proposed heat exchanger network (HEN). According to the results, the combination of the driving force and thermal pinch analysis methods has successfully recorded 48% of energy savings and operating cost, and 58.2% capital cost saving compared to the conventional sequence (direct sequence). Therefore, it can be said that the proposed framework has a great potential to be employed towards the process and economic feasible distillation process.

Article Info

http://doi.org. 10.24191/mjcet.v3i2.XXXX.

Article history:

Received date: 13 October 2020
Accepted date: 30 November 2020

Keywords:

Distillation Columns
Sequence
Energy Saving
Driving Force Method
Energy Integration
Thermal Pinch Analysis

1.0 Introduction

Distillation column is a unit operation commonly used for chemical separation due to its capability for mass production without compromising the quality of the outputs. However, distillation column consumes high amount of energy, which leads to an adverse impacts towards the environment and economy of the process (Hernandez et al., 2006). In fact, 95% of the separation process in the chemical industry have been performed via distillation process. Moreover, it also accounts for 3% of the world energy consumption (Cui et al., 2016). Therefore, energy saving strategies are needed for this process to sustain.

In separating chemical components, using distillation process, especially involving multicomponent mixture, a separation of mixture using distillation process has to be through a series of distillation unit (sequence); with different key outputs in each product stream according to the intended separation tasks (Speight, 2011). The number of possible sequences can be easily determined by the Eq. (1) (Seider et al., 2004).

$$N_s = \frac{[2(P-1)]!}{P!(P-1)!} \tag{1}$$

where:
N_s = Number of possible sequences
P = Number of intended products

One of the common practices in determining optimal sequence of distillation columns would be based on the lowest energy consumption out of all possible sequences (Rahimi et al., 2015). The energy consumptions in distillation process refers to the duty of condenser(s) and reboiler(s). Manual analysis has its limitation particularly in dealing with an increasing number of products as the number of possible sequences increases exponentially. The analysis of the energy consumption involving all sequences becomes tedious and time-consuming (Rahimi et al., 2017). Hence, this forms a basis on introducing the conceptual process synthesis (CPS) which can be implemented to determine the optimal sequence in terms of the energy consumption (Shahruddin et al., 2018). There are few approaches in CPS that can be applied in determining the optimal distillation columns sequence which are heuristic, evolutionary, algorithm, sequential design method (SDM) and driving force (Li and Kraslawski, 2004).

The earliest CPS method, heuristic, requires a lot of experience in processing because there is always possibility for the rules in heuristic to contradict with each other. Evolutionary approach requires assistance by other technology such as computational works to ensure optimal distillation column sequence solution. Algorithm method solved the problem of the first two methods whereby it involved the very complex mathematical modelling and computation, in return, offering a better and accurate solution. Sequential design method (SDM) is almost similar to evolutionary method except that SDM views the alternative process as part of the evolution and making it more systematic in terms of optimal criteria synthesis. Nevertheless, there is still a doubt about the operational part of the design for this method to be applied. Lastly, driving force is the simplest method in CPS, especially in a design stage and screening purpose since it is graphical and less complicated as compared to other methods (Westerberg, 2004).

Driving force method is an approach that manipulates the difference in properties of a binary mixture to obtain the best sequence of distillation columns. It is defined as the difference in composition of a component *i* between the vapour phase and liquid phase. It is caused by a relative volatility of component *i* and other components in the mixture (Adeleke et al., 2012). Theoretically, as the driving force is approaching zero, it becomes difficult to separate the corresponding key component *i* from the mixture (Bek-Pedersen et al., 2000). Bek-Pedersen and Gani (2004) then proposed this graphical method of distillation column sequencing. The driving force graph is plotted according to the liquid or the vapour composition of the feed mixture. Then, the value of driving force determines the optimal sequence of distillation columns. This method has been implemented in several case studies, including the aromatic separation process (Zaine et al., 2015). The method is applied to be compared with the existing direct sequence of distillation column in terms of energy requirement. A total of 7% of energy reduction is recorded proving that the driving force sequence is able to reduce energy consumption of the process. Prior to that, there was also a simple distillation column sequence studies for 3-component alcohol system, also by implementing the driving force method which resulted in 18% energy saving (Mustafa et al., 2014). Meanwhile, the results involving the separation of 5 alkane components also established that the driving force sequence has the highest value of total energy saving which is 6.31% compared to the base case (Shahruddin et al., 2017). The same trend also recorded for a case study of 5-component alcohol mixture whereby the driving force sequence has successfully contributed 1.2% of overall energy saving (Shahruddin et al., 2018).

