SUSTAINABILITY ANALYSIS AND RETROFITTING OF ENERGY EFFICIENT DISTILLATION COLUMNS SEQUENCE

MUHAMMAD ZAKWAN BIN ZAINE

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Chemical and Energy Engineering
Universiti Teknologi Malaysia

NOVEMBER 2016

untuk emak dan nenek yang tersayang,
*arwah abah, arwah nenek serta arwah nyaie yang berada di **SANA**,*
tidak di lupakan juga buat abang-abang dan kakak-kakak ipar
serta yang tersayang.....

ACKNOWLEDGEMENTS

In the name of Allah the Almighty, the most gracious and merciful, with His gracing and blessing. With the prayer to Prophet Muhammad PBUH, has led to success be upon this thesis. All the hard times had been paid off after seeing this thesis project is ended.

Firstly, I would like to express my sincere thanks to Dr. Mohd Kamaruddin Abd. Hamid and Prof. Dr. Kamarul ‘Asri Ibrahim for their supervision, patience and guidance in this study. Thank you so much also to both my supervisors, giving constructive criticism so that I can improve the study with successfully. Thank you to all my postgraduate friends who helped me significantly especially my research team. They have definitely helped ease the path towards completing my thesis.

My sincere appreciations extend to my beloved mom and family who always support me and give motivation. Their advices always accompany me while finishing this research. Thanks to mom since always pray for my health and this successfully study. Same with all my brothers who always support me and give helps when I am needed.

Without the help of everyone mentioned above, the completion and success of my study would deem impossible. Unfortunately, it is not possible to list all them in this limited space. I would also like to recognize my fellow friends for their support and also motivation. Their help and kindness are valuable indeed.

ABSTRACT

Distillation continues to be the most important separation technique in the chemical process industry. Recently, a new energy efficient distillation columns sequence methodology that is able to improve the energy efficiency of the existing separation systems without having major modifications has been developed. However, the developed methodology only considered the energy savings without taking into consideration the sustainability criteria. Therefore, the aim of this study was to extend the energy efficient distillation column sequence methodology by taking into account the sustainability analysis as well as the retrofitting analysis in designing sustainable sequence for distillation columns system in an easier, efficient, and systematic way. Accordingly, the methodology was divided into four hierarchical stages. The analysis of energy consumption in distillation columns sequences was simulated within Aspen HYSYS simulation environment while the sustainability index was analysed using a developed Excel-based sustainability evaluator. The capability of the proposed methodology in designing sustainable and retrofit energy efficient distillation columns sequence was tested using Aromatic Mixtures (AM) separation process, Hydrocarbon Mixtures (HM) separation process, and Natural Gas Liquids (NGLs) separation process. The results obtained shown that the proposed methodology is able to reduce energy consumption to 12 % as well as 13 % reduction in overall sustainability index for the AM separation process. Besides that, 38 % of energy reduction and 32 % of the overall sustainability index reduction was achieved in overall for HM case studies. Furthermore, overall NGLs case study shows a reduction in energy consumption up to 21 % as well as 22 % of overall sustainability index. Thus, the developed methodology is capable of operating the separation process with less energy requirement and also gives better sustainability performance in an easy, practical, and systematic manner.

