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Process Heat Integration between Distillation Columns for Ethylene Hydration Process

Warumporn Pejpichestakul[a], Kitipat Siemanond[a,b,]*

[a]The Petroleum and Petrochemical College, Chulalongkorn University, Chulalongkorn Soi 12, Phayathai Rd., Pathumwan, Bangkok 10330, Thailand
[b]National Center of Excellence for Petroleum, Petrochemicals and Advanced Materials, Chulalongkorn Soi 12, Phayathai Rd., Pathumwan, Bangkok 10330, Thailand
kitipat.s@chula.ac.th

Distillation is a separation technique widely used in the chemical industry and highly energy consuming. The trends of energy price are rising continuously due to the limitation of energy supply and the increase of its demands. There are many ways to improve energy efficiency. Columns targeting is one of them by applying pinch technology for improving distillation columns of the existing process to reduce the energy consumption and the operating cost. By column targeting, columns can be modified by changing reflux ratio, preheating feed, or adding side reboilers and/or side condensers. The use of Column Grand Composite Curve (CGCC) shows the scope of each modification. The results from column targeting can be integrated with the background process by heat exchanger network (HEN) using mathematical programming to help reduce energy usage. The case study of the ethanol production by ethylene hydration is simulated for this study, containing three distillation columns. Process heat integration by using graphical method of column targeting and mathematical programming is applied. The HEN design with maximum net present value (NPV) is selected as the best design.

1. Introduction

Distillation is an energy-intensive separation process widely used in many industries. This highly energy consuming unit shows opportunities for energy saving. Column targeting or Column Pinch Analysis, proposed by Dhole and Linnhoff (1993), is one of Process Heat Integration approaches applying Pinch Analysis. It is a distillation column analyzing tool for identifying energy saving potential and appropriate column modifications. Column Grand Composite Curve (CGCC), constructed at practical near minimum thermodynamics condition (PNMTC), is used as a tool to show scope for modifying columns. Not only for column modification purpose, but CGCC also illustrates possibilities for column integration and/or process integration by HEN. Graphical approach for heat integration helps identify scope of energy efficiency improvement while mathematical programming helps design HEN. Mathematical programming using GAMS software formulates HEN between background process streams and columns. As previous research, Napredakul et al. (2007) applied Pinch Analysis on column targeting and Process Heat Integration techniques to gas separation plant for recovering heat in the process. This work shows the benefit of process heat integration by using graphical method of column targeting, and mathematical programming on the case study of ethanol production by ethylene hydration has three distillation columns. NPV is a considerable economic analysis parameter, used to compare among alternative HEN designs.

2. Methodology

2.1 Simulating base-case process of ethylene hydration processes for ethanol production

Base-case process is simulated by Pro/II simulator with recycle of unreacted reactants. Enthalpy, supply and target temperatures of process hot and cold streams are extracted. Tray temperature, vapour and

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liquid molar flow rate, vapour and liquid enthalpy, condenser duty, and reboiler duty of each tray are extracted from three distillation columns.

2.2 Generating Column Grand Composite Curve (CGCC) and column modifications

CGCC is temperature and enthalpy (T-H) or stage and enthalpy profiles. Enthalpy values for constructing CGCC can be calculated top-down and/or bottom-up procedures from extracted data. It shows scope for columns improvement.

2.3 Performing Process heat integration

Column integration and process integration is done by first using CGCC for seeking integration possibilities and formulating HEN. HEN is designed by using GAMS software with mixed integer linear programming (MILP) model using the n-stage model of Zamora and Grossmann (1996) at various heat recovery approach temperature (HRAT). The most profitable HRAT of each design is selected.

2.4 Performing design validation and cost calculation

Results from HEN formulation are validated by PRO/II simulator for performing actual energy consumption and heat exchanger area. After validation by simulator, cost of each design is calculated to achieve the most profitable design.