Likewise, energy analysis using pinch technique (heat integration) is applied to obtain further energy saving of distillation process. This technique incorporates a systematic thermodynamic analysis to maximize the heat recovery in the process itself. In the case of distillation process, the heat released from the hot stream is integrated with the cold stream at different columns by using heat exchanger and supported by additional auxiliary units (Yoo et al., 2015). The earliest method of heat integration is called *thermal pinch analysis*, which introduced by Hohmann in 1971 by designing the feasibility table of systematic energy targeting for further energy saving in the process (Linnhoff and Flower, 1978). Then, this technique was improved further by Linnhoff and Hindmash to determine the best heat exchanger network design for energy saving (Quirante et al., 2017). The objective is to establish the minimum utility requirement of the process by maximizing possible heat recovery rating as a feature of the minimum differential temperature within the heat exchanger network. Since then, the thermal pinch analysis has been applied widely in the distillation process and obtained a positive result. For instance, a case study of 5-component of alkanes, the best sequence recorded an energy saving of 34.75% for the total loads, which is even higher than the energy saving of driving force sequence (Shahruddin et al., 2017). In another case study, 8 out of 14 possible sequences recorded a range of 1.5 to 36% of energy saving for total load when thermal pinch analysis was applied to the distillation process (Shahruddin et al., 2019). It was also supported by the implementation of the method for a case study of 6-component of aromatic mixture by the same author which lead to the same finding that emphasize on a great potential of the thermal pinch analysis to be employed for a distillation process energy saving (Shahruddin et al., 2020).

Based on the review from the approaches of energy saving of the driving force method and thermal pinch analysis method, both can be combined to achieve further energy saving for the distillation columns sequence. This paper proposes a systematic framework whereby it involves the driving force method for optimal distillation columns sequence and supported by the thermal pinch analysis for further energy saving in the process. A case study of 5-component NGL mixture is employed to assess the feasibility of the proposed framework in terms of process and economy.

2.0 Methodology

2.1 Case Study

The case study selected for this research was adopted from Sobočan and Glavič (2002) and tabulated in Table 1. Each distillation column operates at 98% recovery for each component.

2.2 Methods

Fig. 1 shows a flowchart of the methodology for this research. The methodology starts with the determination of the driving force sequence as suggested by Bek-Pedersen and Gani (2004). It can be determined by using Eq. (2) whereby F_{ij} is the driving force for component *i*, y_i, and x_i is the vapour and the liquid composition of component *i*. Meanwhile, β_{ij} can be defined as the vapour pressure ratio between two components (P_a and P_b) with close boiling point whereby the vapour pressure (Extended Antoine Equation by HYSYS) can be determined by Eq. (3) and (4) (GmbH, 2014).

$$F_{ij} = y_i - x_i = \frac{x_i\beta_{ij}}{1+x_i(\beta_{ij}-1)} \text{--} x_i \quad (2)$$

$$\beta_{ij} = \frac{P_a}{P_b} \quad (3)$$

$$P_a \; or \; P_b = \exp\left(A + \frac{B}{T+C} + Dln(T) + ET^F\right) \quad (4)$$

T in Eq. (4) is the operating temperature (K). A, B, C, D, E, and F are the Antoine vapour pressure component parameters and can be obtained from HYSIS V9 software, whereby the value is specific for each chemical component. The Antoine vapour pressure component parameters have been tabulated as shown in Table 2. Once the driving force for each binary component have been calculated, the plot of driving force versus liquid composition (driving force curve) is plotted. The component that recorded the highest driving force is the first to separate followed by the lower one until driving force sequence has been determined.