ABSTRAK

Penyulingan terus menjadi teknik pemisahan yang paling penting dalam industri proses kimia. Baru-baru ini, metodologi baru ruangan penyulingan cekap tenaga yang berkesan serta mampu meningkatkan kecekapan tenaga sistem pemisahan yang sedia ada tanpa pengubahsuaian utama telah dibangunkan. Walau bagaimanapun, kaedah yang dibangunkan ini hanya mengambil kira penjimatan tenaga tanpa mengambil kira kriteria kemampanan. Oleh itu, tujuan kajian ini adalah untuk melanjutkan kaedah urutan ruangan penyulingan yang cekap tenaga dengan mengambil kira analisis kelestarian serta analisis penyesuaian semula dalam mereka bentuk urutan pemisahan yang mampan bagi sistem ruangan penyulingan dengan cara yang lebih mudah, cekap dan sistematik. Sehubungan dengan itu, kaedah ini dibahagikan kepada empat peringkat hierarki. Analisis penggunaan tenaga dalam urutan ruangan penyulingan di simulasi dalam persekitaran simulasi Aspen HYSYS manakala indeks kemampanan dianalisis dengan menggunakan penilai kemampanan berasaskan Excel. Keupayaan kaedah yang dicadangkan dalam urutan reka bentuk ruangan penyulingan yang mampan serta cekap tenaga dan retrofit diuji menggunakan proses pemisahan Aromatic Campuran (AM), proses proses pemisahan pemisahan Hidrokarbon Campuran (HM) dan proses pemisahan Cecair Gas Asli (NGLs). Keputusan yang diperolehi menunjukkan bahawa kaedah yang dicadangkan dapat mengurangkan penggunaan tenaga kepada 12 % serta pengurangan 13 % dalam keseluruhan indeks kemampanan untuk proses pemisahan AM. Selain itu, 38 % daripada pengurangan tenaga dan 32 % daripada keseluruhan pengurangan indeks kemampanan juga dicapai dalam keseluruhan kajian kes HM. Tambahan pula, keseluruhan kajian kes NGLs juga mampu untuk mengurangkan penggunaan tenaga sehingga 21 % serta 22 % daripada keseluruhan indeks kemampanan dalam kajian ini. Ia dapat di simpulkan bahawa, metodologi yang dibangunkan ini mampu untuk mengendalikan proses pemisahan dengan keperluan tenaga yang kurang dan prestasi kemampanan juga lebih baik dengan cara yang mudah, praktikal dan sistematik.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

EEDCs	-	Energy Efficient Distillation Columns
Sustain-EEDCs	-	Sustainable Energy Efficient Distillation Columns
1D	-	One-dimension
2D	-	Two-dimension
3D	-	Three-dimension
MSA	-	Mass separating agent
CDS	-	Coefficient of difficulty of separation
SOL	-	Stripping operating line
ROL	-	Rectifying operating line
NGLs	-	Natural Gas Liquids
AM	-	Aromatic Mixture
HM	-	Hydrocarbon Mixture
MCP	-	Methylcyclopentane
MCH	-	Methylcyclohexane

LIST OF SYMBOLS

N_S	-	Number of sequences
N_F	-	Number of feed
P	-	Final product
P-1	-	separation point
X_D	-	Mole fractions of the distillate
X_B	-	Mole fractions of the bottoms
X_F	-	Mole fractions of the feed
x	-	Mole fraction in liquid phase
y	-	Mole fraction in vapour phase
F_{ij}	-	Driving force for component *i* property *j*
xi	-	Liquid phase composition of *i*
yi	-	Vapour phase composition of *i*
β_{ij}	-	Relative separability parameter for component *i* respect to property *j*

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Distillation is still remained as one of the most crucial separation methods in the chemical process industry. Currently, a total number of distillation columns in operation around the world is approximately tens of thousands unit (Lucia and Mccallum, 2010). However, one of the major drawbacks from its well-known benefits and widespread use is the significant energy consumptions, since the distillation operation can generate more than 50 % of the plant operating cost (Kiss *et al.*, 2012). Energy efficient analysis and process optimization studies are aggressively conducted each year in order to reduce the capital expenditures (CAPEX) as well as the operational expenditures (OPEX).

Distillation process designs are usually aimed to take the minimum capital expenditure cost since the cost of energy consumed is cheaper in the past years. Due to the unexpected price of crude oil in this few years, it can be assumed that the cost of generating energy will increase each year. Major unit operations of a typical chemical process plant such as distillation operation are having high annual expenditure cost due to large energy consumption and utilities. As an example, according to Lee and Binkley (2011), energy costs are the major percentage of a

hydrocarbon plant's OPEX. Therefore, it shows that the truth of the distillation process requires massive energy consumptions. Awareness of recent high costs of operating energy and global economic pressures has clearly stated the importance of efficient distillation design and operation with consideration of performance. Thus, there is a major increment in developing the energy efficient distillation columns design, which results in lower energy usage and greater economic savings.

