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Research paper

Energy Integrated Distillation Columns Sequence (EIDC) of 5-Component Alcohol Mixture via Driving Force and Thermal Pinch Analysis Approach.

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Abstract

Distillation column is a well-known unit operation to perform the intended separation task in chemical and petrochemical industries. However, the common issue for distillation column is the large energy requirement especially for multicomponent processes. Therefore, the sequence determination could be a key to solve the problem. This paper provides a methodology to produce energy integrated distillation columns sequence via driving force sequence approach. Then, it is supported by the thermal pinch analysis for further the energy saving in the process. The case study selected is distillation process of 5-component alcohol mixture. Based on the input data, two sequences for distillation columns namely direct sequence and driving force sequence were firstly simulated. Then, the resulting information such as target temperature, supply temperature and energy from condensers and reboilers have been extracted for thermal pinch analysis. Lastly, the energy requirements from the analysis (before and after pinch analysis) were compared for energy saving calculation. Based on the analysis results, the driving force sequence with pinch analysis successfully enhanced the 35% of the overall energy saving. Thus, it can be said that the driving force sequence and thermal pinch analysis approach namely energy integrated distillation columns sequence has a potential for further the energy saving of the distillation columns sequence for the selected case study.

Keywords: *Energy Integrated; Distillation Columns Sequence; Driving Force Sequence; Thermal Pinch Analysis; 5-Component Alcohol Mixture.*

1. Introduction

Distillation column is a well-known unit operation to perform the separation task in chemical and petrochemical industries due to its capability to produce the intended products in a large scale (1). However, the usual problem arises from the process using distillation column is the large energy consumption. The amount of energy required is significant with more than 50% of plant operating cost and 3% of world energy consumption (2). Thus, by solving the issue, it will not only protect the environment and promote the sustainability, but will also address the efficiency of the process itself which will ultimately determine the plant economic and business profitability (3).
According to Jobson (4), there are several methods that can be implemented to save energy in distillation column; 1) distillation column conceptual design and synthesis, 2) distillation column monitoring and control, 3) advanced and complex column configuration, 4) evaluation of energy in distillation column and 5) heat integration in distillation column. In different aspect of synthesizing the chemical system, Rathore, Van Wormer (5) has outlined two sub-problems to be solved; 1) separation sequence which can be referred to distillation column conceptual design and synthesis and 2) heat exchanger network for energy recovery which related to heat integration in distillation column. Therefore, this paper will investigate the energy saving in distillation columns sequence in the aspects of separation sequence and heat integration as suggested by Rathore, Van Wormer (5). The methods in this paper will help in producing so-called Energy Integrated Distillation Columns Sequence (EIDC) that will further save the energy for any distillation processes.

2. Literature Review

Industrial distillation process involved more than one distillation column and it is called distillation columns sequence. For the case of two distillation columns it can be denoted as direct sequence and indirect sequence as shown in Figure 1 (a) and (b). In the case of 3 or more columns, another possible sequence is split sequence as illustrated in Figure 1 (c). The number of possible sequences is determined by the numbers of intended products in the process. It can be determined by the following equation (6):

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

whereby:
Ns=number of sequences
P = number of products

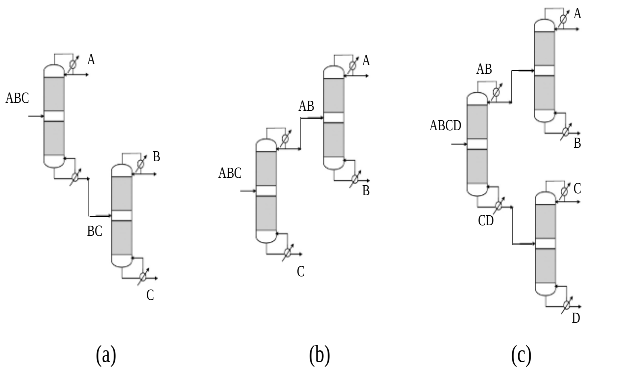

Figure 1. (a) Direct sequence, (b) Indirect sequence, (c) Split sequence

Table 1 shows several results of the number of sequences based on the above formula. It can clearly be seen that the number of sequences is increasing exponentially with the number of products. For instant, 4 products with 3 columns will have 5 different sequences and the number will be further to 4862 for 10-component mixture. In terms of energy analysis of the sequence, it will become challenging to analyze all the sequences to determine the sequence with the lowest energy requirement. Therefore, the conceptual process synthesis (CPS) could be implemented to avoid such scenario.

