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SUSTAINABLE ENERGY EFFICIENCY DISTILLATION COLUMNS SEQUENCE DESIGN OF AROMATIC SEPARATION UNIT

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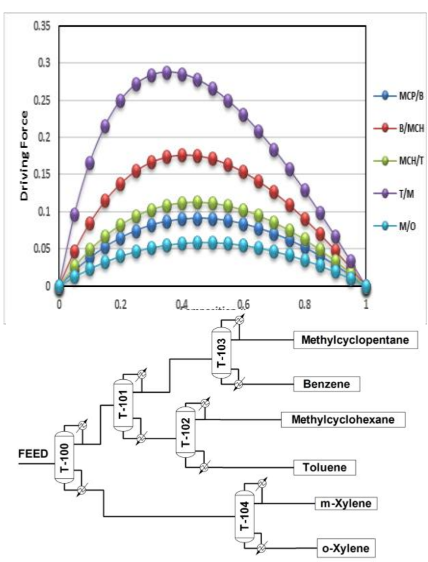
Graphical abstract



Abstract

Distillation operations became a major concern within sustainability challenge, which it becomes a primary target of energy saving efforts in industrially developed countries. However, there is still one problem, which is how do we improve the energy efficiency of the existing distillation columns systems by considering the sustainability criteria without having major modifications. Therefore, the objective of this paper is to present new improvement of existing methodology by including a sustainability analysis to design an optimal sequence of energy efficient distillation columns. Accordingly, the methodology is divided into four hierarchical sequential stages: i) existing sequence sustainability analysis, ii) optimal sequence determination, iii) optimal sequence sustainability analysis, and iv) sustainability comparison and design modification. The capability of this methodology is tested in designing an optimal sustainable energy efficient distillation columns sequence of aromatics separation unit using a simple and reliable short-cut method within Aspen HYSYS® simulation environment. The energy and sustainability analysis is performed and shows that the optimal sequence determined by the driving force method has better energy reduction with total of 6.78 % energy savings and 0.16 % sustainability reduction compared to existing sequence with. In addition, the economic analysis shows that the return of investment of 3.10 with payback period of 4 months. It can be concluded that, the sequence determined by the driving force method is not only capable in reducing energy consumption, but also has better sustainability index for aromatic separation unit.

Keywords: Energy Efficient, Distillation Columns Sequence, Sustainability, Driving Force, Aromatic separation

1.0 INTRODUCTION

Distillation process still become one of the most important unit operation of separation methods in the chemical process industry. Most of chemical mixture require this typical separation process in order to produce individual pure product of chemical. This separation process has well-known contributions and benefits, as well as huge impact on operating expenditure and investment costs in chemical plants.

Reducing energy consumption of distillation columns system is not an easier task. Columns come in many options as well as different operating objectives. It generates different operational degrees of freedom and dynamic behaviours. Differences in columns designs are have significant interaction among control loops and constraints on their operation. Thus, it is more complicating the dynamics and more difficult to optimize the controllability as well as energy efficient. Distillation operations basically involve in energy usage and product recovery as well as the production target which involves the economic value. However, this process is a nonlinear process and any product-valuation patterns will give results in the economic objective function [1].

The determination of feasible sequences of multiple distillation columns, whether on the basis of minimum overall energy consumption, total annualized costs, sustainability, or some other metric, has been the subject of academic and industrial investigation for many years. These include early methodologies such as the use of heuristics, genetic algorithms, mixed integer nonlinear programming (MINLP) methods and others [2].

Significant savings in the utilities for chemical separation process can be achieved by using driving force method in innovative configurations. The driving force can be defined as the difference in composition of a component *i* between the vapour and liquid phase due to the difference of properties such as boiling point and vapour pressure of component *i* and the others. Driving force can be measured by the binary pair of key multi-component mixture or binary mixture. Theoretically, when the driving force near to zero the separation of the key component binary mixture becomes difficult, while, when the driving force near to high peak or maximum value, the separation between two components become easier [3].

Unfortunately, this developed methodology did not consider sustainability aspect in the early of design stage. Distillation column design can be further improved by including sustainability aspect within the developed Energy Efficient Distillation Columns (*EEDCs*) methodology to ensure that the design is energy efficient, as well as sustainable [4]. Sustainability can be known as the maintaining or improving the material and social conditions for human health and the environment over time without obeying and abusing the ecological capabilities that support them. Sustainability is based on balancing three principal objectives: environmental aspect, economic dimension, and societal equity condition as shown in Figure 1. The sustainability performance of a system or chemical process is identifying by metrics and indicators in order to evaluate the progress toward enhancing sustainability [5]. The sustainability indicator or also known as sustainability evaluator can be classify from environmental aspect, economic dimension, and societal equity condition into one, two and three dimensional metrics [6].