Table 1: Feed condition of the selected case study

Input Data		Value	Boiling Point (°C)
Feed composition (%)	Propane (A)	0.05	−42.10
	i-Butane (B)	0.15	−11.73
	n-Butane (C)	0.25	−0.50
	i-Pentane (D)	0.20	27.88
	n-Pentane (E)	0.35	36.06
Feed flowrate (kmole/h)		907.2	
Pressure (atm)		1	
Temperature (°C)		4.37	

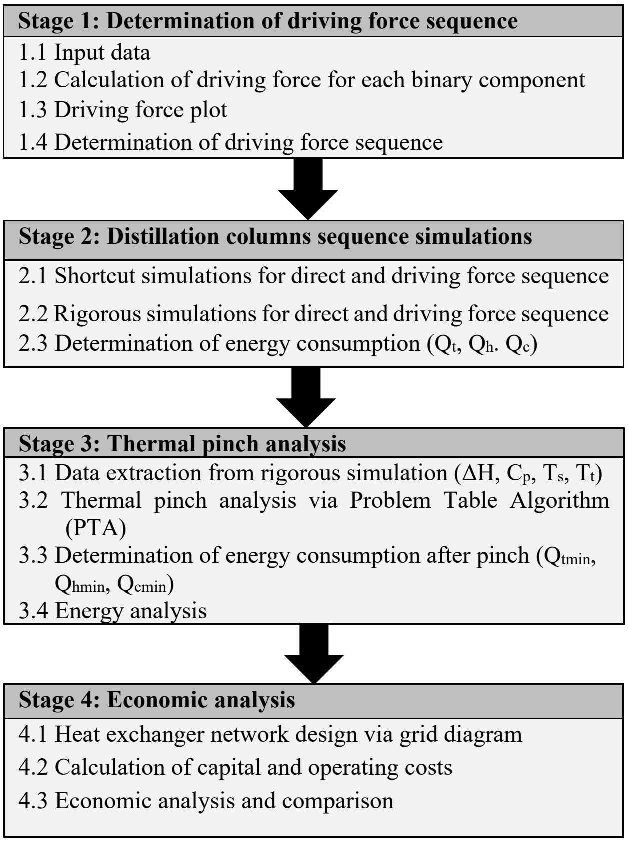

Fig. 1: Research Framework

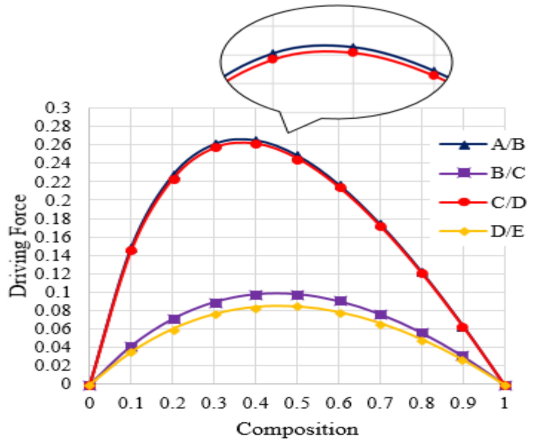

Fig. 2: Driving force plot for the selected case study

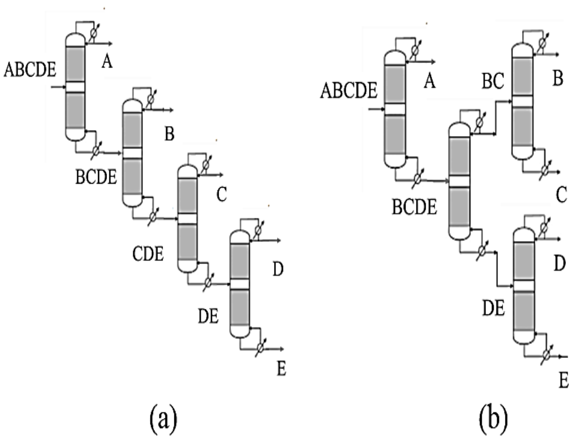

Fig. 3: (a) Direct sequence and (b) Driving force sequence

Table 2: Antoine vapour pressure component parameters

	C_3 (A)	i-C_4 (B)	n-C_4 (C)	i-C_5 (D)	n-C_5 (E)
A	52.38	58.78	66.95	66.76	63.33
B ($\times 10^3$)	−3.49	−4.14	−4.60	−5.06	−5.12
C	0	0	0	0	0
D	−6.11	−7.02	−8.25	−8.09	−7.48
E ($\times 10^{-5}$)	1.12	1.04	1.16	0.93	0.78
F	2	2	2	2	2

Table 3: Utility rates (Zubir et al., 2017).

