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Energy Procedia 142 (2017) 2630–2635

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Systematic design of energy efficient distillation column for alcohol mixture

Muhammad Afiq Zubir[a], Ahmad Nafais Rahimi[a], Muhammad Fakhrul Islam Zahran[a], Munawar Zaman Shahruddin[a], Kamarul Asri Ibrahim[a,b,] Mohd Kamaruddin Abd Hamid[a,b,]*

[a]*Process Systems Engineering Centre (PROSPECT), Research Institue for Sustainable Environment (RISE), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.*

[b]*Department of Chemical Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.*

Abstract

When designing a separation system for mixtures containing close boiling point components, ordinary distillation can be considered not feasible since high purity products require large number of stages and reflux ratio. During the design phase of distillation processes, several problems may occur such as determination of optimal number of plates, optimal location for feed, and optimal reflux ratio. The main objective of this paper is to propose a methodology to design an energy efficient alcohol distillation process using driving force approach. The design concept is to design the distillation column system at maximum driving force. At maximum driving force, the energy required for the system will be minimum. A case study of 5 component alcohol mixture from a literature was selected and investigated. Initially, the literature case study was analysed and simulated by using Aspen HYSYS V9's shortcut design method to determine the energy usage and capital cost. Then, similar feed information from the shortcut design was used for a new design which was developed according to the driving force approach in the methodology. Optimum design variables were determined from the methodology. Both designs were simulated using similar thermodynamic model (RK-Aspen) to ensure reliable data for comparison purposes. Finally, both designs were analysed and compared in terms of capital and operating cost. Based on the findings, the capital cost was reduced up to 12.25 % and operation cost up to 9.39 %. The performance confirms that by using this methodology, optimum or near optimum design for alcohol distillation process can be developed in an easy, practical, and systematic manner.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

* Corresponding author. Mohd Kamaruddin Abd Hamid
E-mail address: kamaruddinhamid@utm.my

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10.1016/j.egypro.2017.12.203

Keywords: Alcohol mixture; Extractive distillation; Driving force design method; Shortcut design method; Economic analysis ;

1. Introduction

Previously, the most common design method used to design a distillation column system is the shortcut design method. One of the popular shortcut methods is a combination of Fenske-Underwood-Gilliland equations to determine the design variables of the distillation system. By using shortcut method, the reflux ratio, number of stages, and feed location can be determined easily by setting the desired product's purity. However, the shortcut method is limited only to ordinary distillation columns. Separation of close boiling components usually require a very high number of stages and a huge reflux ratio. Since capital cost and operating cost of the column are directly affected by those variables, increasing the variables will cause an increase in overall cost. Fig. 1 illustrates the overall flowsheet obtained through shortcut design method for the alcohol system.

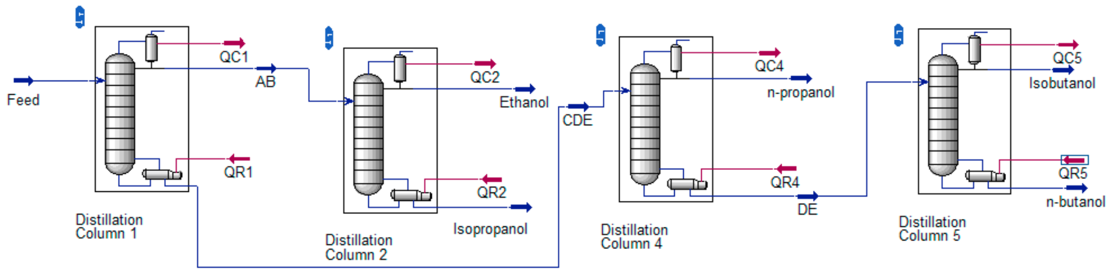

Fig. 1: Flowsheet of shortcut method for alcohol system.

The driving force design method is a graphical method which utilizes a diagram developed by Gani and Bek-pedersen (2000) [1] to obtain design variables required by a distillation column. The method has flourished from year to year and has interested many researchers. By using the driving force diagram, design variables such as optimal reflux ratio, minimum number of stages, and feed stage can be obtained by setting the purity of product specification only. Based on previous works by Mustafa (2015) [2], Rahimi (2016) [3] and Zaine (2015) [4], it also proven that sequence for separation of multicomponent mixture which operate at minimum energy can be determined easily from the diagram.

