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Composition-sensitive energy saving in distillation column sequences for natural gas liquids (NGL) separation

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ABSTRACT

Distillation is the energy-intensive separation process that recorded approximately 40% of the energy usage in the chemical and petrochemical industries. Natural gas liquids (NGL) is a product of distillation process which characterised by the multicolumn setup that leads to high heating and cooling requirements. Therefore, the main purpose of this study is to investigate the application of driving force method (DFM) with the support of the thermal pinch analysis (TPA) to enhance the energy saving of the NGL distillation process under various feed composition scenarios. The NGL distillation process in this case study comprising three types of feed composition of propane, i-butane, n-butane, i-pentane, and n-pentane, were simulated using Aspen HYSYS. Then the TPM was carried out by utilising the Aspen Energy Analyzer to produce grand composite curves (GCC) and to propose the heat exchanger network (HEN) design. From the results, Composition 2 with lighter feed recorded the highest total energy saving of 33.42%, followed by balanced feed (Composition 1) with 32.42% and lastly Composition 1 (heavier feed) with 29.09% energy saving. The analysis from GCC and HEN further explained on the dynamics of the energy requirement based on the feed composition and reaffirm that the combination of DFM and TPM successfully enhanced the energy saving across various composition scenarios.

1. INTRODUCTION

In the era of technological advancement, the energy demand is growing rapidly due to the increment trend of the global population and lifestyle changes. Thus, the related industry also needs to be expanded to meet the demand. This is no different from the distillation process, being one of the huge energy consumers

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which accounts for approximately 40% of total energy consumption in chemical and petrochemical industries (Kiss & Smith, 2020; Markowski et al., 2020). Nevertheless, it is still considered a reliable process due to its versatility and mass production capability. This led to the opportunity for energy saving in the process to ensure the sustainability not only for the process but also for the environment.

On the other hand, natural gas liquids (NGL) can be considered as a very beneficial commodity as fuel and become a feedstock for petrochemical products. Methane, ethane, propane, butanes and pentanes are common components of the NGL. This multicomponent scenario will lead to the needs of sequence of separation by means of distillation columns sequence to extract each component in the NGL. Eventually, the separation trains that employed condenser and reboiler as heat sources for the distillation columns resulting in high energy consumption. It is regarded as the process with the highest energy demands in the gas processing plants (Yasmin et al., 2014; Duan et al., 2022).

In response to the energy management issue in the distillation process, several strategies have been proposed such as operational improvements and advanced column configuration and heat integration. In terms of operational improvements, the related parameters in the distillation column such as reflux ratio, feed stage, column temperature and pressure, number of columns and distillate rate can be optimised, however it limits the potential for more energy saving for the process (Zhang et al., 2018). In the aspects of advanced column configurations, many methods or approaches have also been suggested. Among others are thermally coupled distillation columns, heat-pump assisted columns and dividing wall columns (DWC) resulting a ranging of energy saving from 25 to 40% from the original energy consumption (Dejanović et al., 2010; Caballero & Grossmann, 2014; Rahimi, 2021). Having said that, the complexity of the setup in the end hinders this method to be widely implemented in the industry. Meanwhile, heat integration offers an alternative way to energy saving of the process. It started from the early concept of thermal pinch analysis (TPA) which has been introduced in 1971 by Hohmann and extended by Linnhoff and Hindmarsh in 1980. The existence of exchangeable heat in the common heating and cooling process for energy saving has been brought to the application of distillation process whereby the hot and cold streams are coming from the condenser and reboiler heat loads (Kemp, 2007; Rahimi et al., 2015).

Another critical consideration with regards to the energy usage in distillation column is column sequencing especially that process with multicomponent such as NGL. For multicomponent mixtures, separation typically requires a train of distillation units, where the number of possible sequences is given by:

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

where N_s is the number of possible sequences and P is the number of products (Ahmadi Pouya & Soltanali, 2017). As a result, the number of possible sequences will increase exponentially as the number of product increases which will involve tedious process to determine the sequence with the less energy consumption. This is where driving force method (DFM) comes into the picture. With the fundamental concept of the relative volatility for a binary component, this method identifies the sequence based on the highest value of the driving force thus producing the optimal sequence without having to analyse all possible sequences as stated in equation for a multicomponent case. Studies have reported energy savings ranging from 7% to

18% when applying DFM compared to direct or heuristic sequencing (Mustafa et al., 2015; Shahruddin et al., 2020; Li et al., 2023).

