CHEMICAL ENGINEERING TRANSACTIONS
VOL. 45, 2015
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216
DOI: 10.3303/CET1545202

Sustainable Energy Efficient Distillation Columns Sequence Design of Hydrocarbon Mixtures Separation Unit

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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. Recently, a new energy efficient distillation columns methodology that will able to improve energy efficiency of the existing separation systems without having major modifications has been developed. However, this developed methodology was only considered the energy savings without taking into consideration the sustainability criteria. 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. In the first stage, a simple and reliable short-cut method is used to simulate a base (existing) sequence. The sustainability index of the base sequence is calculated and taken as a reference for the next stage. In the second stage, an optimal sequence is determined by using driving force method. All individual driving force curves is plotted and the optimal sequence is determined based on the plotted driving force curves. Then, by using a short-cut method, the new optimal sequence is simulated and the new sustainability index is calculated in the third stage. Lastly, in the fourth stage, the sustainability index for both sequences (base and optimal) is compared. The capability of this methodology is tested in designing an optimal sustainable energy efficient distillation columns sequence of hydrocarbon mixtures separation unit. The existing hydrocarbon mixtures separation unit consists of eleven compounds (propane, i-butane, n-butane, i-pentane, n-pentane, n-hexane, benzene, cyclohexane, n-heptane, toluene, and n-decane) with ten indirect sequence distillation columns is simulated using a simple and reliable short-cut method and rigorous 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 4.64 % energy savings and sustainability reduction of 4.78 % based on existing sequence. 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 hydrocarbon mixtures separation unit.

1. Introduction

Distillation process still becomes 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 (Karacan and Karacan, 2014). This separation process has well-known contributions and benefits, as well as huge impact on operating expenditure and investment costs in chemical plants. The determination of feasible sequences of multiple distillation columns, whether

Please cite this article as: Zaine M.Z., Mustafa M.F., Ibrahim K.A., Ibrahim N., Hamid M.K.A., 2015, Sustainable energy efficient distillation columns sequence design of hydrocarbon mixtures separation unit, Chemical Engineering Transactions, 45, 1207-1212 DOI:10.3303/CET1545202

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 (Osuolate and Zhang, 2014). Significant savings in the utilities for chemical separation process can be achieved by using driving force method in innovative configurations as stated in research study by Bek-Pedersen and Gani (2004).
Although with all steps or sequence that lead to energy efficient distillation columns and energy savings, does it sustain? Does it following the sustainability? 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. The sustainability performance of a system or chemical process is identified by metrics and indicators in order to evaluate the progress toward enhancing sustainability. Besides that, it can assist decision makers in evaluating alternatives.
Based on review by Sepiacci and Manca (2015), there are lots of sustainable evaluation tools that are used and published by researchers as well as professional organizations such as American Institute of Chemical Engineer (AIChE) and Institution of Chemical Engineers (IChemE). 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. One-dimensional metrics are based on only one of the principal objectives which are economic, environment and social. The two-dimensional metrics can be identified based on simultaneous assessment of two out of three sustainability principal objectives or dimensions. It includes either socio-economic, socio-environmental or economic-environmental indicators. Last but not least, the three-dimensional metrics integrates all principal objectives of economic, environment and social (Mata et al., 2014).
In this paper, the study and analysis of the sustainability and energy saving improvement for the hydrocarbon mixtures separation sequence by using driving force method without having any major modifications to the major separation units, is presented. There will be only modifications to the separation sequences based on the driving force results, which will reduce the energy requirement and have better sustainability index.

2. Sustainable Energy Efficient Distillation Columns Sequence Design Methodology

To perform the study and analysis of the energy saving improvement as well as sustainability for the sustainable energy efficient distillation columns (SEEDCs) separation sequence, SEEDCs sequence methodology is developed based on the driving force method (Mustafa et al., 2014). Accordingly, the methodology consists of four hierarchical steps as shown in Figure 1.