Distillation column process energy requirements can be improved using technologies and optimisation of the process itself. Process optimisation and controllability are some of the best ways to reduce the operating costs, which result in the efficiency improvement. However, all these methods will require a huge amount of modifications cost. The distillation column design by using the driving force method as introduced by Bek-Pedersen and Gani (2004) is one of the improvements in the design of distillation columns research, which leads to the energy efficient distillation process. Basically, the number of ordinary distillation column used in separating individual fractions is much depending on the number of components that need to be purified in a sequence. The different sequence will require different energy requirements in order to obtain the desired product purity. Therefore, determining the best and optimal sequence in which energy requirements are at the minimum has become an important research nowadays.

Mustafa and co-workers have successfully developed a new methodology for designing an energy efficient distillation columns sequence that is able to reduce energy consumptions for a distillation columns sequence in an easy, systematic, and efficient way (Mustafa *et al*., 2014). However, the developed methodology did not consider the sustainability aspects in its sequence design and analysis. Distillation columns sequence design can be further improved by including sustainability aspect within the developed energy efficient distillation columns methodology to ensure that the design is energy efficient, cost optimal, as well as sustainable to meet product quality specifications.

Sustainability can be defined as maintaining or improving the material and social conditions for human health and the environment over time without exceeding the ecological capabilities that support them. Based on Figure 1.1, sustainability is categorised based on three principal objectives: environmental protection, economic growth, and societal equity. In order to assess the performance of the sustainability of a process or a system, metrics or indicators can be used. This can be done by using a model based software or calculator developed in the Excel spreadsheet. With this indicator, it can perform the progress enhancing the sustainability as well as help the decision makers in evaluating design alternatives in easier and systematic manner.

Designing energy efficient together with the sustainability analysis in the distillation columns sequence is another challenge faced by researchers or engineers. The developed energy efficient distillation columns methodology together with consideration of the sustainability criteria will satisfy the objective to meet product quality specifications and optimize the aspects of design efficiently as well as the sustainability criteria. This can be successfully generated by improving the developed methodology with the sustainability analysis.

The sustainability performance can be assessed through the evaluation of three different indices, which consist of the one-dimension (1D), two-dimension (2D), and three-dimension (3D) indices as shown in Figure 1.1. Details of the sustainability performance can refer to Chapter 2, Section 2.3.