3. Case study

Ethylene hydration process, as shown in Figure 1, is for producing azeotropic ethanol solution from feed with impurities of excess ethylene from other processes. Ethylene reacts with steam at 570 K isothermally, yielding ethanol and by-products. Distillation is used for purifying ethanol from unreacted reactants, impurities, and by-products. The process is simulated by Pro/II with recycle of reactants. The remaining step for this conceptual design is to improve energy efficiency of process by heat integration. The existing columns and process streams data are shown in Table 1 and 2. Cost of heat exchanger is shown in Eq(1). The project lifetime is 5 y with annual interest rate of 15 %. Process operates for 350 d/y. The overall heat transfer coefficient is assumed constantly at 0.5 kW/K for all exchangers. Cost and properties of utilities are shown in Table 3. HU1 is used to heat a cold stream J1 only while HU2 is used to heat reboilers. CU1 is used to cool the condenser of column 2 only while other condensers and hot streams use CU2 as cold utility. The existing process has no Heat Integration.

$$\text{Exchanger (\$)} = 26{,}440 + [418.79 \times \text{Area (m}^2\text{)}] \quad (1)$$

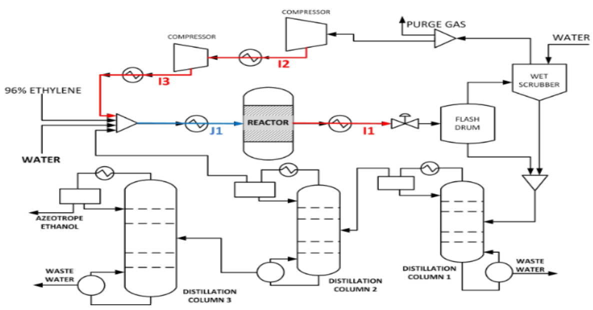


Figure 1: Ethanol production by ethylene hydration process

Table 1: Existing columns specifications

Specification	Column 1	Column 2	Column 3
Number of stages	7	8	28
Feed stage	4	4	22
Condenser duty (kW)	5,316.97	7,693.59	17,297.93
Reboiler duty (kW)	21,084.55	1,115.03	16,476.57

Table 2: Process streams properties

Stream	FCp, (kW/ K)	Tin, (K)	Tout, (K)
I1	235.28	570	330.34
I2	65.68	411.13	350
I3	74.47	434.55	360
J1	284.78	372	570

Table 3: Cost and properties of utilities

Utility	Supply Temp. (K)	Target Temp. (K)	Cost ($/kW)	Type
HU1	623.15	603.15	446	Heating
HU2	485	485	373	Heating
CU1	280.15	285.15	160	Cooling
CU2	298	303	15.9	Cooling

4. Results and discussion

CGCCs of three existing columns are generated by calculating enthalpy and temperature at each stage as shown in Figure 2. Gaps between pinch point and vertical axis of CGCCs of column 2 and column 3 show scope for energy saving by reducing reflux. After reducing reflux, CGCCs of column 2 and column 3 are shown in Figure 3. CGCC of column 1; as shown in Figure 2 has no scope for energy saving by reflux reduction. Specifications of reduced-reflux columns are shown in Table 4.

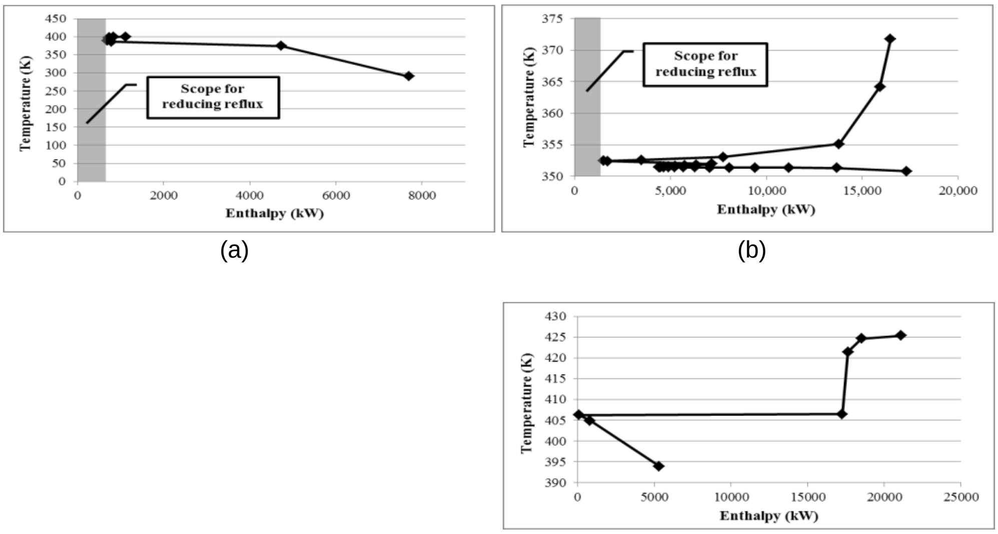


Figure 2: CGCCs of base case column 2 (a), column 3 (b), and column 1(c)

