Energy saving potential of 6-component aromatic mixture via Energy Integrated Distillation Columns Sequence (EIDCS) method

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Abstract. Distillation column is a well-known unit operation in chemical and petrochemical industries for an intended separation task. However, the energy usage still becomes a problem particularly for a multicomponent system of distillation columns sequence. Therefore, this research aims to investigate the applicability of Thermal Pinch Analysis to be employed in a distillation columns sequence to solve the problem. The method is complemented by the sequencing method of Driving Force which leads to a novel method namely Energy Integrated Distillation Columns Sequence (EIDCS). This systematic method has been designed for optimal distillation columns sequence and further energy saving by Thermal Pinch Analysis. The Driving Force Sequence was firstly determined by the use of Driving Force Plot. Then the shortcut and rigorous simulations have been carried out and the resulting data were extracted for Thermal Pinch Analysis at a fixed value of $\Delta T_{\text{min}}$ at 10 °C. Next, the Problem Table Algorithm (PTA) was constructed to indicate the possible energy saving for the distillation columns sequence. Finally, the proposed Heat Exchanger Network (HEN) via Grid Diagram that satisfies the energy requirement was constructed. A case study of 6-component Aromatic Mixture has been selected to evaluate the proposed EIDCS method in this study.

1. Introduction
Distillation process via distillation column plays a major role in the chemical and petrochemical industry due to its versatility with respect to the separation and purification task [1]. Nevertheless, the nature of this thermal-driven process leads to huge energy sinking in the process, especially for a multicomponent system. Therefore, an effective strategy should be employed to avoid any adverse effect not only towards the economy but the environment as well. According to Rathore et al. [2], there are two concerns to be considered for a good chemical processing system: 1) basis and sequence
of separation and 2) energy recovery via Heat Exchanger Network (HEN). This can be interrelated with the distillation columns sequence whereby all these years researches have been done to improve the energy efficiencies of this established process.

Sequencing in a distillation column has long been realized as a method to save energy. For the case of conventional distillation columns sequence, Seider et al. [3] demonstrated the use of an equation to calculate the possible number of sequences based on the number of the products in the process. Logically, the simplest way is to analyze all sequences and select the one with less energy consumption. However, the problem arises when the number of products increases which will lead to the increment of the possible number of sequences exponentially. So a method called Conceptual Process Synthesis (CPS) has been carried out. One of it is called a Driving Force Method which has been introduced by Bek-Pedersen et al. [4] and best described by the following equation:

\[ F_{ij} = y_i - x_i = \frac{x_i \beta_{ij}}{1 + x_i (\beta_{ij} - 1)} 	imes y_i \]  

(1)

\( F \) is a Driving Force, while \( y_i \) and \( x_i \) are vapour and liquid composition. \( \beta_{ij} \) denotes Separability Factor. The higher value of Driving Force will indicate the easier for a binary component to be separated thus make it easy to arrange the sequence based on this concept. This is all shown by the works of several researchers that employed the same method in their studies for a case study of Hydrocarbon Mixture [5, 6], Olefin Mixture [7], Alcohol Mixture [8, 9] and Aromatic Mixture [10-12]. All found that this method has successfully enhanced the energy saving as to compare with the existing sequence.

On a different aspect, heat integration via Thermal Pinch Analysis has been an established method for energy saving in the plant. However, the works by Linnhoff and Hindmarsh [13] and several other works which employed this method to the case study of 5-component Hydrocarbon Mixture [14], Crude Oil Distillation Tower [15], Gas Separation Plant [16] and the cases study of Ethylene Hydration [17] have yet to integrate the system within the columns as per suggested by Jain et al. [18]. Therefore, this study proposes EIDCS, a step by step methodology for energy saving in the process. Not only focusing on integration within the system, but it also caters for the optimal sequence via Driving Force Method.