Table 1. Number of products and the resulting number of sequences

No. of Products	No. of Sequences
2	1
3	2
4	5
5	14
6	42
7	132
8	429
9	1430
10	4862

There are several methods in CPS that can be employed for the determination of distillation columns sequence; 1) heuristic, 2) evolutionary, 3) algorithm, 4) Sequential Design Method (SDM) and 5) driving force (7). Heuristic, an earliest CPS method requires a lot of experience about a process. Furthermore, there is always a possibility for the rules in heuristic to contradict with each other. Meanwhile for evolutionary method, the basis is still heuristic, but the changes will occur until the best solution has achieved. Along the way, evolutionary method needs the support from other method such as computational etc. to ensure optimal solution for distillation column sequence. The problem of the first two methods has been addressed by algorithm method whereby it will involve mathematical modeling and computation and will yield far better and accurate solution. Nevertheless, the complexity of the model will become hindrance for this method to be applied especially to relate the model description for non-technical or 'laymen' terms. SDM in return is the latest method in CPS. The approach is almost the same with evolutionary except for SDM consider the process alternative as a part of the evolution and make it more holistic in terms of optimal criteria analysis. However, the operational part of the design is still become a doubt for this method to be employed. Meanwhile, driving force method which has being introduced by Gani and Bek-Pedersen (8) is one of the simplest method in CPS especially in design stage and screening purpose.

Driving force method on the other hands is a method that manipulates the properties difference of a binary mixture to yield the best possible distillation column sequence. Based on the theory that the larger the value of driving force between the components, the easier to separate, Bek-Pedersen and Gani (9) proposed the graphical approach for this method. Driving force was plotted based on liquid or vapour composition at the feed-plate location. Then the value of driving force will determine the distillation column sequences. Zaine, Mustafa (10) proposed this method for the distillation of aromatic components. Based on driving force plot between paired components, the optimal sequence was obtained, and the energy analysis demonstrated that the driving force method saves the condenser, reboiler and total energy at 7.0, 6.6 and 7.0% respectively. Meanwhile, the result of using the same method for eleven hydrocarbon components showed further energy saving at 19.6, 16.8 and 19.1% for the same energy from condenser, reboiler and both (11). Another case study which involved with three alcohol components namely ethanol, n-propanol and n-butanol also showed the same trend for the saving of 18% total energy (12). The case studies discussed earlier proved that driving force method enhanced the energy saving in distillation column compared to the conventional sequence base case.

Meanwhile, heat integration is a widely used method in chemical and petrochemical industry. The earliest method is called Thermal Pinch Analysis and it was proposed by Hohmann in 1971 by developing the feasibility table for systematic energy targeting for energy saving in the process (13). The concept was then adopted by the influential publications on pinch analysis including Linnhoff and Flower (14), Flower and Linnhoff (15), Umeda, Itoh (16) and Linnhoff (17). Since then, thermal pinch analysis has been employed for energy saving in the plant. In relation with the application of thermal pinch analysis in distillation column, there are many works that have been successfully published. For instance, Dhole and Linnhoff (18) using the concept of column targeting which involved the usage of composite curve and grand composite curve as a tool to integrate distillation column with background process for the case study of distillation of 5 alkane components. Napredakul, Siemanond (19) used pinch analysis to integrate the distillation process with background process for the retrofitting process of gas separation plant. The value of 13.32% energy saving was recorded by integrating the distillation process with the background process. Pejpichestakul and Siemanond (20) then referred to this publication for case study of Ethylene Hydration that also integrated the distillation process with the background process. It involved the modification option of reduced reflux and reduced reflux with pump-around from column 2 (in the case study). The interesting part is that they did both for retrofit and grassroots scenarios whereby each achieved 28.3% and 25.1% energy saving within the columns and 10.2% and 16% energy saving for the entire process.

Most of the concepts explained previously involved with the application of thermal pinch analysis in distillation column with the background process. Jain, Smith (21) on the other hand investigate the heat integrated for specific application of distillation column sequences. According to the author there are several ways to improve distillation column efficiency including; 1) internal column modification, 2) develop the integrated column or complex column, 3) varies the operating condition and 4) HEN enhancement or intensification. Then the author also outlined the available heat integration options for distillation column which are; 1) inter-column heat recovery (heat exchange among condensers/reboilers within distillation column sequences), 2) heat integration with other process stream or background process (common method in heat integration), 3) heat integration with utility and 4) feed preheat or pre-cool by condenser or reboiler or process stream or external utility. This has paved a way to strengthen the fact that the inter-column heat recovery can also become attractive technique for distillation column sequence as applied by the author. By doing that, they had achieved a range of 8 to 17% overall cost savings. Nevertheless, the research was supported by the application of mathematical modelling to formulate the best sequences which tend to be very complex to solve.

Based on the review in both approach of energy saving by driving force method and thermal pinch analysis method, both can be combined to obtain further energy saving for distillation column sequence which being called as EIDC. The idea will be able to solve the key problems in synthesizing distillation systems according to Rathore, Van Wormer (5) which are 1) basis and sequence of distillation column and 2) heat exchanger network for energy recovery. The case study of 5-component alcohol mixture will be used to evaluate the methods of EIDC for energy saving purpose.