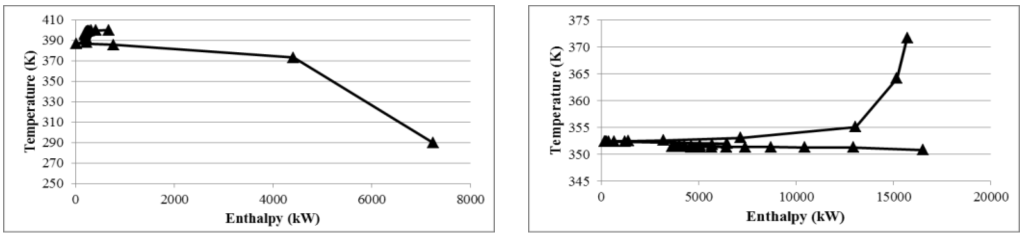


Figure 3: CGCCs of reduced reflux column 2 (a), and column 3 (b)

Table 4: Column specifications after reducing reflux

Specification	Column 2	Column 3
Number of stages	16	36
Feed stage	5	24
Condenser duty (kW)	7,244.97	16,539.72
Reboiler duty (kW)	666.81	15,718.31
Capital cost ($)	735,837	1,076,527

Process heat integration can be done by four main options; column integration, HEN design for background process (process without columns), HEN design between background process and individual columns, and HEN design between background process and columns modified by column integration.

Column integration between column 1, column 2 with reduced reflux and column 3 with reduced reflux in Figure 4a shows the energy saving scope for adding pumparound (like side condenser) to column 2 for recovering heat for reboiler of column 3. Heat integration between background process streams and column 3 with reduced reflux shows the energy-saving scope for adding side reboiler of column 3 as shown in Figure 4b. HEN design between background process streams and columns are divided into two categories. The first category is to design HEN of background process and columns without side exchanger on both existing columns and columns with reduced reflux. The second category is to design

HEN of background process and columns with reduced reflux and side exchangers as various design options. Results of column integration are shown Figure 5a-5c. HEN design of background process is shown in Figure 5d. Cost of each column integration design, shown in Table 5, indicates that integration of columns with reduced reflux and pumparound of column 2 provides the highest NPV, using graphical method of column targeting. Cost of HENs between background process and column integration, shown in Table 6, indicates that HEN of background process using mathematical programming helps reduce heating utility consumption of stream J1. HEN of background process and columns without side exchangers are shown in Figure 6. Utility consumption and cost of them are displayed in Table 7. HEN designs between background process streams and columns with side exchangers are shown in Figure 7. Utility consumption and cost of them are displayed in Table 8. HEN between background process and columns with reduced reflux and side exchanger, using graphical and mathematical programming approaches, provides the highest NPV.

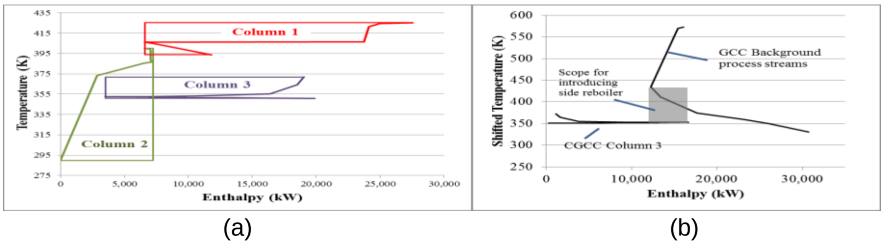


Figure 4: CGCCs of column 2 with reduced reflux (a), and column 3 with reduced reflux (b)