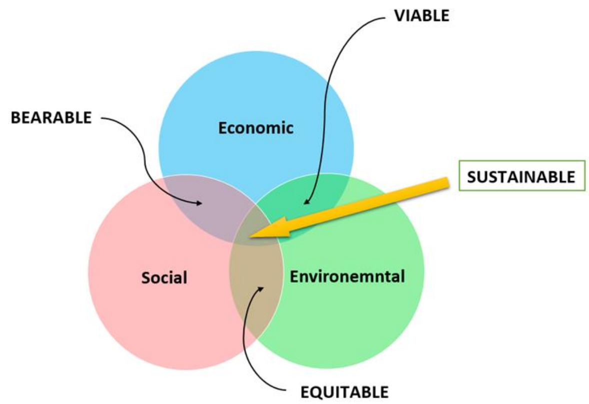


Figure 1 Principles of sustainability

In this paper, the study and analysis of the sustainability and energy saving improvement for the aromatic mixtures separation sequence by using driving force method without having any major modifications to the major separation units, is presented. There will be modifications to the separation sequences based on the driving force results, which will reduce the energy requirement and addition of better sustainability index as well as the economic analysis.

2.0 SUSTAINABLE ENERGY EFFICIENT DISTILLATION COLUMNS SEQUENCE DESIGN METHODOLOGY

In order to perform the study and analysis of the energy saving improvement as well as sustainability for the sustainable energy efficient distillation columns (*Sustain*-EEDCs) separation sequence, *Sustain*-EEDCs sequence methodology is developed based on the driving force method [3]. Accordingly, the methodology consists of four hierarchical stages as shown in Figure 2.

In the first stage, a simple and reliable short-cut method of distillation column in process simulator (Aspen HYSYS) is used to simulate a base (existing) columns sequence. The short-cut method in the Aspen HYSYS simulation environment basically is a command operator in the software itself in order to estimate energy results of the process. The energy results from the process simulator is analysed in the sustainability evaluator to perform the sustainability analysis. The three-dimension (3D) sustainability index is used due to simplicity and reliability based on the case study that need to be conducted [7]. Figure 3 shows the metrics that used in the calculation of 3D sustainability index.

The 3D metric is used in this work since it is common for this type of processes, because it takes into consideration those aspects directly related to sustainability, in particular, the aspects that link to the potential chemical risk (human health impact in the immediate environment of the process) and to potential environmental impact (hazardous to the surrounding environment).

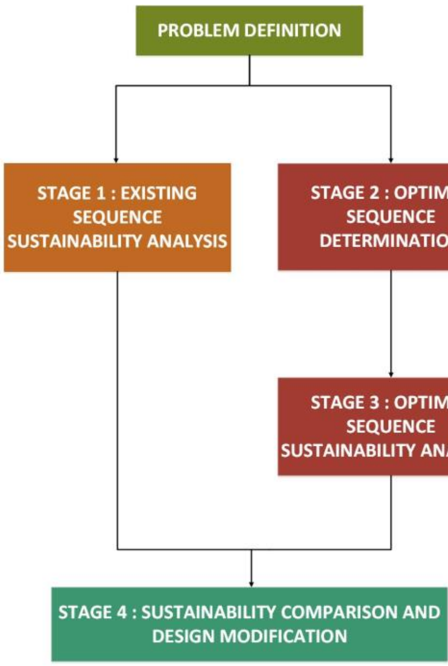


Figure 2 Sustainable design energy efficient distillation columns sequence methodology

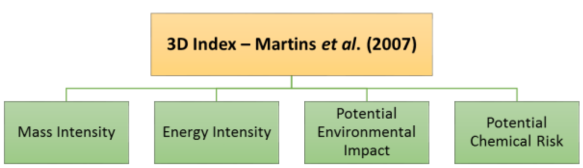


Figure 3 Metrics for three-dimension (3D) sustainability index

The sustainability index of the existing sequence is taken as a reference for the next stage. In the second stage, an optimal columns sequence is determined by using driving force method. All individual driving force curves for all adjacent components are plotted and the optimal sequence is determined based on the plotted driving force curves. Details step-by-step algorithm in plotting the driving force can be obtained elsewhere [3].