Utility	Temperature (°C)		Price (USD/GJ)
	In	Out	
LP Steam	125	124	6.22
MP Steam	175	174	7.66
HP Steam	250	249	9.85
Cooling Water	20	25	0.675

Then, the simulation of distillation columns sequence for both direct and driving force sequence were carried out by using Aspen HYSYS V9 software for both shortcut and rigorous simulations. The output is the energy consumption of the process.

In Stage 3, the resulting data from the simulations (supply and target temperatures, and energy requirement (reboilers (cold stream, C), and condensers (hot stream, H)) were extracted as an input data for the thermal pinch analysis using PTA technique at ΔT_{min} at 10 °C. From the PTA, the minimum energy requirement for both heating and cooling load were calculated. Then, energy analysis involving the comparison in terms of sequence, before and after pinch was performed.

In the last stage, the heat exchanger network (HEN) was designed for both sequences to indicate the number of auxiliary units to satisfy the minimum energy requirement. Then, the capital and operating costs were calculated based on the proposed HEN design. For capital cost, it only considers the modified column with the addition of auxiliary units including heat exchanger(s), heater(s), and cooler(s). It is calculated by using the formula as shown in Eq. (5) (Zubir et al., 2017):

$$\text{Cost (USD)} = 30800 + 1644A^{0.81} \qquad (5)$$

where: A is the area of the additional unit.

The operating cost was calculated based on the price in Table 3 according to the utilities used, at the plant operating condition of 24 hours per day and 330 days per year. Utility rates can be found in Table 3.

Finally, once the costs have been calculated, the comparison study was carried out to determine the economic feasibility of the proposed HEN design.

3.0 Results and discussion

The driving force curve has been plotted as shown in Fig. 2. From the plot, the highest driving force value is A/B component followed by C/D, B/C, and lastly D/E. The arrangement of the driving force sequence has been determined and illustrated in Fig. 3 together with the direct sequence. With the help of the information in Table 1, this result, specifically for the components in the case study, it can clearly be seen that, the component with large difference in boiling point is easily separated as shown by component A/B (propane–i-butane) and C/D (n-butane–i-pentane). While the remaining binary components have close boiling points one to another (Mustafa, 2014). This reflects the energy consumption of the process.

Table 4 summarises the results of energy analysis using PTA technique for both direct and driving force sequences. The discussion on energy consumption of the process can be divided into two perspectives: 1) the effective of driving force method towards energy saving, and 2) the effect of thermal pinch analysis towards further energy saving for both direct and driving force sequence.

From the first perspective, it can be seen that the driving force method reduces the energy consumption of the distillation process. The driving force sequence recorded a saving of 7.0 × 10^7 kJ/h which is approximately 26.5% compared to direct sequence for the total load. This proves that driving force method can improve the energy saving of distillation columns sequence for this case study. This is also aligning with the arrangement in the driving force sequence whereby the higher driving force value results in lower energy consumption. It can be said that separating C/D earlier produces better results as compared to separating it according to the common heuristic (i.e., according to the boiling points).

From Table 4, comparisons were made between before and after thermal pinch analysis. The direct sequence recorded a saving of 32.61%, 33.02%, and 32.81% for heating, cooling, and total load, respectively. For the driving force, the percentage of energy saving is 28.80%, 29.39%, and 29.14% for heating, cooling, and total load, respectively. The existence of transferable heat in the process has led to reduction in the energy consumption for both sequences (Shahruddin et al., 2017). This shows the capability of thermal pinch analysis to further saving the energy consumption of the distillation process.

From the percentage of savings based on the two perspectives, it can be concluded that thermal pinch analysis is more favourable for energy saving as compared to the driving force approach for this case study, since the percentage value is higher. Essentially, it has been demonstrated that a great result produced from the combination of the two methods with the lowest total energy consumption at 1.37 × 10^8 kJ/h or roughly estimated at 48% less than the total load of the direct sequence before thermal pinch analysis. This energy saving can be explained through composite curves as shown in Fig. 4 and Fig. 5.