2. Methods

The method of EIDCS can be presented by the framework in Figure 1. This method consists of 4 stages. Driving Force Sequence will be determined in the First Stage by using the concept of Driving Force [4]. The binary component with the highest Driving Force will be the first to separate followed by the rest in descending order. Then, the shortcut and rigorous simulation of the Driving Force Sequence will be carried out in Stage 2 by using Aspen HYSYS V10 as a simulation software prior to the application of Thermal Pinch Analysis via Problem Table Algorithm in the following stage. The value of \( \Delta T_{min} \) is fixed at 10 °C (in the range of 5 to 20 °C for the chemical process). Last, the energy requirement before and after the application of Thermal Pinch Analysis (Heating, Cooling and Total Loads) will be analyzed complete with the construction of the proposed HEN via Grid Diagram. Meanwhile, a case study of Aromatic Mixture has been selected for this research to evaluate the proposed framework and the feed information can be found in Table 1. The process can be assumed as a sharp separation which does not involve any side draws within the process.
Figure 1. Flow of Research.

Table 1. Feed information of the selected case study [10].

| No. | Data                  | Value       |
|-----|-----------------------|-------------|
| 1   | Feed Flowrate         | 1000 kmole/h|
| 2   | Composition           |             |
|     | Methylcyclopentane (A)| 0.1         |
|     | Benzene (B)           | 0.1         |
|     | Methylcyclohexane (C) | 0.1         |
|     | Toluene (D)           | 0.1         |
|     | m-Xylene (E)          | 0.1         |
|     | o-Xylene (F)          | 0.5         |
| 3   | Pressure              | 2 atm       |
| 4   | Temperature           | 30 °C       |
3. Results and Discussion

The Driving Force concept has been successfully employed to the case study and the Driving Force Sequence was then determined based on the Driving Force Plot below:

![Driving Force Plot](image)

According to the Driving Force Plot, the easiest to separate is D/E component followed by B/C, C/D and A/B. The hardest to separate, E/F component will draw out from the last column. From the results of Driving Force Sequence, it splits at Column 1 and 2 which further draws out C and D in Column 3 followed by the rest. The sequence has then undergone both shortcut and rigorous simulations before the application of Thermal Pinch Analysis via Problem Table Algorithm for a fixed $\Delta T_{min}$ at 10 °C. Then the energy analysis has been carried out and the results are tabulated as shown in Table 2.

|                   | Heating Load | Cooling Load | Total Load |
|-------------------|--------------|--------------|------------|
| Base              | 90.6         | 84.6         | 175.2      |
| Integrated        | 66.9         | 60.9         | 127.8      |
| % Saving          | 26.2         | 28.0         | 27.1       |

Based on the results in the above table, it clearly indicates that the Thermal Pinch Analysis has a good potential in enhancing the energy saving for the case study with the help of the Driving Force Sequence. The arrangement of the sequence or the arrangement of hot-cold stream pairing will determine the location of the pinch point which will contribute to promoting the existence of the exchangeable heat within the system thus resulted in the energy saving in the process [19]. For this case study, the Thermal Pinch Analysis managed to reduce the energy consumption at approximately 26 to 28% for Heating, Cooling and Total Loads.

The proposed HEN is represented by the Grid Diagram in Figure 3. Based on the energy requirement, the heat in hot stream of H3 can be exchanged with cold streams of C5, C2 and C4. An additional cooler is needed to further reduce the temperature in the former stream as per required. This has led to 23.7 MW maximum energy recovery for the process.
4. Conclusion
This paper investigates the energy saving potential of the Thermal Pinch Analysis in the distillation columns sequence with the help of the sequencing method of Driving Force. It is called Energy Integrated Distillation Columns Sequence (EIDCS). A case study of a 6-component Aromatic Mixture was used to assess the proposed framework. The Driving Force Sequence was firstly determined prior to the simulation of the sequence. Then, Thermal Pinch Analysis was performed and the HEN was represented by the Grid Diagram. With an overall percentage of saving at 27%, it can be concluded that the Thermal Pinch Analysis has a good potential to be employed for a distillation columns sequence. The optimization of the value of $\Delta T_{min}$ should be carried out in the future to further improve the energy saving of the process. Other case studies with more components should also be used to measure the extent of this proposed EIDCS method.

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