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Thermal Pinch Analysis Application on Distillation Columns Sequence of 5-Component Alcohol Mixture

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Distillation column is a well-known unit operation in chemical and petrochemical industries. However, large energy requirement has always become major concern to perform the intended separation task. Therefore, heat integration via thermal pinch analysis is proposed for energy saving purpose. This paper provides a methodology for thermal pinch analysis application on distillation columns sequence. The case study selected is distillation process of 5-component alcohol mixture. Based on the input data, 14 possible sequences for distillation columns 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 requirement from the analysis was then compared for energy saving calculation. Based on the analysis results, 8 out 14 sequences recorded overall energy saving ranging from 1.5 to 36 %. Thus, it can be said that the thermal pinch analysis has a potential for further the energy saving of the distillation columns sequence for the selected case study. In addition, the methodology can be extended to any other related distillation columns sequence case studies.

1. Introduction

Distillation column is an important unit operation in chemical and petrochemical industries. It has a capability to separate the chemical components in a large volume without compromising the quality of the products. Thus, distillation column has been widely used in the industry (Leeson et al., 2017). Due to the nature of the process which is thermal based process, there is opportunity to improve the energy efficiency in the process. By doing that it will lead to sustain the plant operation in terms of economic and environmental aspects (Zaine et al., 2015). It becomes more significant for the case of multicomponent distillation process since it involves more column with different variation of the column sequence (Zhang et al., 2017).
According to Jobson (2014), there are several methods that can be employed as energy saving strategy; 1) conceptual design and process synthesis, 2) monitoring and control (operational), 3) advanced and complex column configuration, 4) evaluation of energy and 5) heat integration. The most common way among the methods is heat integration (Bakar et al., 2017). It is originated from the concept of energy targeting which the method is the arrangement of utilities on-site such as heat exchanger, heater and cooler by manipulating the hot and cold stream, the best possible network can be constructed to save energy (Hohmann, 1971). It can also be called as thermal pinch analysis (Bakar et al., 2016).
In industry, the heat integration is carried-out by manipulating the heat from external source namely latent heat, then the term for it is Total Side Heat Integration (Chew et al., 2013). For a simple distillation column as a single process, the potential for employing thermal pinch analysis could be possibly related to the existence of heat

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source in the column; condenser and reboiler (Linhoff and Hidmarsh, 1982). This has been discussed by Masoumi and Kadkhodaie (2012) whereby the term forward and backward integration has been introduced.
Meanwhile with regards to the application of thermal pinch analysis related to distillation columns sequence, Liebmann et al. (1998) employed the thermal pinch analysis towards crude oil towers and found that, the strategy successfully resulted-in 20 % savings in utility costs. The same trend recorded by another author for the case study of Ethylene Hydration (Pejpichestakul and Siemanond, 2013). They considered both cases of grassroot and retrofit scenarios and managed to achieve 28.3 % and 25.1 % energy saving within the columns and 10.2 % and 16 % energy saving for the entire process. Napredakul et al. (2007) used the same method for the retrofitting process of gas separation plant. The value of 13.32 % energy saving was successfully recorded. Overall, it can be said that thermal pinch analysis has a potential to save energy. However, the examples stated just now are merely the heat integration with the process background. According to Jain et al. (2012), there is an opportunity to integrate heat within the distillation columns sequence without the helps from process background; the same approach that has been demonstrated by Masoumi and Kadkhodaie (2012). Nevertheless, the process of forward and backward integration in the later case study will involve variation in pressure thus leads to another problem to be solved. Furthermore, the case study discussed was only limited to two columns integration and there is a need to access the capability of thermal pinch analysis in terms of distillation columns sequence application. Therefore, this research proposes a method of energy saving by thermal pinch analysis for distillation columns sequence as per suggested by Shahruddin et al. (2017). It can be an initial screening process for early stage process synthesis or process design of a chemical or petrochemical distillation columns which helps in producing the process namely energy integrated distillation columns sequence. Moreover, this paper will also be addressing the different perspective in terms of intercolumn energy integration rather than integration with the background processes as mentioned in the earlier publication.