3. Methodology

The methodology for this paper can be divided based on the proposed sequences which are direct sequence (conventional sequence) and driving force sequence. The only difference is the first step of determining the driving force sequence. The subsequent steps remain the same for both sequences. The research flow is illustrated in Figure 2.

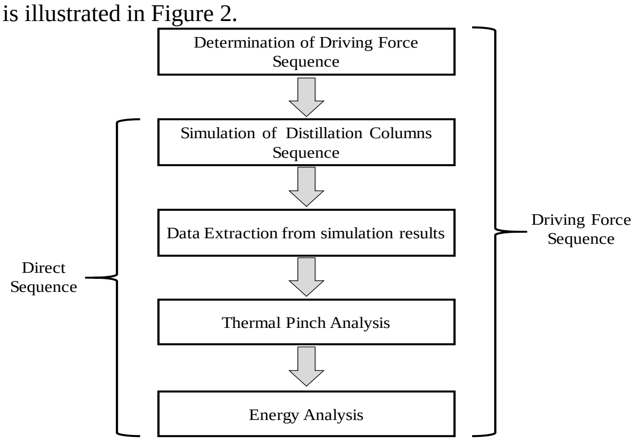

Figure 2. Research Flow

The methodology starts with the determination of driving force sequence based on the methodology suggested by Bek-Pedersen and Gani (9). Then the proposed driving force distillation columns sequence is carried out by using ASPEN HYSYS V9 software. The resulting data from the simulation which are supply temperature, target temperature and energy consumption from condensers (hot stream, H) and reboilers (cold stream, C) is extracted for thermal pinch analysis. The thermal pinch analysis is performed via the construction of problem table algorithm (PTA) with fixed value of ΔT_{min} at 10 ℃ and as a result, the minimum energy requirement for heating (Q_{hmin}) and cooling (Q_{cmin}) loads are generated. Lastly, the energy before and after pinch analysis is analysed. The same method is applied for direct sequence except for the first step which dedicated to driving force sequence.

The case study selected for this research is the distillation process of 5-component alcohol mixture which was adopted from Andrecovich and Westerberg (22). The process can be defined as sharp separation with saturated liquid feed. The feed conditions can be found in Table 2.

Table 2. Feed compositions and input conditions for the selected case study (Andrecovich & Westerberg, 1985)

Input conditions		
Feed Compositions (Mole Fractions)	Ethanol (A)	0.25
	Isopropanol (B)	0.15
	n-propanol (C)	0.35
	Isobutanol (D)	0.10
	n-butanol (E)	0.15
Feed Flow (kgmole/s)		0.139
Pressure (kPa)		100
Recovery of Components		0.98

4. Results and Discussion

Based on the method by Bek-Pedersen and Gani (9), the arrangement of sequence was successfully determine as illustrated in Figure 3 together with direct sequence.

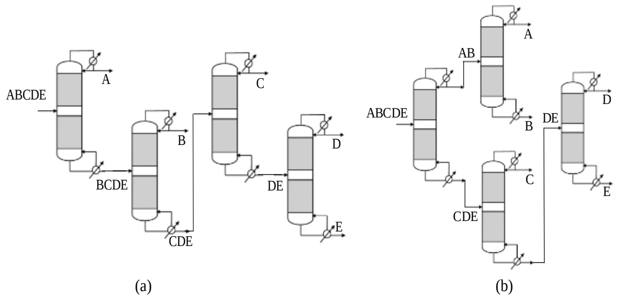

Figure 3. (a) Direct Sequence and (b) Driving Force Sequence for the Selected Case Study

Then, the simulation for both sequences have been performed and the extracted data for both sequence is tabulated in the following table:

Table 3. Data Extracted from the Simulation

Stream	Direct Sequence			Driving Force Sequence		
	T_{sup}	T_{tar}	Q	T_{sup}	T_{tar}	Q
	℃		10^7 kJ/h	℃		10^7 kJ/h
H1	77.89	77.88	6.53	79.48	79.32	2.77
C1	93.08	96.92	6.55	100.92	102.46	2.81
H2	82.10	82.01	1.97	78.01	77.98	5.57
C2	100.98	102.39	1.98	81.77	81.80	5.57
H3	96.79	96.73	2.98	96.84	96.82	2.98
C3	112.29	113.08	2.99	112.29	113.08	2.99
H4	107.55	107.52	1.56	107.54	107.51	1.56
C4	117.48	117.48	1.56	117.48	117.48	1.56

Please note that H and C represent hot stream and cold stream in a column respectively. Supply and target temperature are denoted by T_{tar} and T_{sup} while Q is energy requirement for the stream. The results from Table 3 have been used to compute the PTA for both sequences whereby the value of ΔT_{min} is fixed at 10 ℃. The results are depicted in Table 4 along with the energy from Table 3 in terms of heating, cooling and total loads.