The aim of this work is to propose a driving force design to obtain optimal design variables for alcohol distillation processes with five alcohol components as case study. Most of the design variables were obtained through very simple calculations. The design developed takes both capital and operating cost into consideration.

Nomenclature

X_D	mole fraction of light product in the distillate
X_B	mole fraction of light product in the bottom
D_X	x-axis point at maximum driving force
D_Y	y-axis point at maximum driving force

2. Design Configuration

An alcohol mixture consists of five different components as shown in Table 1 was taken from Westerberg and Andrecovich (1985) [5] as case study for this work. In this work, the separation system was designed using the methodology shown in Fig. 2. By using the methodology, ordinary and extractive distillation can be designed and the important variables can be obtained in an easy and systematic manner. Initially, the separation was designed using the shortcut design method. Feed mixture flowed at 0.139 kmol / s with operating pressure of all columns at 100 kPa. All work was developed using Aspen HYSYS Simulator V9. Thermodynamic model of RK-Aspen was imported from the aspen properties to be used in Aspen HYSYS. According to Aspen Physical Properties System (2007) [6], basic equations of state such as Peng Robinson and Soave Redlich Kwong should not be used for moderate to highly non-ideal mixture. Most of close boiling point mixtures usually do not behave ideally. Since there is a very close boiling point separation between ethanol and isopropanol, proper thermodynamic model selection is crucial to ensure reliable simulation results. In addition, the manual stated that RK-Aspen thermodynamic model is capable of handling polar components such as alcohols [6]. The design obtained from the shortcut method was used as a base design for comparison purposes.

Table 1: Feed information of alcohol system

Component	Feed molar composition	Boiling point (K)
Ethanol	0.25	351.4
Isopropanol	0.15	355.4
n-propanol	0.35	370.3
Isobutanol	0.10	381.0
n-butanol	0.15	390.9

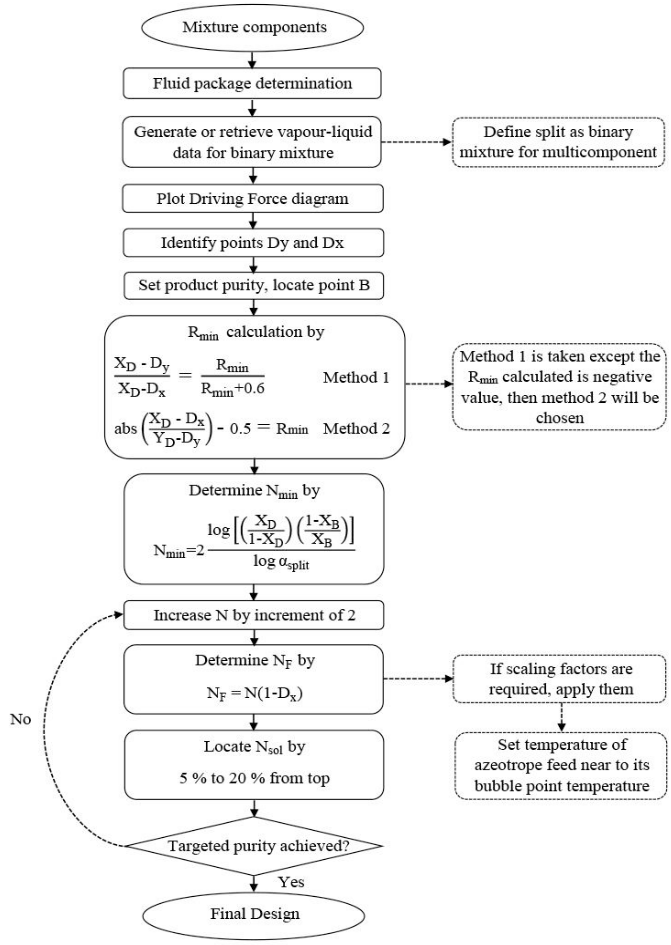

Fig. 2: Methodology of energy efficient extractive distillation driving force design