2. Research method

2.1 Flow of research

The flow of research can be found in Figure 1.

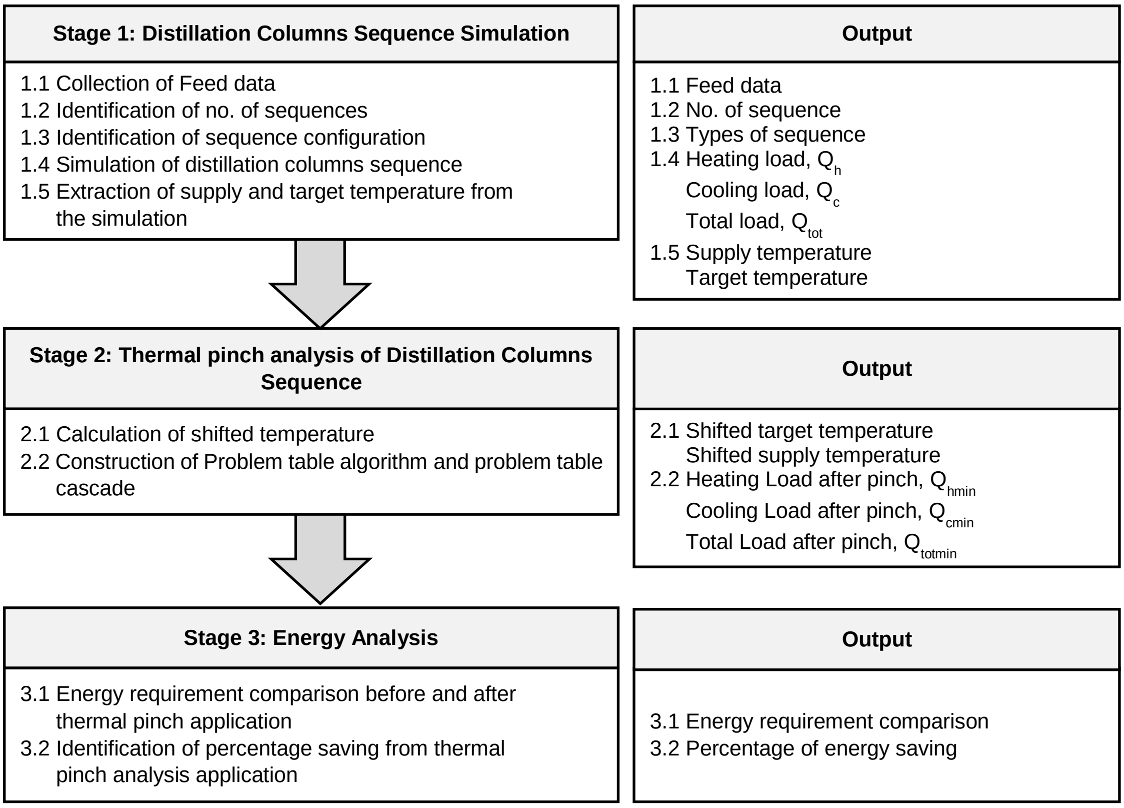

Figure 1: Flow of research

The distillation column simulation has been carried out in stage 1. Based on the selected case study, the feed data is firstly gathered and extracted. Then, the number of different sequences will be determined along with the arrangement of the sequences. Upon that, the simulation for the selected sequence has been carried out using Aspen Hysys V9 (2016). The resulting data from the simulation which comprised of supply and target temperature and heating, cooling and total loads were then extracted for thermal pinch analysis.
Then, the thermal pinch analysis will be carried out in stage 2 via the development of problem table algorithm and problem table cascade. Prior to that, based on the fixed value of ΔT_{min} at 10 °C, the value of shifted temperature for both supply and target temperature were calculated. The output in stage 2 were heating, cooling and total loads after pinch or the minimum energy requirement.
Lastly, the energy obtained from stage 1 and stage 2 were compared and the percentage saving were computed for all possible sequences.