The difference between Fig. 4 and Fig. 5 is that, in the region above pinch (23 °C for direct, 37 °C for driving force), the amount of cold stream for driving force sequence is 2 whereby amount of cold stream for direct sequence is 3. It means that the driving force will have lower heating load since it only need to heat up 2 streams while in the direct sequence, there are 3 streams need to be heated up, thus, resulted such trends as shown in Table 4.

The last topic to be discussed is the economic analysis and comparison based on the sequence including the HEN designs. The output of this last stage was tabulated and shown in Table 5.

Based on Table 5, it can be seen that the driving force sequence has lower capital cost. Obviously, it is contributed from the need of an additional auxiliary units for direct sequence compared to the driving force

Table 4: Energy analysis for the selected case study

Sequence	Pinch	Heating Load (10^8 kJ/h)	Cooling Load (10^8 kJ/h)	Total Load (10^8 kJ/h)
Direct	Before	1.330	1.310	2.640
	After	0.896	0.879	1.780
Driving force	Before	0.978	0.961	1.940
	After	0.695	0.679	1.370

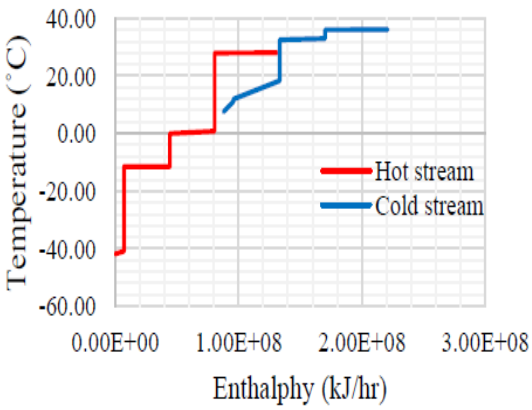

Fig. 4: Composite curve for direct sequence

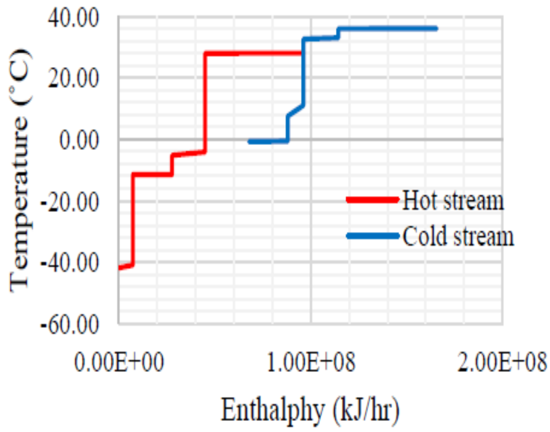

Fig. 5: Composite curve for driving force sequence

sequence. There are 4 and 3 additional auxiliary units needed for direct and driving force sequence respectively. This provides a good reason on why the driving force sequence recorded a massive of 58.2% difference in terms of the capital cost compared to the direct sequence.

On the other hand, driving force sequence also demonstrated a good operating cost before pinch at 26.6% difference and recorded 22.3% cost reduction after pinch analysis compared to the direct sequence. Meanwhile, the application of thermal pinch analysis also affects the operating cost as the values decrease for both sequences whereby for direct sequence it successfully saved for almost a million USD. Driving force also recorded an excellent operating cost reduction at 29% after pinch analysis. Although it recorded a percentage saving lower than direct sequence for both scenario before and after pinch analysis, driving force sequence recorded the lowest operating cost whereby almost half of the operating cost in the process has been successfully reduced. In other word, driving force method has successfully reduce the capital and operating cost. Then, the operating cost saving has been further enhanced by the thermal pinch analysis. This is the results from the difference of energy consumption in these two sequences whereby in this case, again driving force is lower. Therefore, these two combined methods have the potential to reduce cost for the process which make it more feasible to operate. Furthermore, it also aligned and might be extended from the publication of Zubir et al. (2019) whereby they manage to obtain the same decreasing trend on capital and operating cost as a result form the driving force method. Therefore, this study proved that the application of the thermal pinch analysis can further enhanced the energy saving of the distillation columns sequence.