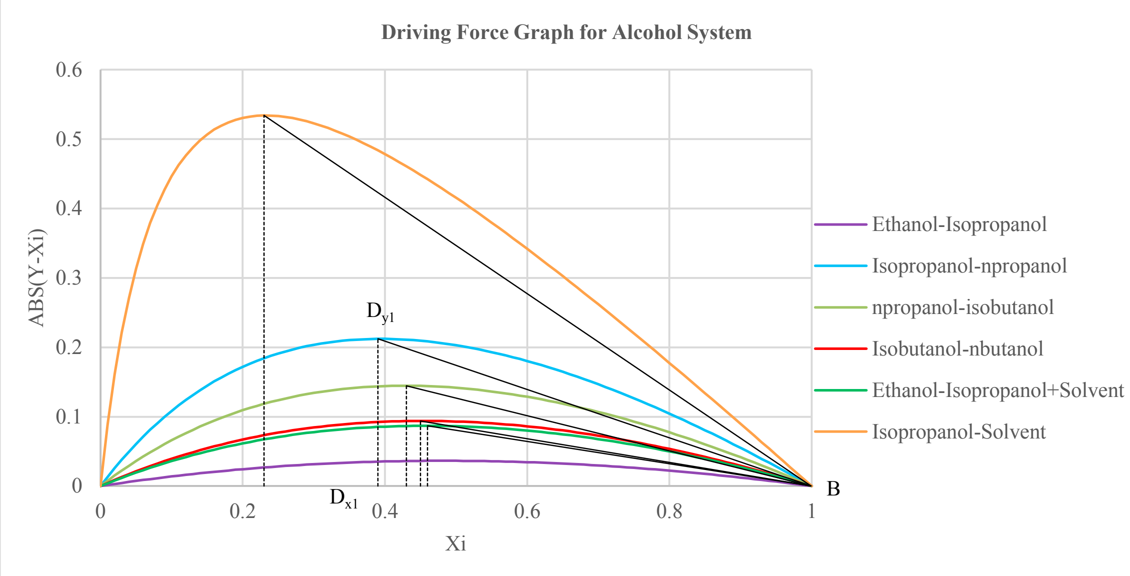

Fig. 3: Driving force diagram for alcohol system.

In this work, driving force design method was used to develop the optimum design for an alcohol separation system. For a multicomponent mixture, the components were arranged according to their boiling points. Then, splits were defined as binary mixtures. Maximum driving force point for each split was located and the desired purity for each product was set. Then, point B was located from the driving force diagram according to the specified light product purity for each split. From the driving force diagram in Fig. 3, optimal design variables for the alcohol system were determined easily. Minimum reflux ratios were calculated using method 2 from the methodology in Fig. 2. The optimal reflux ratio for each column operation was set at 1.2Rmin while 1.5Rmin for recovery column. In this work, methyl caproate with a flow rate ratio 1:1 to ethanol-isopropanol separation was selected as a solvent to alter the volatility of the mixture based on a patent by Berg (1995) [7]. Minimum number of stages for both columns was calculated as shown in the methodology. The feed location was determined and the location was adjusted based on the scaling factor on Mansouri et al.'s (2000) work [8]. Aspen HYSYS simulator was used for next purposes to determine the actual number of stages. The driving force design was simulated using the same thermodynamic model and simulator with the shortcut design to obtain reliable data and results for comparison purposes. The design variables obtained by using this methodology was shown in Table 2.

Table 2: Design variables by Shortcut method and design obtained in this studies

Operating Variable	Shortcut Design Method			Driving Force Design Method		
	Number of Stages	Feed Location	Reflux Ratio	Number of Stages	Feed Location	Reflux Ratio
Distillation Column 1	48	27	2.720	43	22	2.844
Distillation Column 2	217	97	14.000	110	5 (Solvent) 64	6.842
Distillation Column 3	-	-	-	10	7	1.410
Distillation Column 4	79	33	3.868	66	35	4.118
Distillation Column 5	86	47	7.628	116	53	6.412

Based on the operating variables shown in Table 2, there are significant differences in the number of stages between both design methods. According to the driving force design method, it was proposed to use extractive distillation column for ethanol-isopropanol separation due to its high number of stages requirement. High number of stages might be infeasible especially due to safety and economic concerns. Hence, by using an extractive column distillation, the number of stages obtained from the shortcut method was reduced significantly from 217 stages to 110 stages for extractive and 10 stages only for recovery column. Most of other distillation columns' stages were reduced when driving force design was used except for distillation column 5. This is because the reflux ratio obtained for this column by driving force design method is much lower than the reflux ratio from shortcut design method.