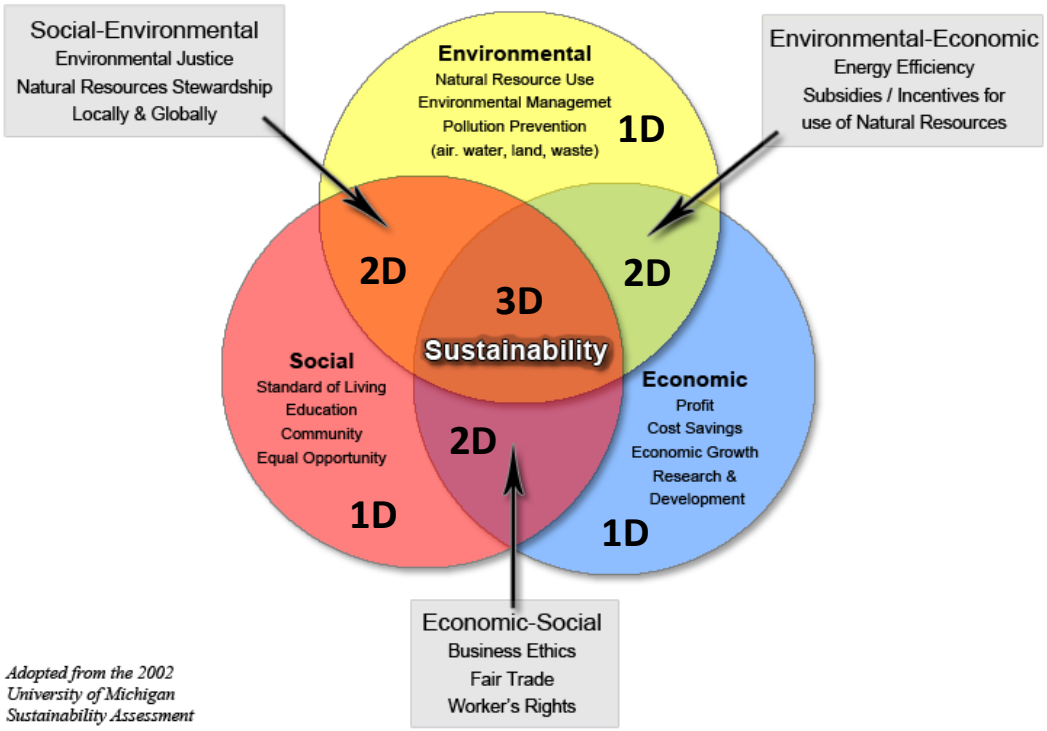

Figure 1.1 The three spheres of sustainability (Rodriguez, 2002)

Solving the energy efficient distillation columns sequence problem together with sustainability aspects could cause complexity in the optimization aspect. A complex computational solution is required in order to solve this problem, thus, makes this approach impractical to be used in real industrial for case studies or problems. In order to solve the intricacy and obtain the optimal solution of the sustainable design of the energy efficient distillation columns sequence problem, the decomposition approach can be applied in this study since it can manage and solve the intricacy of various optimization problems in the chemical process (Hamid, 2011). Basically, optimization problems usually have constraints, where it defines the search space within, whereby all feasible solutions lie. Furthermore, the objective function can be used to identify one or more of optimal solutions.

1.2 Problem Statement

An energy efficient distillation columns sequence methodology that able to reduce energy consumptions for a distillation columns sequence has been developed (Mustafa *et al*., 2014). However, the developed methodology did not consider the sustainability aspects in its design and analysis. It can be further improved by including sustainability criteria within the developed sequence methodology to ensure that the design is energy efficient, cost optimal, as well as sustainable to meet product quality specifications. Besides that, the application of sustainability analysis can be found based on the study done by Nordin *et al*. (2014) and Zakaria *et al*. (2014). However, the application of the developed sustainability analysis or known as *SustainPlus*© is limited only for the controllability aspect in a reactor system as well as the distillation columns system.

Current energy efficient distillation columns sequence methodology only addressed the energy saving and economic factors during the design of distillation columns sequence. This methodology performance in terms of sustainability is not guaranteed. Thus, sustainability criteria should be considered in energy efficient distillation columns sequence methodology. Exclusion of sustainability analysis during distillation columns sequence design process may lead to unattainable sequence design. Neglecting environmental and social impacts during the design process may affect the environment as well as social conditions. Therefore, it is vital to analyse the sustainability in order to propose new energy efficient distillation columns sequence. The problem statement of this study is summarized as follows:

Given the existing distillation columns sequence of a chemical separation process, it is desired to improve the sustainability of the distillation columns sequence design. In addition, it is desired to systematically use the concept of driving force method to design the optimal distillation columns sequence to maximise energy saving, reduce the capital, operating, and modification costs and improve the sustainability.

1.3 Objective of Study

This study was aimed to extend the energy efficient distillation column sequence methodology by taking into account the sustainability analysis as well as the retrofitting analysis that applied into the extended energy efficient distillation columns sequence methodology. The research objectives are shown as below:

i. To apply the extended methodology by considering the energy consumption in the energy efficient distillation columns sequence.

ii. To develop an extended methodology of energy efficient distillation columns sequence by taking into account of sustainability criteria and retrofitting analysis

iii. To modify or improve the sustainability assessment tool, *SustainPlus*© that is able to use the extended methodology of energy efficient distillation columns sequence.