Overall, based on energy and economic analysis for the selected case study, it can be seen that the driving force method leads to lesser energy consumption compared to the conventional sequence (direct sequence) and it was complemented by the thermal pinch analysis which enhanced the energy saving in the process. Therefore, the proposed framework can be employed to any other type of chemical mixtures or number of distillation columns sequence for the purpose of obtaining feasible process in terms of energy usage and economy of the process.

Table 5: Economic analysis for both sequences

Sequence	Capital cost (10^6 USD)	Operating Cos (10^6 USD)		
		Before pinch	After pinch	% Diff
Direct	14.20	30.80	20.60	33.1
Driving force	5.94	22.60	16.0	29.2
% Diff	58.2	26.6	22.3	-

4.0 Conclusions

The driving force approach has been proposed to work along with thermal pinch analysis to obtain further energy saving for distillation columns sequence. The case study selected is a separation process of 5-components natural gas liquids (NGL). Based on the energy analysis results, the driving force sequence shows lower energy consumption compared to direct sequence. It records a percentage of 26.5% of overall energy saving. From the PTA, the minimum energy requirement for heating and cooling load are calculated for both sequences. Both direct and driving force sequence recorded a saving of roughly 33% and 29% respectively from the original total loads. With the combination of these two approaches, 48% of energy saving are recorded which is almost half of the initial energy consumption. Besides that, the application of both methods also leads to lower capital and operating cost as stated in Table 5. In short, it can be concluded that the combination of the driving force and thermal pinch analysis methods has the capability to reduce energy consumption in the distillation columns sequence. It also contributed to the economic feasibility which indicated by the capital and operating cost. For future works, several studies can be carried out in the future to establish the impacts of the value of ΔT_{min}, type and number of the chemical mixtures/products towards the feasibility of the distillation columns sequence.

Acknowledgement

This research is financially supported by the Ministry of Education Malaysia via Skim Latihan Bumiputera (SLAB), Universiti Teknologi MARA and Universiti Teknologi Malaysia (UTM).

References

A. E. Adeleke, O. J. Alamu, O. A. Olawal, P. O. Aiyedun, O. U. Dairo, (2012). A Parametric Study of The Effect of Relative Volatility of The Feed on The Design of Distillation Column of a Bioethanol Plant Using Cassava as Feedstock. *Transnational Journal of Science and Technology. 2.* 74–88.

A. N. Rahimi, M. F. Mustafa, M. Z. Zaine, N. a. M. Rosely, M. F. I. Zahran, M. Z. Shahruddin, M. A. Zubir, N. Ibrahim, K. A. Ibrahim, M. K. A. Hamid (2017). Olefin Mixture Direct Sequence Retrofitting and Feed Compositions Sensitivity Analysis. *Energy Proceedia. 142.* 2598–2603.

A. N. Rahimi, M. F. Mustafa, M. Z. Zaine, N. Ibrahim, K. A. Ibrahim, N. Yusoff, E. M. Al-Mutairid, M. K. A. Hamid, (2015). Energy Efficiency Improvement in the Natural Gas Liquids. *Chemical Engineering Transactions. 45.* 7.

A. W. Westerberg, (2004). A Retrospective on Design and Process Synthesis. *Computers & Chemical Engineering. 28.* 447–458.

B. Linnhoff & J. R. Flower, (1978). Synthesis of Heat Exchanger Networks: I. Systematic Generation of Energy Optimal Networks. *AlChE Journal. 24.* 633–642.

C. Cui, H. Yin, J. Yang, D. Wei, J. Sun, C. Guo, (2016). Selecting Suitable Energy-Saving Distillation Schemes: Making Quick Decisions. *Chemical Engineering and Processing: Process Intensification. 107*. 138–150.

D. S. S. T. Gmbh, (2014). Pure Component Equations. Oldenburg Germany: DDBST Software & Separation Technology GmbH.

E. Bek-Pedersen & R. Gani, (2004). Design and Synthesis of Distillation Systems Using A Driving-Force-Based Approach. *Chemical Engineering and Processing: Process Intensification. 43.* 251–262.

E. Bek-Pedersen, R. Gani, O. Levaux, (2000). Determination of Optimal Energy Efficient Separation Schemes Based on Driving Forces. *Computers and Chemical Engineering. 24.* 253–259.