2.2 Case study

The selected case study is the separation of 5-component alcohol mixtures and was adopted from Andrecovich and Westerberg (1985). The feed condition was tabulated and can be found in Table 1.

Table 1: Case study feed condition (Andrecovich and Westerberg, 1985)

Feed Condition			Value
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
Flowrates (kgmole/s)			0.139
Pressure (kPa)			100

The process can be defined as sharp separation process with saturated liquid feed. The external reflux ratio is assumed at 1.1 times minimum reflux ratio. The recovery is 98% for all components.

3. Results and discussion

The simulation of distillation columns for 14 possible sequences have been successfully performed and can be found in Figure 2.

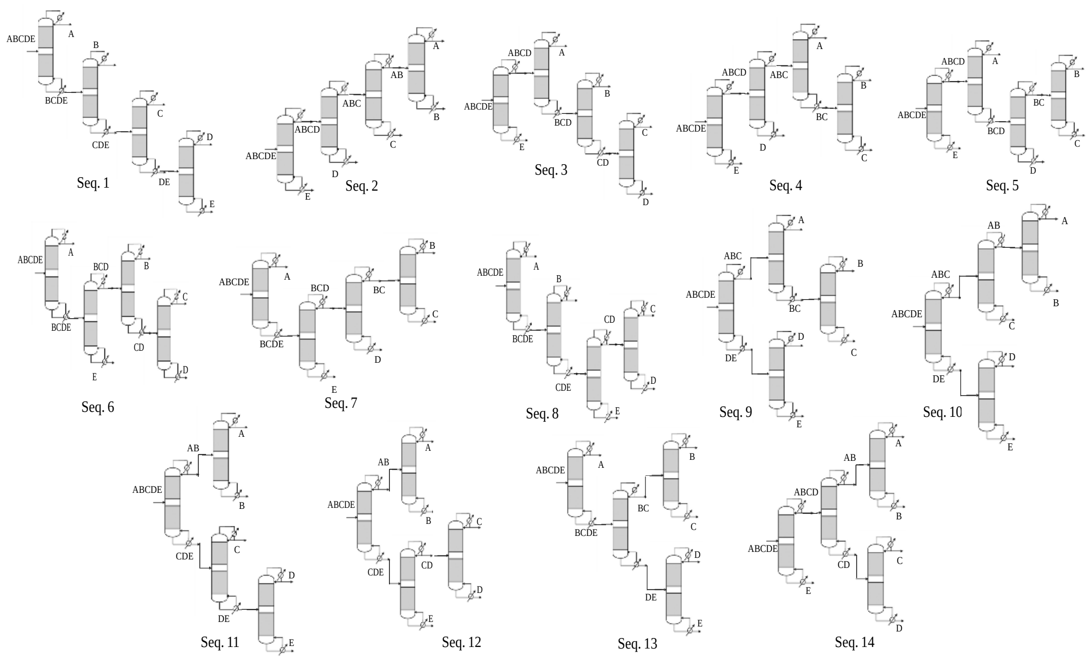

Figure 2: Distillation columns sequences for the case study

Table 2: Data from simulation of Seq. 1

Stream	T_{sup} (℃)	T_{tar} (℃)	ΔH (10^7 kJ/h)	C_p (10^8 kJ/(h.℃))
H1	77.890	77.880	6.53	88.50
C1	93.080	96.920	6.55	0.17
H2	82.100	82.010	1.97	2.04
C2	100.980	102.390	1.98	0.14
H3	96.790	96.730	2.98	5.24
C3	112.290	113.080	2.99	0.38
H4	107.550	107.520	1.56	5.50
C4	117.479	117.484	1.56	32.00