1.4 Scope of Study

A series of research scope was designed with the intention of achieving objectives of the study, which includes

i. A review of energy efficient distillation columns sequence and sustainability topics, their analysis, and identifying the research gap.

ii. Development of a new methodology for determining sustainability and retrofitting analysis of energy efficient distillation columns sequence.

iii. Development of a modification or an improvement for the sustainability assessment tool, *SustainPlus*© in the energy efficient distillation columns sequence.

iv. Implementation of the proposed methodology for several case studies, which consist of simple case study and complex case studies.

1.5 Research Contributions

This research has resulted in the following contributions:

i. Applications of the methodology by considering energy consumption in the energy efficient distillation columns sequence.
   - Analysing the energy for different case studies which consist of a simple case study, Aromatic Mixtures (AM) and complex case studies, the Hydrocarbon Mixtures (HM) and Natural Gas Liquids (NGLs) separation processes.

ii. A methodology for determining sustainability and retrofitting analysis of energy efficient distillation columns sequence.
   - The developed methodology is able to integrate energy efficient distillation columns sequence and sustainability analysis, as well as the retrofitting analysis, which focusses at retrofit modification.

iii. A modification or an improvement of the sustainability assessment tool, *SustainPlus*©
   - The developed sustainability assessment tool is modified or improved, which aims to be used in the energy efficient distillation columns sequence rather than a single unit of a distillation column.

A substantial part of the results in this thesis has been published in reputable international conferences as listed in Table 1.1a and Table 1.1b.

Table 1.1a : International conference paper publications

Paper Title	Type	Status	Contribution Towards Knowledge
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Energy Efficient Distillation Columns Analysis for Aromatic Separation Process. *3rd International Science Postgraduate Conference 2015 (ISPC2015).* 24-26 February 2015, Johor Bahru	International Conference	Oral Presentation	(i)
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Minimum Energy Distillation Columns Sequence for Aromatics Separation Process. *Energy Procedia,* 75**,** 1797-1802.	SCOPUS Indexed (Journal)	Published	(i),(ii)

Table 1.1b : International conference paper publications (Continued)

Paper Title	Type	Status	Contribution Towards Knowledge
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Sustainable Energy Efficiency Distillation Columns Sequence Design of Aromatic Separation Unit. *1st ICRIL-International Conference on Innovation in Science and Technology (lICIST 2015)*. 20th April 2015, Kuala Lumpur	International Conference	Oral Presentation	(i), (ii), (iii)
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Sustainable Energy Efficient Distillation Columns Sequence Design of Hydrocarbon Mixtures Separation Unit. *Chemical Engineering Transactions*, 45**,** 1207-1212.	SCOPUS and WOS indexed (Journal)	Published Impact Factor : 1.03	(i), (ii), (iii)
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Sustainability Improvement for Hydrocarbon Mixtures Direct Sequence Separation Process. *5th International Conference On Fuel Cell & Hydrogen Technology (ICFCHT 2015)*. 1-3 September 2015, Kuala Lumpur.	International Conference	Oral Presentation	(i), (ii), (iii)

Table 1.1c : International conference paper publications (Continued)

Paper Title	Type	Status	Contribution Towards Knowledge
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Methodology Development for Sustainable Energy Efficient Distillation Columns (*Sustain*-EEDCs) Sequence Design. *28th Symposium of Malaysian Chemical Engineers (SOMChE 2015)*. 21-22 October 2015, Putrajaya.	International Conference	Poster Presentation	(i), (ii), (iii)
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Design of Sustainable Energy Efficient Distillation Columns (*Sustain*-EEDCs) Sequence. *International Conference on Fluids and Chemical Engineering (FluidsChE 2015*). 25-27 November 2015, Langkawi.	International Conference	Oral Presentation	(i), (ii), (iii)
Zaine, M. Z., Mustafa, M. F., Ibrahim, N., Ibrahim, K. A. & Hamid, M. K. A. (2015). Sustainability Improvement for Natural Gas Liquids (NGLs) of Direct Sequence Separation Process. *4th Conference on Emerging Energy and Process Technology 2015 (CONCEPT 2015).* 15-16 December 2015, Melaka.	International Conference	Oral Presentation	(i), (ii), (iii)