In a way to discuss on the energy saving by DFM, there are also a factor needed to be considered to enhance the energy savings, which is the feed composition, in the sense that the impact of having light-based composition to heavy-based composition as emphasised by the recent studies (Rahimi et al., 2015; Zin et al., 2021; Li et al., 2024). According to Zin et. al (2021), feed composition influencing the energy saving of the thermally coupled arrangement of the distillation column as high as 39%. This is due to the multicomponent nature of the process and to also relate it with the relative volatility of the binary component in the process. The higher the lighter component will create a large gap between one component to another which will eventually lead to easier separation thus lowering the energy usage, vice versa with the mixture dominated by the heavier component. On top of that, in terms of the energy integration, the composition of a mixture will be influential with for a temperature-enthalpy profile whereby the higher the lighter component will promote higher temperature gap and will lead to higher potential for energy recovery opportunity as to oppose to the heavier-component dominated composition (Kiss & Smith, 2020). Based on these principles, this study adopts the hypothesis that feed composition plays a decisive role in determining the achievable energy savings in distillation sequences through its concurrent effect on separation difficulty and heat-integration behaviour.

This study addresses that gap by applying an integrated framework that combines the driving force method (DFM) and thermal pinch analysis (TPA) to evaluate three feed compositions of a five-component NGL mixture (propane, i-butane, n-butane, i-pentane, n-pentane). Using Aspen HYSYS and Aspen Energy Analyzer V14, the research aims to (i) identify optimal sequencing arrangements, (ii) quantify heat recovery potential, and (iii) demonstrate how composition-dependent design reduces external utility demand. By linking sequencing and heat integration under varying feed conditions, this work advances a practical pathway toward more energy-efficient and sustainable NGL fractionation.

2. RESEARCH METHODOLOGY

2.1 Case study

The case study involves a five-component NGL mixture consisting of propane, i-butane, n-butane, i-pentane, and n-pentane. The purity of each distillation column is set at 99% for all components, consistent with previous work (Shahruddin et al., 2020). The feed composition scenarios and the feed condition can be found in Table 1 whereby Composition 1 represents the heavy-component dominated composition, Composition 2 higher composition for light component and balanced composition for Composition 3. This variation enables systematic assessment of how feed composition influences energy consumption in distillation column sequences.

Table 1. Feed condition for NGL mixture case study (Shahruddin et al., 2020)

Item	Boiling Point (°C)	Composition		
		1	2	3
Propane (A)	−42.10	0.05	0.35	0.20
i-Butane (B)	−11.73	0.15	0.15	0.20
n-Butane (C)	−0.50	0.25	0.25	0.20
i-Pentane (D)	27.88	0.20	0.20	0.20
n-Pentane (E)	36.06	0.35	0.05	0.20
Feed flowrate (kmole/h)			907.2	
Pressure (atm)			1	
Temperature (°C)			4.37	

Source: Shahruddin et. al. (2020)

2.2 Research Framework

The methodology consists of four sequential steps, as shown in Fig. 1.