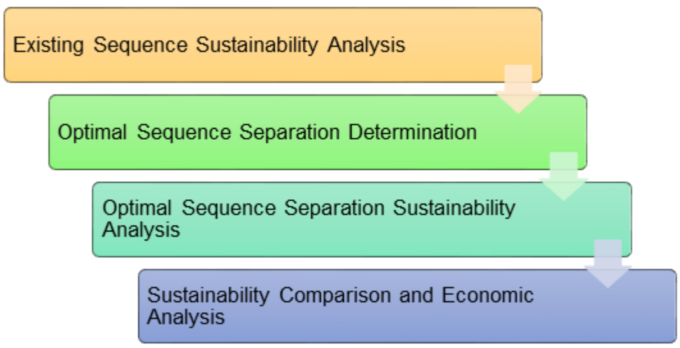

Figure 1: Sustainable energy efficient distillation columns sequence methodology

In the first step, a simple and reliable short-cut method of Aspen HYSYS® process simulator (Aspen Technology, 2013) is used to simulate a base (existing) columns sequence. 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 needs to be conducted. The sustainability index of the existing sequence is taken as a reference for the next step. 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.
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 maintaining 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. Once the optimal sequence has been determined, the new optimal sequence is then simulated in step 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 hydrocarbon mixtures separation process, which consists of eleven compounds (propane, i-butane, n-butane, i-pentane, n-pentane, n-hexane, benzene, cyclohexane, n-heptane, toluene, and n-decane) with ten indirect 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. Case Study: Hydrocarbon Mixtures Separation Process

The capability of proposed methodology is tested in designing sustainable energy distillation column sequence for hydrocarbon mixture separation process. The objective of the hydrocarbon mixture separation process is to recover individual fractions using distillation columns. In this paper, we assumed that the existing hydrocarbon mixture separation process consists of eleven compounds (propane, i-butane, n-butane, i-pentane, n-pentane, n-hexane, benzene, cyclohexane, n-heptane, toluene, and n-decane) with ten indirect sequence distillation columns.

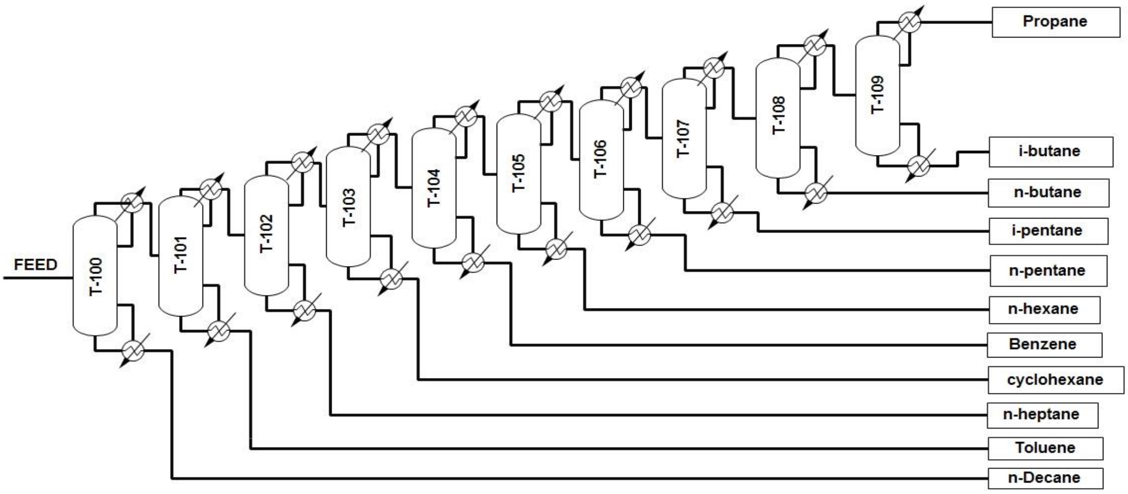

Figure 2: Simplified flow sheet illustrating the existing indirect sequence of hydrocarbon mixtures separation process

Table 1: Feed conditions of the mixture

Component	Feed Conditions Mole fractions	Component	Feed Conditions Mole fractions
Propane	0.057	Cyclohexane	0.039
i-Butane	0.035	n-Heptane	0.111
n-Butane	0.092	Toluene	0.164
i-Pentane	0.067	Decane	0.274
n-Pentane	0.052	Temperature (°F)	150
n-Hexane	0.084	Pressure (psia)	200
Benzene	0.025		

3.1 Existing Sequence Sustainability Analysis

Figure 2 illustrates the existing separation sequence (indirect sequence) of the hydrocarbon mixture separation process. The feed composition, temperature and pressure are described in Table 1. The existing hydrocarbon mixture separation process was simulated using a simple and reliable short-cut method within Aspen HYSYS® environment. A total of 157.96 MW energy is used to achieve 99.9 % of product recovery. From the results, the calculated sustainability index is 5.02 obtained from the sustainability evaluator.

3.2 Optimal Sequence Determination

The optimal sequence of hydrocarbon mixtures was determined by using driving force method. All individual driving force curves was plotted as shown in the Figure 3, 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 4.