The highest value of maximum driving force which corresponds to the splitting of the adjacent component will be separated first, while the lowest value of the maximum driving force will be separated last. According to the driving force method, at the highest value of the maximum driving force, the separation becomes easy and the energy required to maintain the separation is at the minimum. Whereas, at the lowest value of the maximum driving force, the separation becomes difficult and energy required to make the separation feasible is at the maximum [3]. Once the optimal sequence has been determined, the new optimal sequence is then simulated in stage three using a simple and reliable short-cut method by using Aspen HYSYS, where the 3D sustainability index for this optimal sequence is analysed based on the energy results from the simulation environment. Finally, the 3D sustainability index in the optimal sequence is compared with the base sequence.

The capability of this methodology is tested in designing sustainable energy distillation column sequence for aromatics separation process, which consists of six compounds (methylcyclopentane (MCP), benzene, methylcyclohexane (MCH), toluene, *o*-xylene, *m*-xylene) with five direct sequence distillation columns. In addition, the economic analysis is done in terms of rate of return on investment (*ROI*). In order to analyse the economic performance, the operating cost and modification cost must be calculated.

3.0 CASE STUDY: AROMATIC SEPARATION PROCESS

The capability of proposed methodology is tested in designing sustainable energy distillation column sequence for aromatic mixture separation process. The objective of the aromatic mixture separation process is to recover individual fractions using distillation columns. In this paper, we assumed that the existing aromatic mixture separation process consists of six compounds (methylcyclopentane (MCP), benzene, methylcyclohexane (MCH), toluene, *o*-xylene, *m*-xylene) with five direct sequence distillation columns. The feed composition, temperature and pressure are described in Table 1. In addition, the economic analysis is done in terms of rate of return on investment (*ROI*). In order to analyse the economic performance, the operating and modification costs must be calculated as well as the sustainability to show the differences between research study in this paper and the driving force approach [8].

3.1 Existing Sequence Sustainability Analysis

Figure 4 illustrates the existing separation sequence which is the direct sequence of the aromatic mixture separation process. The existing aromatic mixture separation process was simulated using a simple and reliable short-cut method within Aspen HYSYS environment. A total of 20.07 MW energy used to achieve 99.9 % of product recovery. From the results, the calculated sustainability index is 848.71 obtained from the sustainability evaluator.

Table 1 Feed conditions of the mixture

Components	*Mole Fractions*	*Temp (°C)*	*Pressure (atm)*
Methylcyclopentane (MCP)	0.1		
Benzene	0.1		
Methylcyclohexane (MCH)	0.1	30	2
Toluene	0.1		
o-Xylene	0.1		
m-Xylene	0.5		

3.2 Optimal Sequence Determination

The optimal sequence of aromatic mixtures was determined by using driving force method. All individual driving force curves was plotted as shown in the Figure 5, and the optimal sequence was determined based on the plotted driving force curves. The new sequence based on driving force is shown in the Figure 6.

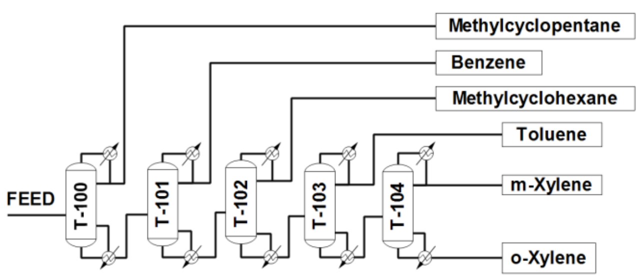


Figure 4 Existing Separation Sequence (Direct Sequence) of Aromatics Separation Process

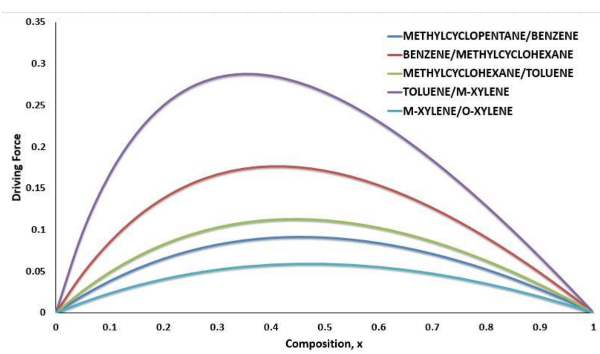


Figure 5 Driving Force Curve for set of binary component at uniform pressure

3.3 Optimal Sequence Sustainability Analysis

A new optimal sequence determined by driving force method (see Figure 6) was simulated using a short-cut method within Aspen HYSYS environment where a total of 18.71 MW of energy was used for the same product recovery. The calculated sustainability index obtained from the sustainability calculator is 847.35 based on the energy analysis.