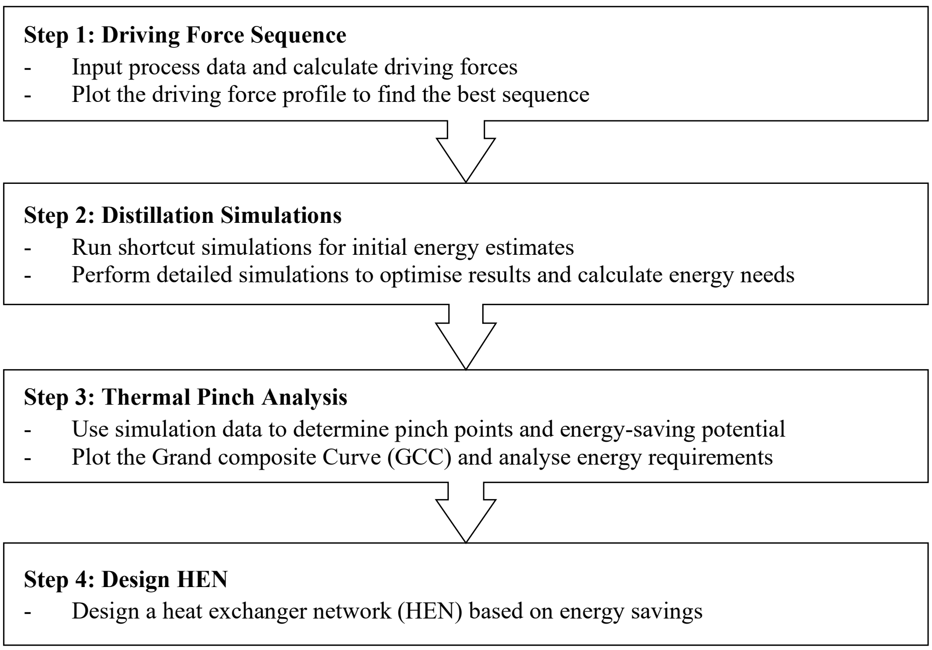

Fig. 1. Research framework

Source: Author

The framework starts with the determination of driving force sequence. In this step, the relative volatility for each binary pair in the mixture will be calculated and the resulting plots called the driving force plot will be produced. The pair with the highest driving force value will be the one that separates first followed by the less driving force values. Then, it will eventually determine the optimal sequence namely the driving force sequence (Mustafa et al., 2015; Ahmadi Pouya & Soltanali, 2017).

In Step 3, the thermal pinch analysis is carried out by using the Aspen Energy Analyzer V14 to determine the pinch point and the minimum energy requirement for the process. The hot and cold streams data from Step 2 will be utilised via the approach namely problem table algorithm (PTA) (Kemp, 2007; Zhang et al., 2020). This will produce the minimum heating and cooling requirement of the overall process and can be portrayed by the grand composite curve. From there, the energy saving analysis will be carried out to determine the percentage of energy saving by comparing the energy obtained in Step 2 with the minimum energy requirement from the PTA.

Finally, heat exchanger network (HEN) design is then proposed to determine the configuration of the heat exchanger that match with the minimum energy requirement. Grid diagrams are developed to map hot and cold streams, ensuring all matches comply with pinch design rules (Caballero & Grossmann, 2014; Zin et al., 2021). By systematically coupling sequencing, rigorous simulation, pinch analysis, and network design, the methodology provides a comprehensive evaluation of how feed composition influences both separation behaviour and heat-integration performance in multicomponent distillation.

3. RESULTS AND DISCUSSION

3.1 Optimal sequencing arrangements

The first step was to determine the optimal sequence, driving force sequence as suggested in the framework based on the literature that regards it as the sequence that guarantee lower energy usage compared to the conventional sequence based on boiling point which being called direct sequence (Mustafa et al., 2015; Shahruddin et al., 2020). The driving force calculation was carried out through the relative volatility calculation and then the sequence was arranged in such a way that the higher driving force will be the first to separate followed by the lower one. This yields the sequence shown in Fig. 2. For the various composition scenarios, the sequence remained unaffected, as the relative volatility was independent of the composition. Then this sequence was adopted and brought to Aspen HYSYS V14 for shortcut and rigorous simulation to determine the hot stream and cold stream thermodynamic data for the thermal pinch analysis.