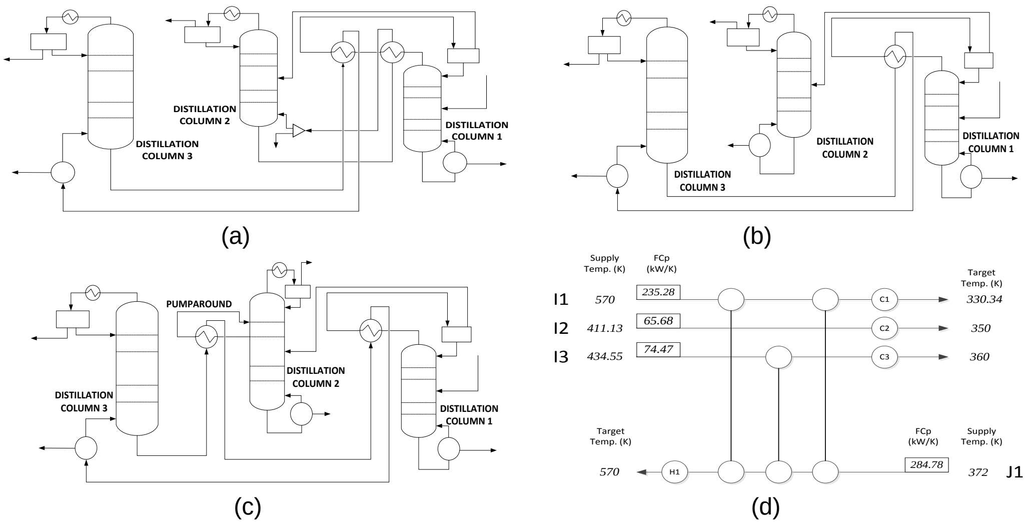


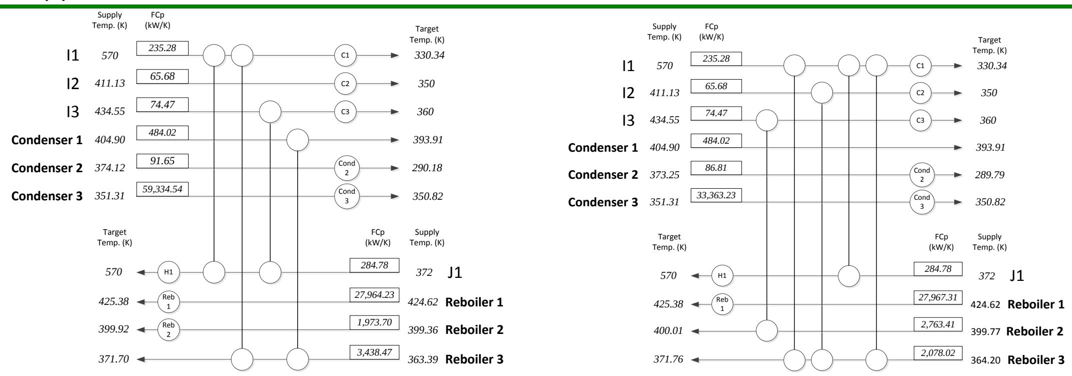
Figure 5: Column integration of (a) existing columns, (b) columns with reduced reflux, (c) columns with reduced reflux and pumparound from column 2 , and (d) HEN of background process

Table 5: Cost comparison between column integration designs

	Column without modification	Columns with reduced reflux	Columns with reduced reflux and pumparound of column 2
Total condenser utility consumption (kW)	25,097.75	23,685.73	20,540.97
Total reboiler utility consumption (kW)	33,465.40	32,055.52	28,914.63
Capital cost ($)	1,010,088	2,448,154	3,134,891
Operating cost ($/y)	13,990,297	13,377,304	11,697,032
Saving ($/y)	2,067,768	7,347,725	9,027,997
NPV ($)	5,921,392	22,182,559	27,128,353

Table 6: Cost of HEN of background process, and HEN of background process with modified columns

	HEN of background process	HEN of background process and column integration		
		Existing columns	Columns with reduced reflux	Columns with reduced reflux and pumparound of column 2
Total cooling utility consumption (kW)	48,961.47	43,750.72	42,338.70	39,193.94
Total heating utility consumption (kW)	42,674.53	37,463.79	36,053.90	32,913.01
Capital cost ($)	2,749,006	3,759,094	5,197,159	5,883,897
Operating cost ($/y)	2,079,860	16,070,158	15,457,164	13,776,892
Saving ($/y)	24,117,174	26,144,141	26,757,135	28,437,407
NPV ($)	78,095,502	83,880,123	84,496,907	89,442,701



(a) (b)

Figure 6: HEN of background process with (a) existing columns, and (b) columns with reduced reflux

Table 7: Cost comparison of HEN of background process and columns without side exchangers

	HEN of background process and existing columns	HEN of background process and columns with reduced reflux
Total cooling utility cons. (kW)	43,587.57	37,073.60
Total heating utility cons. (kW)	33,687.94	28,233.00
Capital cost ($)	2,948,909	2,790,067
Operating cost ($/y)	15,205,950	12,686,099
Saving ($/y)	27,008,348	29,311,885
NPV ($)	88,011,575	95,467,916