1.6 Thesis Outline

This thesis comprises of five chapters. Chapter 1 explains the background of this study, problem statement, objectives, scopes, and significance of this study. Chapter 2 reviews the theories behind sustainability, energy consumption in distillation columns, energy efficient distillation columns, and factor that affected them. Chapter 3 describes the details of the proposed methodology that is used to analyse sustainability and retrofitting design analysis for energy efficient distillation columns sequence as well as the modification or improvement steps in the sustainability assessment tool. The findings obtained from the modified sustainability assessment tool of the methodology for a simple case study are presented in the first part of Chapter 4 followed by the results obtained from the application of the proposed methodology for simple and complex case studies. Chapter 5 summarises the major findings of this study and provides recommendations for future study.

REFERENCES

Achour, M., Haroun, A., Schult, C. & Gasem, K. (2005). A new method to assess the environmental risk of a chemical process. *Chemical Engineering and Processing: Process Intensification*, 44, 901-909.

Afgan, N. H. & Da Graça Carvalho, M. (2000). Energy system assessment with sustainability indicators. In Afgan, N.H (ed.) *Sustainable Assessment Method for Energy Systems*. (pp. 83-125). New York : Springer US.

Amale, A. & Lucia, A. (2008). A two-level distillation design method. *AIChE Journal*, 54, 2888-2903.

Baroi, C. & Dalai, A. K. (2015). Process sustainability of biodiesel production process from green seed canola oil using homogeneous and heterogeneous acid catalysts. *Fuel Processing Technology*, 133, 105-119.

Becker, C. U. (2012). *Sustainability ethics and sustainability research*. (1st ed.) Amsterdam : Springer Netherlands.

Bek-Pedersen, E. & Gani, R. (2004). Design and synthesis of distillation systems using a driving-force-based approach. Chemical Engineering and Processing: *Process Intensification*, 43, 251-262.

Bek-Pedersen, E., Hostrup, M. & Gani, R. (2000). Using driving force based separation efficiency curves within an integrated system for process synthesis/design. *Computer Aided Chemical Engineering*, Volume 8, 955-960.

Carvalho, A., Matos, H. A. & Gani, R. (2013). SustainPro - A tool for systematic process analysis, generation and evaluation of sustainable design alternatives. *Computers & Chemical Engineering*, 50, 8-27.

Daoutidis, P., Zachar, M. & Jogwar, S. S. (2016). Sustainability and process control: A survey and perspective. *Journal of Process Control*, 44, 184-206.

Gani, R. & Bek-Pedersen, E. (2000). Simple new algorithm for distillation column design. *AIChE Journal*, 46, 1271-1274.

Geankoplis, C. (2003). *Transport processes and separation process principles (includes unit operations)*. (4th ed.) New York : Prentice Hall Press.

Hamid, M. K. B. A. (2011). Model-based integrated process design and controller design of chemical processes. *Technical University of Denmark (DTU) PhD Thesis*. ISBN: 978-87-92481-39-9.

Heikkilä, A.-M. (1999). *Inherent safety in process plant design: an index-based approach*, VTT Technical Research Centre of Finland.

Holmberg, J. & Karlsson, S. (1992). *On designing socio-ecological indicators. Society and the Environment: A Swedish Research Perspective*. (2nd ed.) Amsterdam : Springer Netherlands.

Kiss, A. A., Flores Landaeta, S. J. & Infante Ferreira, C. A. (2012). Towards energy efficient distillation technologies – Making the right choice. *Energy*, 47, 531-542.