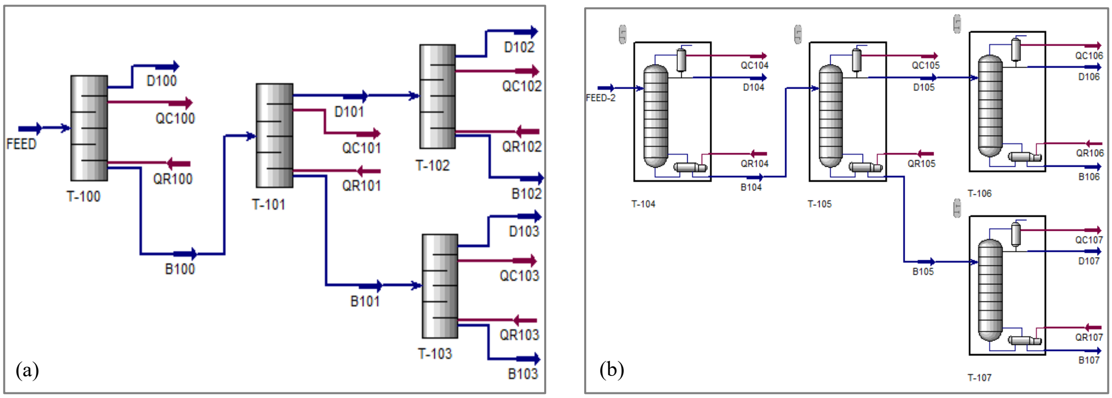

Fig. 2. Driving force sequence for (a) shortcut and (b) rigorous distillation simulations in Aspen HYSYS

Source: Author's own simulation (Aspen HYSYS)

3.2 Heat recovery potential: Energy analysis

From the rigorous simulation, the data was used in the TPA via problem table algorithm and the results were analysed and summarised in Table 2. The energy analysis was done by comparing the energy requirement from the rigorous simulation (before pinch) with the energy requirement resulted from TPA (after pinch). From the table, the trend of energy based on the composition of the mixture was obvious. The lighter component-based composition, Composition 2 recorded the highest energy saving for a total of 33.44% followed by the balance mixture at 32.56% and Composition 3 with lowest one at 29.09%. The volatility gap played a very influential role in here, whereby the higher the lighter component will increase the volatility gap thus lowering the enthalpy demands for vapor liquid separation in the distillation process (Rahimi et al., 2015; Li et al., 2024). In fact, it already shown event without the application of TPA, whereby both heating and cooling loads for Composition 2 recorded the lowest energy consumption for a respective value of 8.19×10^7 kJ/h and 10.21×10^7 kJ/h.

In terms of heating and cooling loads, the composition redistributes the separation workload whereby the light-rich feeds shift the energy burden toward the condenser as reflected by Composition 2 that recorded a saving of 30.13%, to complement the large decrement of the heating loads. While in heavier feed, the composition setting seems to limit the heating and cooling recovery and cannot maximise it due to the limitation of having lower volatility gap thus lowering the chances of the ability for energy integration (Mustafa et al., 2015; Shahruddin et al., 2020).

Overall, the findings from Table 2 emphasise the importance of considering feed composition prior to the application of DFM and TPA. Mixture rich in lighter components tend to achieve the lowest energy requirement due to the gap in volatility of the binary component. In contrast, a balanced mixture provides stronger overall efficiency by distributing energy requirements more evenly between condenser and reboiler on the distillation column. While heavy-component feeds recorded lower energy saving for the limited energy saving opportunity due to the lower volatility gap in between the binary component in the mixture.

Table 2. Energy analysis for the selected case study

Composition		Heating Load (Q_h)	Cooling Load (Q_c)	Total Load (Q_t)
			$\times 10^7$ kJ/h	
1	Before Pinch	11.75	11.58	23.34
	After Pinch	8.36	8.19	16.55
	Difference	3.39	3.39	6.79
	% Energy Saving	**28.88**	**29.30**	**29.09**
2	Before Pinch	8.19	10.21	18.40
	After Pinch	5.11	7.13	12.25
	Difference	3.08	3.08	6.15
	% Energy Saving	**37.56**	**30.13**	**33.44**
3	Before Pinch	9.93	10.96	20.89
	After Pinch	6.53	7.56	14.09
	Difference	3.40	3.40	6.80
	% Energy Saving	**34.24**	**31.04**	**32.56**

Source: Author

3.3 Heat recovery potential: Grand composite curve (GCC)

The grand composite curve (GCC) is one of the best ways to illustrate the energy saving from the problem table algorithm in a graphical form to complement the values recorded in Table 2. The GCC for all cases can be found in Fig. 3 to Fig. 5. The profile can be seen as consistent with the findings from the previous section with regards to the extent of energy recovery.