Table 8: Cost comparison of HEN of background process and columns with reduced reflux and side exchangers

	HEN of background process and column with reduced reflux		
	and pumparound to column 2 only	and side condenser to column 3 only	and pumparound from column 2 and side-exchanger from column 3
Total cooling utility consumption (kW)	33,913.33	33,481.82	33,826.29
Total heating utility con. (kW)	27,697.81	27,169.28	27,513.83
Capital cost ($)	4,896,568	4,879,540	5,047,531
Operating cost ($/y)	11,938,383	12,093,716	11,805,049
Saving ($/y)	30,275,916	30,120,583	30,409,250
NPV ($)	96,592,999	96,089,326	96,888,991

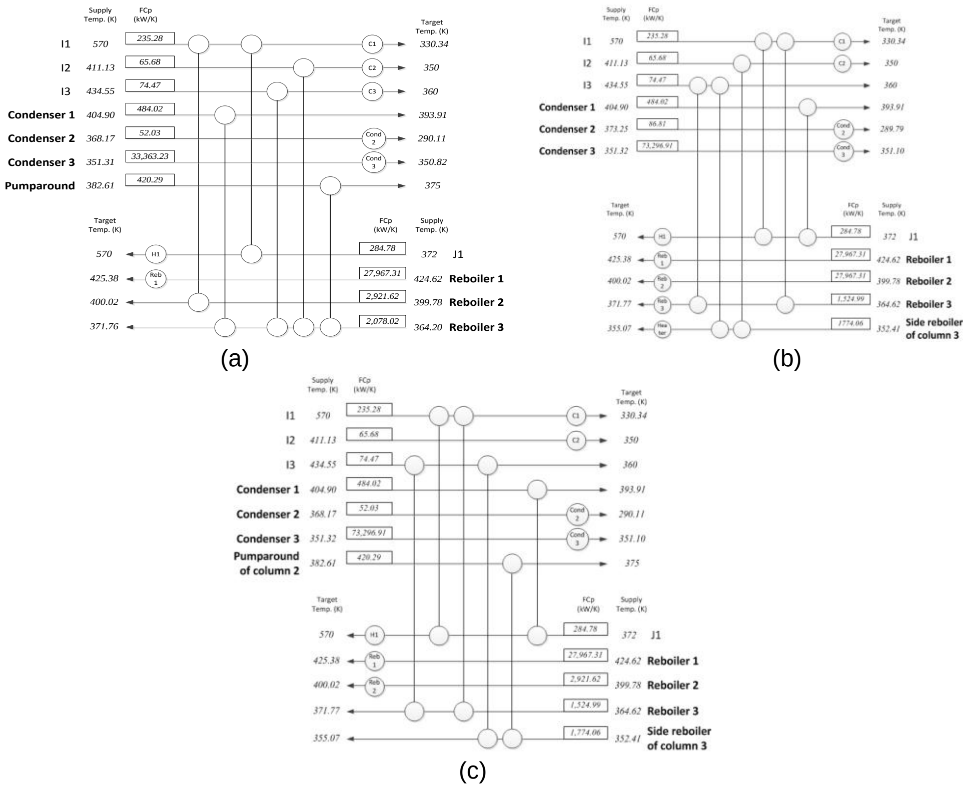


Figure 7: HEN of background process and columns with reduced reflux and; (a) pumparound from column 2, (b) side condenser from column 3, and (c) side exchangers to column 2 and column 3

5. Conclusion

Column targeting using CGCC with first reducing reflux of column 2 and column 3 can save energy consumption of 3.5 % from existing columns and 1.6 % from entire processes. From CGCC of column integration, the most economical design of column integration is the integration of columns with reduced reflux and pumparound from column 2 which saves energy up to 28.3 % from existing columns and 10.2 % from entire processes. Grassroots HEN design of background process can save energy up to 25.1 % from background process and 16 % from entire processes. HEN of background process and integration of columns with reduced reflux and pumparound of column 2 provides energy saving of 62.3 % from entire processes. From T-H diagram, HEN of background process and columns with reduced reflux and pumparound to column 2, and side condenser to column 3, provide the highest return of NPV about $96,888,991 with energy saving of 67.9 % from entire process without Heat Integration. This study shows that the graphical method and mathematical programming provide high energy saving potential by HEN design for process containing distillation columns.

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