Table 2 is the example of resulting data from the simulation of Seq. 1 distillation columns sequence. H1 to H4 can be defined as hot streams (streams at condensers) and C1 to C4 are the cold streams (streams at reboilers). Based on the information from Table 2, the heating (Q_h), cooling (Q_c) and total (Q_{tot}) loads can be calculated by sum-up the value of enthalpy of interest. For instance, the heating loads obtained is total enthalpy of C1 to C4. So the value of Q_h, Q_c and Q_{tot} is 1.31 x 10^8 kJ/h, 1.30 x 10^8 kJ/h and 2.61 x 10^8 kJ/h .
Next problem table algorithm and problem table cascade were developed as shown in Table 3. Since the value of ΔT_{min} is fixed at 10 ℃, the shifted temperature would be +5 ℃ for cold steams and -5 ℃ for hot streams. The temperature values were then arranged in descending order as shown in the table.

Table 3: Problem table algorithm and problem table cascade for Seq. 1

Temperature (℃)	Interval	ΔT (℃)	ΔC_p (10^8 kJ/(h.℃)	ΔH (10^7 kJ/h)	Cumulative ΔH (10^7 kJ)
122.484			Q_{hmin}		11.50
	1	0.005	-32.00	-1.56	
122.479					9.97
	2	4.401	0	0	
118.080					9.97
	3	0.783	-0.382	-2.99	
117.290					6.98
	4	9.900	0	0	
107.390					6.98
	5	1.416	-0.140	-1.98	
105.980					4.99
	6	3.429	0	0	
102.550					4.99
	7	0.028	5.50	1.56	
102.520					6.55
	8	0.602	0	0	
101.920					6.55
	9	3.840	-0.171	-6.55	
98.080			Pinch Point 1		0
	10	6.287	0	0	
91.790			Pinch Point 2		0
	11	0.057	5.24	2.98	
91.730					2.98
	12	14.629	0	0	
77.100					2.98
	13	0.0965	2.04	1.97	
77.010					4.95
	14	4.120	0	0	
72.890					4.95
	15	0.007	88.50	6.53	
72.880			Q_{cmin}		11.50

From the above table, both values of Q_{hmin} and Q_{cmin} obtained from the analysis for sequence no. 1 is 11.5 x 10^7 kJ/h. Therefore, Q_{totmin} which is the total for both heating and cooling loads would be 23.0 x 10^7 kJ/h. Dual pinch points were recorded for this sequence at 98.080 ℃ (103.080 ℃ for hot stream and 93.080 ℃ for cold stream) and 91.790 ℃ (96.790 ℃ for hot stream and 86.790 ℃ for cold stream). The dual pinch point phenomenon for distillation system is normal and it can also be found in the publication by Kemp (2007). It is largely determined by the value of ΔT_{min} which in this case 10℃. Therefore, there is also an opportunity to investigate the effect of ΔT_{min} value towards the pinch point(s) location that will definitely influence the energy saving in the system.

Lastly, the energy analysis is carried out; the value of energy before and after thermal pinch analysis was compared and the percentage of saving was determined. The results are shown in Table 4 complete with the percentage of energy saving for all possible distillation columns sequences.

Table 4: Energy analysis of distillation columns sequences

Sequence no.	Heating Loads (10^8 kJ/h)		Saving (%)	Cooling Loads (10^8 kJ/h)		Saving (%)	Total Loads (10^8 kJ/h)		Saving (%)
	Q_h	Q_{hmin}		Q_c	Q_{cmin}		Q_{tot}	Q_{totmin}	
Seq. 1	1.31	1.15	11.89	1.30	1.15	11.94	2.61	2.30	11.92
Seq. 2	1.58	1.55	1.46	1.57	1.55	1.47	3.15	3.10	1.47
Seq. 3	1.53	1.53	0	1.52	1.52	0	3.05	3.05	0
Seq. 4	1.54	1.54	0	1.54	1.54	0	3.08	3.08	0
Seq. 5	1.55	1.55	0	1.55	1.55	0	3.10	3.10	0
Seq. 6	1.40	1.40	0	1.40	1.40	0	2.80	2.80	0
Seq. 7	1.43	1.43	0	1.43	1.43	0	2.86	2.86	0
Seq. 8	1.40	1.40	0	1.40	1.40	0	2.80	2.80	0
Seq. 9	1.36	1.20	11.44	1.36	1.20	11.48	2.72	2.40	11.46
Seq. 10	1.44	1.28	10.82	1.43	1.28	10.86	2.87	2.56	10.84
Seq. 11	1.29	0.84	35.08	1.29	0.83	35.23	2.58	1.67	35.15
Seq. 12	1.39	0.84	39.52	1.38	0.83	39.67	2.77	1.67	39.60
Seq. 13	1.30	1.14	11.99	1.30	1.14	12.03	2.59	2.28	12.01
Seq. 14	1.48	1.18	20.23	1.48	1.18	20.30	2.96	2.36	20.26