The GCC profiles obtained in this study are consistent with earlier findings that demonstrate how feed composition governs the shape of temperature–enthalpy curves and, consequently, the extent of heat recovery. For instance, in Composition 2 (Fig. 4) where the light-based component produces big gap of hot-cold separation that leads to the largest reduction in heating duty. This is aligned with the works by Kemp (2007) and Zhang et. al (2020) which stated that the higher gap in temperature driving force and larger vertical separations in the GCC, the higher opportunity for energy saving.

Composition 1 also reflected the same trend as also supported by Zin et. al (2021), the heavier feeds will tend to narrow the GCC around the pinch point thus limit the energy recovery due to the higher energy demand for heating (higher reboiler duty). Similarly for Composition 3 resembles the thermodynamic behaviour noted by Rahimi et al. (2015), who reported that mixtures with intermediate volatility distributions tend to generate more uniform GCC curves and support stable energy savings across both heating and cooling utilities.

Taken together, the parallels with prior studies confirm that the GCCs from this study are consistent with the established thermodynamic principles which stated that the light-rich feeds broaden the integration ability of the process, vice versa with the heavy-rich feeds while moderate and stable zones showed by the balanced feeds. These findings not only reinforce earlier work but also extend it to the application of DFM and TPA for NGL distillation process. The trend shows that the feed composition influences both the magnitude of the energy demand and the scope for effective heat integration.

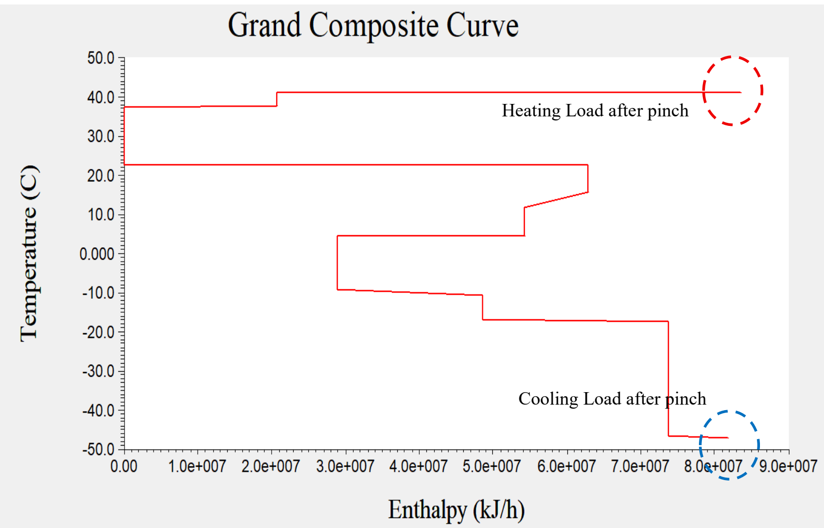

Fig. 3. Grand composite curve for (a) Composition 1 in the Case Study

Source: Author's own simulation (Aspen Energy Analyzer)

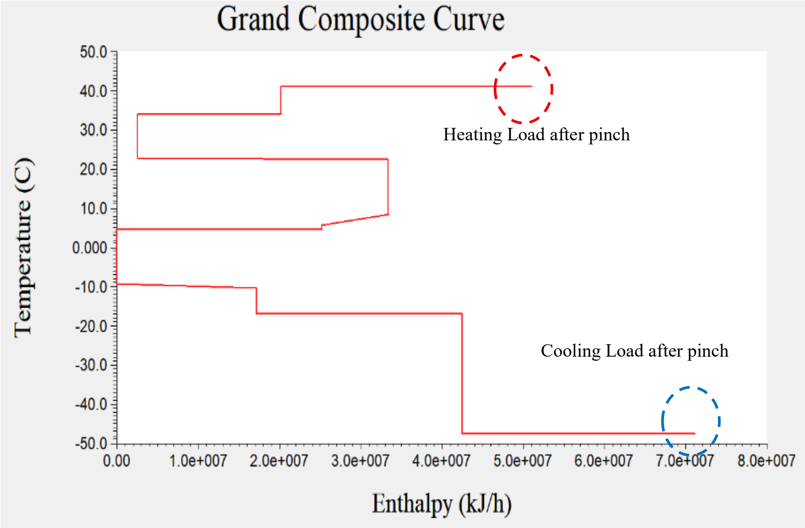

Fig. 4. Grand composite curve for (a) Composition 2 in the Case Study

Source: Author's own simulation (Aspen Energy Analyzer)