Krotscheck, C. & Narodoslawsky, M. (1996). The Sustainable Process Index a new dimension in ecological evaluation. *Ecological Engineering*, 6, 241-258.

Lee, S. H. & Binkley, M. J. (2011). Optimize design for distillation feed: Use these steps for enhanced performance. *Hydrocarbon processing*, 90, 101-105.

Liu, Y., Pehler, F. & Cahela, D. (1983). Studies in Chemical Process Design and Synthesis. *AIChE Journal*, 29, 926-934.

Lucia, A. & Mccallum, B. R. (2010). Energy targeting and minimum energy distillation column sequences. *Computers & Chemical Engineering*, 34, 931-942.

Martins, A. A., Mata, T. M., Costa, C. A. V. & Sikdar, S. K. (2007). Framework for Sustainability Metrics. *Industrial & Engineering Chemistry Research*, 46, 2962-2973.

Mustafa, M. F., Samad, N. A. F. A., Ibrahim, K. A. & Hamid, M. K. A. (2014). Methodology Development for Designing Energy Efficient Distillation Column Systems. *Energy Procedia*, 61, 2550-2553.

Nath, R. & Motard, R. L. (1981). Evolutionary synthesis of separation processes. *AIChE Journal*, 27, 578-587.

Nordin, M. Z., Jais, M. D. & Hamid, M. K. A. (2014). Sustainable Integrated Process Design and Control for a Distillation Column System. *Applied Mechanics and Materials*, 625, 470-473.

Prescott-Allen, R. (1995). *Barometer of sustainability; a method of assessing progress toward sustainable societies.* (1st ed.) Victoria, BC. : IUCN.

Rodriguez, S. I. (2002). *Sustainability assessment and reporting for the University of Michigan's Ann Arbor Campus*. Master's Project, The University of Michigan.

Rousseau, R. W. (1987). *Handbook of Separation Process Technology*. (1st ed.) New York : John Wiley and Sons, Inc.

Santaella, M. A., Orjuela, A. & Narváez, P. C. (2015). Comparison of different reactive distillation schemes for ethyl acetate production using sustainability indicators. *Chemical Engineering and Processing: Process Intensification*, 96, 1-13.

Seader, J. D., Seider, W. D., Lewin, D. R. & Widagdo, S. (2008). *Product and Process Design Principles: Synthesis, Analysis and Design*. (3rd ed.) New York : John Wiley & Sons.

Seader, J. D. & Westerberg, A. W. (1977). A combined heuristic and evolutionary strategy for synthesis of simple separation sequences. *AIChE Journal*, 23, 951-954.

Shadiya, O. O. (2010). *Social, economic and environmental metrics for the sustainable optimization of chemical and petroleum processes*. Doctor of Philosophy, Oklahoma State University.

Shadiya, O. O. & High, K. A. (2013). Sustainability evaluator: Tool for evaluating process sustainability. *Environmental Progress & Sustainable Energy*, 32, 749-761.

Sikdar, S. K. (2003). Sustainable Development and Sustainability Metrics. *AIChE Journal*, 49, 1928-1932.

Tanzil, D. & Beloff, B. R. (2006). Assessing impacts: Overview on sustainability indicators and metrics. *Environmental Quality Management*, 15, 41-56.

Towler, G. & Sinnott, R. K. (2012). *Chemical engineering design: principles, practice and economics of plant and process design.* (2nd ed.), Oxford, UK: Elsevier.

Uhlman, B. W. & Saling, P. (2010). Measuring and communicating sustainability through eco-efficiency analysis. *Chemical Engineering Progress*, 106, 17-26.

Zakaria, S. A., Zakaria, M. J. & Hamid, M. K. A. (2014). Sustainable Integrated Process Design and Control for a Continuous-Stirred Tank Reactor System. *Applied Mechanics and Materials*, 625, 466-469.