Based on Table 4, the thermal pinch analysis has successfully enhanced the energy saving for most of the sequences. By also referring and relating it to Figure 2, it can be observed that, for this case study, the sequence without split columns recorded zero saving except for direct sequence and indirect sequence (Seq. 1 and Seq. 2). From there, it can be confirmed that the arrangement of the sequence will affect the ability of the process to be integrated. By arranging the columns sequence, it may create the exchangeable heats thus leads to the energy saving within the columns (Mustafa et al., 2014). The same theory can be applied to the sequence without energy saving whereby the pinch point separates the flow of energy between hot and cold streams in such a way that there is no heat can be exchanged between those two utilities. Therefore, there is a need to assess the sequence with the lowest energy before thermal pinch analysis can be employed by the process. Nevertheless, it should also be noted that ΔT_{min} still playing an essential role along the process.
Another interesting point to emphasize in this research is the role of thermal pinch analysis in the system. It can be seen for Seq. 11, 12 and 13. The value of Q_h (before pinch) for Seq. 11 is the smallest among those sequences and even Seq. 13 recorded much lower energy consumption compared to Seq. 12. However, when the thermal pinch analysis is applied, Seq. 12 resulted-in better performance with almost 40% energy saving for all loads despite of having the same energy value with Seq. 11. Therefore, it can be a very good example to demonstrate that the thermal pinch analysis has a capability to further save the energy saving in the case of distillation columns sequence. Therefore, it has a good potential to be applied in any other case studies of distillation columns sequence especially for the multicomponent and complex cases with higher energy consumption.

4. Conclusion

The thermal pinch analysis has been employed for potential energy saving of distillation columns sequence. The 5-component alcohol mixture has been selected as the case study for this paper. There are 14 different sequences that have been successfully simulated in Aspen Hysys V9. The data obtained from the simulation have been extracted. Next thermal pinch analysis has been carried out via the development of problem table algorithm and problem table cascade to determine the minimum energy requirement (MER) based on the perspectives of thermal pinch approach with fix value of ΔT_{min} at 10℃. The results from base case and thermal pinch analysis were then analyzed and the percentage of saving for each sequence were then calculated. From the results, it is clear that the application of thermal pinch analysis has successfully enhanced energy saving in the distillation columns sequence which indicated clearly by the example from seq 11, 12 and 13. However, due to the arrangement of the columns within the sequences, several sequences with non-split columns resulted in zero energy saving. The highest saving recorded for the selected case study is Seq. 12 with 39.52 %, 39.67 % and 39.60 % saving for heating, cooling and total loads. Further investigation should be done to assess the effect of ΔT_{min} towards the energy saving of distillation columns sequence especially for the sequence with zero saving and also to assess its effect towards pinch point(s) location in the system. Furthermore, the conceptual process synthesis (CPS) methods such as algorithms, driving force and sequential design method (SDM) can also be applied to ensure the distillation columns sequence with the lowest energy consumption could be produced prior to thermal pinch analysis application. For the purpose of verifying the extend of the proposed method, it can also be applied to other multicomponent and complex case studies which involve more than 5 components and higher energy consumption for potential energy saving in the system.

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