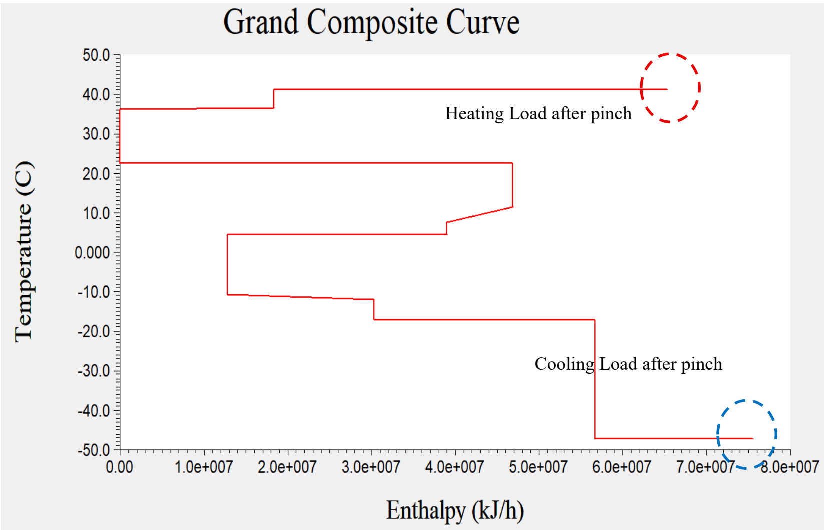

Fig. 5. Grand composite curve for (a) Composition 3 in the Case Study

Source: Author's own simulation (Aspen Energy Analyzer)

3.4 Compositional analysis and heat exchanger network (HEN) design

The heat exchanger network (HEN) was proposed to satisfy the energy requirement that has been obtained from the application of TPA. The grid diagram was used to illustrate the HEN for all cases, as shown in Fig. 6, Fig. 7, and Fig. 8, respectively. This is very important to determine the dynamics of the energy requirements of the process with the changes in the composition of the mixture. Generally, all grid diagram showed that the energy saving can be obtained whether it is light-feed composition or even heavy-feed composition since all have gained energy saving from the TPA results.

Based on the grid diagrams, the composition difference will drive the heat flow on different pathway with the major factor being the pinch point itself. For instance, in Fig. 6, the heavy-feed based composition tends to produce the integration opportunity at below the pinch point region. The lower volatility gap push energy concentration into fewer hot streams and limit the opportunity for exchangeable heat in between hot and cold streams, below the pinch region which then lead to higher energy consumption to satisfy the additional needs of the external cooling requirements compared to slightly better for balanced system in Fig. 8 (Caballero & Grossmann, 2014; Zin et al., 2021). But still, the region of integration remained below the pinch region. Eventually, for light-rich case, lighter component increases the condenser duties, which can then be matched with the cold-side heating requirement thus maximise the internal recovery while the integration region shifted from below pinch point region to above pinch point region. This leads to the needs of heating requirement of 2.63×10^6 kJ/h, considered lowest compared to cooling duty for Composition 1 and Composition 3.

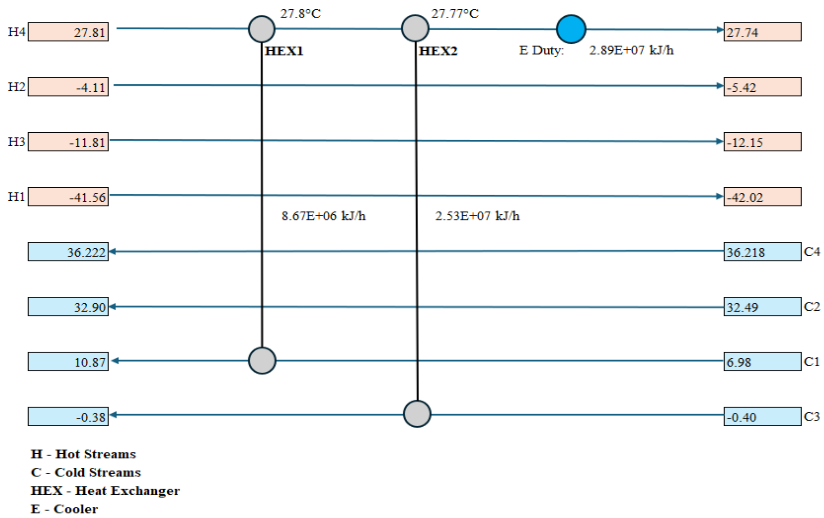

Fig. 6. Grid diagram for Composition 1

Source: Author’s own simulation (Aspen Energy Analyzer)