Table 4. Energy Requirement for All Sequences Scenario

Sequence	Heating Loads	Cooling Loads	Total Loads
	10^8 kJ/h	10^8 kJ/h	10^8 kJ/h
Direct Sequence Before Pinch	1.308	1.303	2.611
Direct Sequence After Pinch	1.152	1.147	2.299
Driving Force Sequence Before Pinch	1.293	1.287	2.580
Driving Force Sequence After Pinch	0.839	0.834	1.673

The discussion can be divided into two key perspectives; 1) the effect of Driving Force Sequence towards energy saving of distillation column sequence (before pinch) and 2) the effect of thermal pinch analysis for further the saving (after pinch) for both sequences. For former perspective, the sequence determination via driving force according to the results in Table 3 whereby it recorded the saving of $1.5\text{x}10^6$ kJ/h, $1.6\text{x}10^6$ kJ/h and $3.1\text{x}10^6$ kJ/h for heating, cooling and total loads compared to direct sequence. However, in terms of percentage, the value is slightly low with percentage saving of only about 1.2% for overall energy saving. Thus, it can be said that the driving force method successfully enhanced the energy saving of distillation columns sequence for this case study with minimal percentage saving. This is when the thermal pinch analysis become a handy approach. The results in Table 3 suggested that the thermal pinch analysis has a capability to further the energy saving for both sequences. For direct sequence, with the application of thermal pinch analysis, the amount of energy saving increased approximately 12% for all loads. Based on that percentage of saving alone, the thermal pinch analysis approach is more favorable than driving force approach for the selected case study. Fascinatingly, when both are combined, it recorded the highest percentage of energy saving for more than 35% for heating, cooling and total loads compared to the one before the analysis and obviously the energy saving for the driving force sequence with thermal pinch analysis is far better as to compare with the conventional sequence with thermal pinch analysis (around 27% difference). The reason behind the results can be clearly justified by looking at the composite curve for both sequences as shown in Figure 4.

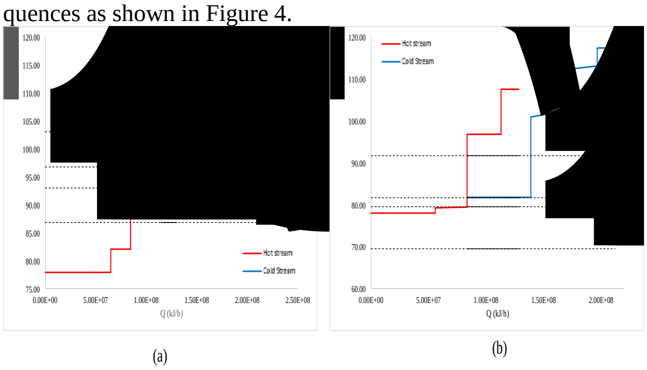

Figure 4. Composite Curves for (a) Direct Sequence, (b) Driving Force Sequence for the Case Study

Both sequences showed identical trend for hot and cold stream in the Composite Curve. The key difference that can be seen is that, by driving force method, there is an additional hot stream in the region above pinch whereby it created the transferable heat in the system. So, driving force sequence has two hot streams above the pinch compared to only one hot stream for direct sequence. The observation supported the justification provided by Mustafa, Ibrahim (12) whereby the arrangement of the distillation columns by driving force which originated from the concept of relative volatility facilitates the existence of the transferable heat or energy in the system. In other words, the sequence has influenced the location of the pinch point in the system. Nevertheless, this is really subjected to the value of ΔT_{min} and the feed condition such as temperature, feed flowrate and feed composition. This will create a possibility for the implementation both approaches to address those variability in other processes.

5. Conclusion

The driving force method together with thermal pinch analysis have been implemented in this to enhance the energy saving in distillation columns sequence. The case study selected is the separation process of 5-component alcohol mixture. Two types of sequences namely direct sequence and driving force sequence have been successfully simulated and the thermal pinch analysis have been performed via problem table algorithm. Based on the results of energy requirement, the combination of the driving force method and thermal pinch analysis successfully enhanced the energy saving in the process as to compare with the direct sequence with the percentage saving of more than 35% overall. Therefore, the distillation process with the driving force and thermal pinch analysis method which can be termed as ‘Energy Integrated Distillation Columns Sequence’ (EIDC) has a capability to enhance the energy saving in the process. Nevertheless, the effect of ΔTmin and variability of feed condition towards the energy saving in EIDC could be a good future study pertaining to widen the implementation of EIDC to any other processes particularly the complex and advanced processes.

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