G. Sobočan & P. Glavič, (2002). A Simple Method for Systematic Synthesis of Thermally Integrated Distillation Sequences. *Chemical Engineering Journal. 89***.** 155–172.

H. Yoo, M. Binns, M.-G. Jang, H. Cho, J.-K. Kim (2015). A Design Procedure for Heat-Integrated Distillation Column Sequencing of Natural Gas Liquid Fractionation Processes. *Korean Journal of Chemical Engineering. 33***.** 405–415.

J. G. Speight, (2011). *The Refinery of the Future,* Burlington, MA 01803, USA, Elsevier.

M. A. Zubir, A. N. Rahimi, M. F. I. Zahran, M. Z. Shahruddin, K. A. Ibrahim, M. K. Abd. Hamid, (2017). Systematic design of energy efficient distillation column for alcohol mixture. *Energy Procedia. 142***.** 2630–2635.

M. A. Zubir, M. F. I. Zahran, M. Z. Shahruddin, K. A. Ibrahim & M. K. A. Hamid 2019. Economic, Feasibility, and Sustainability Analysis of Energy Efficient Distillation Based Separation Processes. *Chemical Engineering Transactions. 72***.** 109–114.

M. F. Mustafa, N. a. F. A. Samad, K. A. Ibrahim & M. K. A. Hamid 2014. Methodology Development for Designing Energy Efficient Distillation Column Systems. *Energy Procedia*. 61. 2550–2553.

M. F. Mustafa. 2014. *Retrofitting Direct Sequence Distillation Columns Using Driving Force Method.* Master's Degree Thesis, Universiti Teknologi Malaysia.

M. Z. Shahruddin, A. N. Rahimi, M. A. Zubir, M. F. I. Zahran, K. Ibrahim & M. K. A. Hamid 2020. Energy saving potential of 6-component aromatic mixture via Energy Integrated Distillation Columns Sequence (EIDCS) method. *IOP Conference Series: Materials Science and Engineering.* 884.

M. Z. Shahruddin, A. N. Rahimi, M. A. Zubir, M. F. I. Zahran, K. A. Ibrahim & M. K. A. Hamid 2017. Energy Integrated Distillation Column Sequence by Driving Force Method and Pinch Analysis for Five Components Distillation. *Energy Procedia. 142*. 4085–4091.

M. Z. Shahruddin, T. Xinyi, A. N. Rahimi, M. A. Zubir, M. F. I. Zahran, K. A. Ibrahim & M. K. Abd. Hamid. Thermal Pinch Analysis Application for Driving Force Distillation Columns Sequence of 5-Component Alcohol Mixture. *International Graduate Conference on Engineering, Science and Humanities (IGCESH)*, 13–15 August 2018 2018 UTM Skudai, Johor Bahru.

M. Z. Shahruddin, T. Xinyi, A. N. Rahimi, M. A. Zubir, M. F. I. Zahran, K. A. Ibrahim & M. K. Abd. Hamid 2019. Thermal Pinch Analysis Application on Distillation Columns Sequence of 5-Component Alcohol Mixture. *Chemical Engineering Transactions. 72.* 271–276.

M. Z. Zaine, M. F. Mustafa, N. Ibrahim, K. A. Ibrahim & M. K. A. Hamid 2015. Minimum Energy Distillation Columns Sequence for Aromatics Separation Process. *Energy Procedia. 75*. 1797–1802.

N. Quirante, J. A. Caballero & I. E. Grossmann 2017. A novel disjunctive model for the simultaneous optimization and heat integration. *Computers & Chemical Engineering. 96***.** 149–168.

S. Hernandez, J. Gabrielsegoviahernandez & V. Ricoramirez 2006. Thermodynamically equivalent distillation schemes to the Petlyuk column for ternary mixtures. *Energy. 31***.** 2176–2183.

W. Seider, J. Seader & D. Lewin 2004. *Product and Process Design Principles,* New York, Wiley.

X. Li & A. Kraslawski 2004. Conceptual Process Synthesis: Past and Current Trends. *Chemical Engineering and Processing: Process Intensification.43*. 583–594.