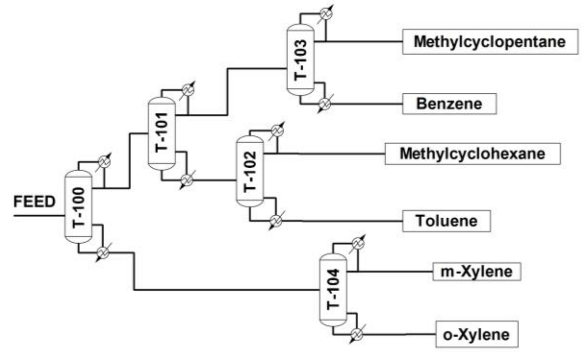


Figure 6 Simplified flow sheet illustrating the optimal Driving Force sequence of Aromatic mixture separation process

3.4 Sustainability Comparison and Design Modification

Sustainability index for the recovery of the aromatic mixture for the existing direct sequence and the new optimal sequence determined by the driving force method is calculated and the results show that 0.16 % sustainability reduction was able to achieve by changing the sequence suggested by the driving force method. Sustainability index as well as energy consumption for the recovery of the aromatic separation process for the existing indirect sequence and the new optimal sequence determined by the driving force method is shown in Table 2. The results show that 4.78 % sustainability reduction was able to achieve by changing the sequence suggested by the driving force method. It can be concluded that, the sequence determined by the driving force method is able to reduce energy used for aromatic separation process.

Table 2 Comparison in energy required and sustainability index between direct sequence and driving force sequence

	Direct Sequence	**Driving Force Sequence**	**Percentage (%)**
Energy Required	20.073	18.712	4.78
Sustainability Index (SUI)	848.71	847.35	0.16

The economic analysis is carried out by considering the cost of modifying the direct sequence distillation unit arrangement into that of the driving force, the cost of re-piping works as the capital cost and the reduction in condenser and reboiler duty as the net earnings. In order to evaluate the economic analysis, the length of pipes needed for re-piping works is estimated by comparing the drawing of the original sequence as well as drawing of the direct sequence with the modified one that is illustrates in Figure 7.

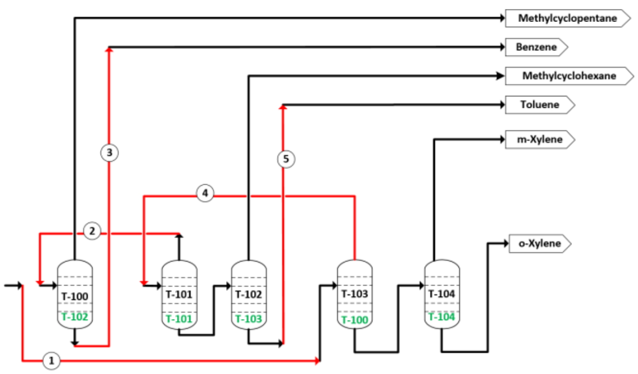


Figure 7 Design modification from the existing sequence design into the optimal sequence design

Based on calculation regarding the economic analysis, the return of investment (*ROI*) generated with amount of 3.10. The payback period for the modification of the process from direct method into the driving force method is about 0.32 year or approximately 4 months. Table 3 summarized all the economic analysis of the modification process of the aromatic separation plant.

Table 3 Return of Investment (ROI) and Payback Period

Repiping Cost (US$/yr)	159,973
Reboiler Saving (US$/yr)	247,632
Condenser Saving (US$/yr)	247,631
ROI	3.10
Payback Period (yr)	0.32

4.0 CONCLUSION

The study and analysis of the energy saving and sustainability improvement for the aromatics separation process by using driving force method has been successfully performed. The existing aromatics separation process consists of six compounds (methylcyclopentane (MCP), benzene, methylcyclohexane (MCH), toluene, *o*-xylene, *m*-xylene) with five direct sequence distillation columns was simulated using a simple and reliable short-cut method within Aspen HYSYS environment with a total of 20.1 MW energy used to achieve 99.9 % of product recovery. A new optimal sequence determined by driving force method was simulated using a short-cut method within Aspen HYSYS environment where a total of 18.7 MW of energy was used for the same product recovery. The results show that the maximum of 0.16 % sustainability index reduction was able to achieve by changing the sequence suggested by the driving force method. In addition, this typical methodology can be used in other separation sequences or different chemical product which involve the distillation process in future research and case studies. It can be concluded that, the sequence determined by the driving force method is able to reduce energy used as well as improve the sustainability for aromatics separation process in an easy, practical and systematic manner.

Acknowledgement

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