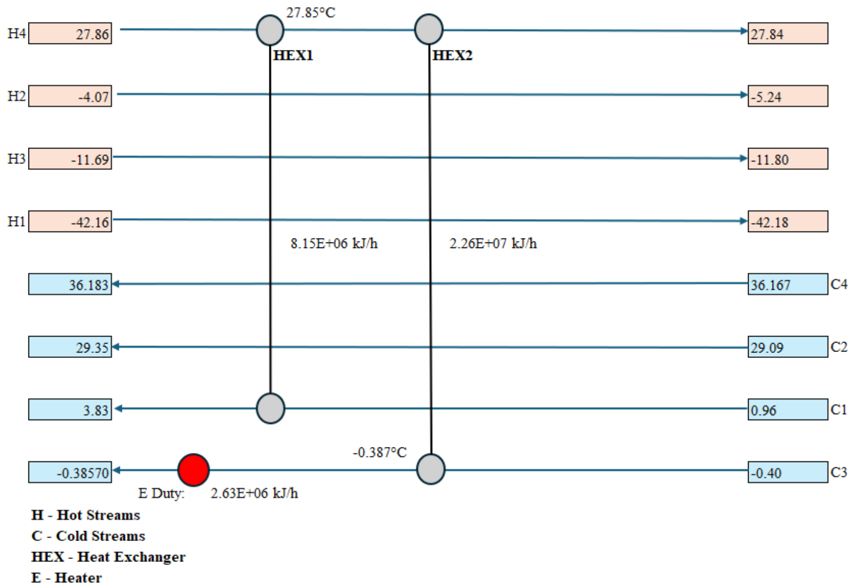

Fig. 7. Grid diagram for Composition 2

Source: Author's own simulation (Aspen Energy Analyzer)

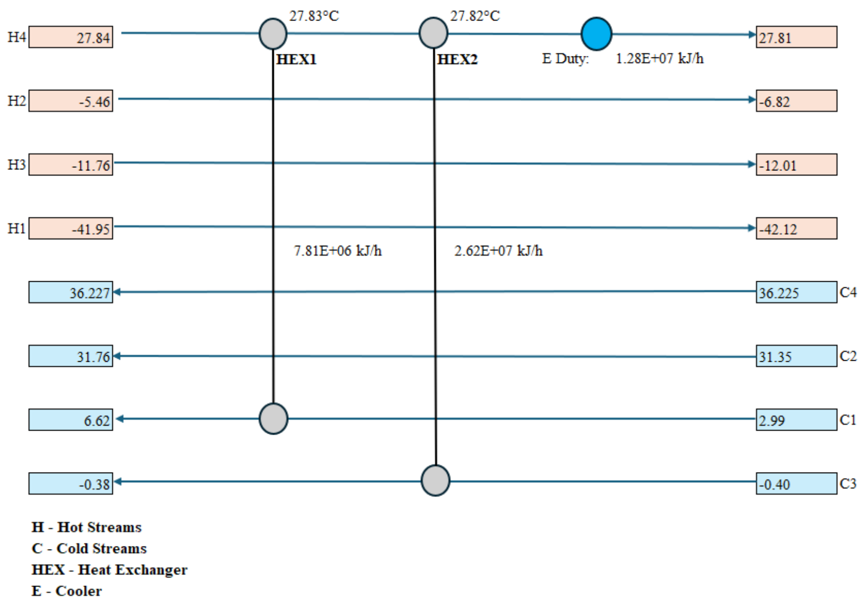

Fig. 8. Grid diagram for Composition 3

Source: Author's own simulation (Aspen Energy Analyzer)

In conclusion, the feed composition has been proved to have a big role in determining not only the energy requirement but also the configuration of the energy flows in the process. It was also observed that the changes from lighter-based component to heavier-based component will shift the region of integration from above pinch point (Composition 2) to below pinch point region (Composition 1 and Composition 3). This comparative evidence reinforces the broader conclusion that composition-sensitive design, supported by methods such as driving force sequencing and pinch analysis, is essential to unlock the full potential of energy savings in NGL distillation (Rahimi, 2021; Mustafa et al., 2015; Li et al., 2023).