Product purities obtained from both designs are displayed in Table 3. Based on the results, the purity achieved from driving force design method is much higher than the purity from shortcut design method. Even though shortcut design method has a higher total number of stages, designs according to the driving force method proved that by using this method, purity of desired product can be improved while reducing the distillation column's number of stages.

Table 3: Purity of product comparison for ethanol dehydration technologies

Process Type	Purity (mol %)					
	Ethanol	Isopropanol	n-propanol	Isobutanol	n-butanol	Solvent
Shortcut Design Method	96.8	94.5	99.5	98.6	99.9	-
Process Studied (Driving Force Design)	99.9	99.7	99.6	98.5	99.5	99.9

3. Economic Analysis

Previous studies on alcohol distillation systems only focussed on the sequence of the distillation columns. Hence, the aim of this study is to design an optimum alcohol distillation process which takes into account both operation and capital cost. In order to estimate the operating cost of the process, the amount of energy and utilities to be used by both columns were identified. Overall energy usages consumed by both shortcut design method and the current study are displayed in Table 4. Based on the findings, by using driving force design method, energy usage can be reduced especially for the close boiling point separation process. Separation of ethanol-isopropanol requires a huge amount of energy and number of stages if designed according to the shortcut design method. One of the disadvantages of shortcut design method is the method is limited only to ordinary distillation column designs. Hence, shortcut design method cannot be used for complex distillation based separation processes.

The operating cost was calculated using the utility prices in Yu and Chien's (2016) works [9]. In order to calculate the operating cost, suitable utilities were selected from Table 5 based on the operating temperature of condenser and reboiler of the column. Then, the operating condition per year was estimated by assuming that the plant operates 24 hours per day and 330 days per year. For capital cost, Aspen Economic Analyser was used. Overall operating and capital cost of the designs are shown in Table 6. Based on the results, by using driving force design, capital and operating costs can be reduced up to 12.25 % and 9.39 % respectively.

Table 4: Energy comparison between Shortcut design method and Driving force design method

	Shortcut Design Method	Driving Force Design Method
Condenser Energy 1, GJ/hr	29.570	30.549
Condenser Energy 2, GJ/hr	75.082	39.289
Condenser Energy 3, GJ/hr	-	7.1286
Condenser Energy 4, GJ/hr	34.819	36.608
Condenser Energy 5, GJ/hr	17.347	14.930
Reboiler Energy 1, GJ/hr	29.855	30.834
Reboiler Energy 2, GJ/hr	75.166	46.006
Reboiler Energy 3, GJ/hr	-	11.535
Reboiler Energy 4, GJ/hr	34.902	36.698
Reboiler Energy 5, GJ/hr	17.359	14.939
Total Energy, GJ/hr	314.100	268.517

Table 5: Utilities price used in this work [9]

Utility	Price [USD/GJ]	T_{in} [°C]	T_{out} [°C]	Assumed minimum T-difference
LP steam	7.78	160	160	10
HP steam	9.88	254	254	10
Cooling water	0.354	35	45	-

Table 6: Capital and operating cost comparison

	Shortcut Design Method	Driving Force Design Method
Capital Cost, USD	15,565,200	13,658,200
Operating Cost, USD/ yr	10,131,008.21	9,179,310.19
Capital Saving, %	12.25%	
Operating Saving, %	9.39%	

4. Conclusion

In this work, a methodology for energy efficient distillation process design for alcohol system was proposed. A case study of five component alcohol mixture from past literature was selected and simulated via Aspen HYSYS simulator. The proposed methodology required less effort and is easier to be applied at earlier design phases. The economic analysis was carried out to compare the design obtained from this methodology and past works. Based on the findings, by using driving force design, up to 12.25 % capital cost and 9.39 % operation cost can be saved. Purity of product obtained from driving force design method is also higher compared to the purity from shortcut design method. The aim of this work is to highlight the use of the methodology for design purposes. The energy usage can be further reduced in the future with identification of a new solvent which is more efficient for the alcohol system with proposed driving force design method.

Acknowledgements

The financial support from Universiti Teknologi Malaysia (RUGS Tier 1 Q.J130000.2546.12H67) and (RUGS Flagship Q.J130000.2446.03G68) are highly acknowledged.

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