3.5 Compositional implications for energy efficiency

From the comprehensive analysis that have been carried out and discussed so far, it is worthwhile to establish that, there are three vantage points pertaining to the energy saving in the NGL distillation process. First, the feed composition plays a significant role in the energy saving. Depending on the relative volatility of the component, the higher the composition of the light component in the mixture, the higher opportunity for energy saving. Second, regardless of composition, the integrated methods of DFM and TPA has proved to be very effective in ensuring energy saving of the NGL process. This approach enables the identification of process sequences that are not only thermodynamically advantageous but also conducive to effective heat integration. Last, the study also covers on the practical side of the process through the minimisation of the number of reboilers and condensers thereby supporting the sustainability goals of modern NGL facilities.

These results not only validate prior findings (Mustafa et al., 2015; Shahruddin et al., 2020) but also extend them by demonstrating composition-dependent differences. By systematically evaluating energy saving across feed scenarios, the study emphasises the importance of tailoring distillation strategies to actual feed variability rather than applying standardised designs which would be much relevant.

Nevertheless, to ensure that it can be implemented successfully, several considerations such as operational and safety need to be addressed. The use of heat exchanger might create dependencies whereby should its failure, fouling or malfunction, it will disrupt more than one distillation process simultaneously. This will complicate the plant including the maintenance or turnaround activities and the process control. Therefore, operational measures such as utility capacity, standby or backup heat exchangers, bypass lines and isolation valve are among the items that should be considered prior to the implementation of the HEN. The dynamic studies and advanced control could also be the options as well for recommended future research works. Finally, economic and reliability indicators, such as availability, redundancy, and lifecycle cost should be considered alongside energy targets to select the most balanced configuration. These factors represent essential design constraints, and dynamic or operability studies are strongly recommended before moving to full-scale implementation.

4. CONCLUSION

The study was carried out to identify the optimal sequence by driving force method (DFM) and enhancing the energy saving of the distillation process by thermal pinch analysis (TPA), with the changes of composition of natural gas liquid (NGL). The findings suggested that the composition played a critical role in determining the exchangeable heat within the process which highly depends on the volatility gap of the binary component in the mixture. Following that, light-rich feeds (Composition 2) recorded the highest total energy saving of 33.42% and vice versa for the heavy-rich component (Composition 1) at 29.09%. The balanced feed (Composition 3) recorded the moderate energy reduction of 32.59%. The optimised heat exchanger networks further highlight that significant utility reductions and minimised reboiler–condenser dependence are achievable when composition-driven thermodynamic behaviour is explicitly incorporated, verifying that up to one-third of total energy use in NGL fractionation can be eliminated by aligning sequence design and heat-integration strategies with actual feed characteristics, while also underscoring the need to extend such optimisation to operability, reliability, and economic evaluation for industrial application.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Munawar Zaman Shahruddin: Conceptualisation, methodology, formal analysis, investigation, supervision, and writing–original draft; **Nur Syahirah Azhari:** Methodology, formal analysis, and investigation; **Tengku Amran Tengku Mohd:** Validation, resources, and supervision; **Rohani Mohd Zin:** Conceptualisation, supervision, writing–review and editing, and validation; **Mohd Fadhil Majnis:** Project administration, supervision, and resources.

DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT5.3 in order to help in arranging the wording and flow of the paper. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. All data generated or analysed during this study are included in this published article.

ETHICAL COMPLIANCES STATEMENT

The authors confirm that this study was conducted in accordance with established ethical standards and institutional guidelines. All procedures complied with the Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA. The authors further confirm that the research was conducted with integrity, and all data was reported accurately without fabrication, falsification, or inappropriate manipulation.

ETHICAL APPROVAL STATEMENT

The authors declare that this study did not involve human or animal subjects and complies with institutional ethical guidelines.

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