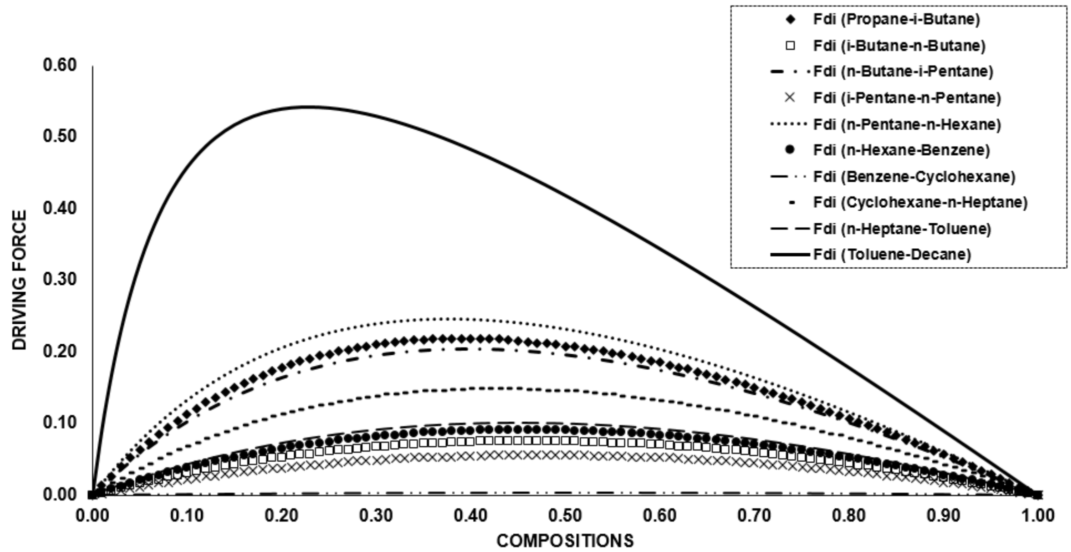

Figure 3: Driving force curves for set of binary component at uniform pressure

3.3 Optimal Sequence Sustainability Analysis

A new optimal sequence determined by driving force method (see Figure 4) was simulated using a short-cut method within Aspen HYSYS® (Aspen Technology, 2013) environment where a total of 150.63 MW of energy was used for the same product recovery. The calculated sustainability index obtained from the sustainability calculator is 4.78 based on the energy analysis.

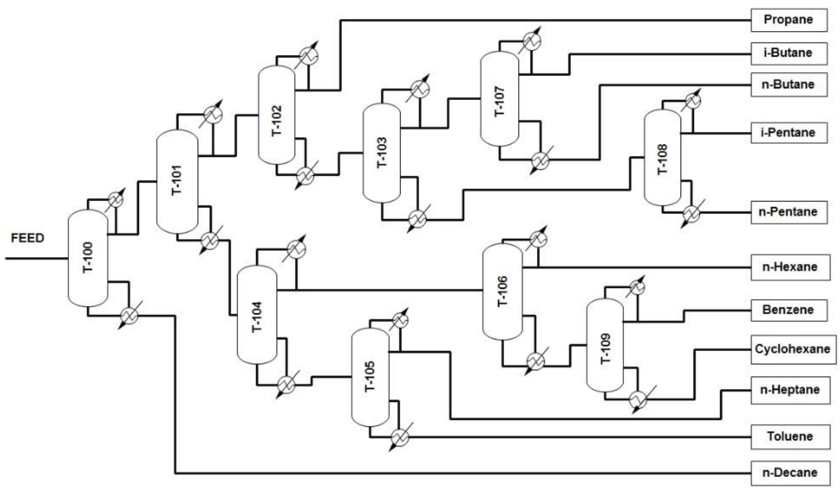

Figure 4: Simplified flow sheet illustrating the optimal Driving Force sequence of Hydrocarbon mixture separation process

3.4 Sustainable Comparison and Economic Analysis

Sustainability index for the recovery of the hydrocarbon mixture 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 hydrocarbon mixtures separation process.

Table 2: Sustainable comparison for indirect sequence and driving force sequence for hydrocarbon mixture separation process

	Indirect Sequence	Driving Force Sequence	Percentage (%)
Sustainability Index (SUI)	5.02	4.78	4.78

The economic analysis is carried out by considering the cost of modifying the indirect sequence distillation unit arrangement into that of the driving force, the cost of repiping 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 indirect sequence with the modified one that is illustrates in Figure 5.

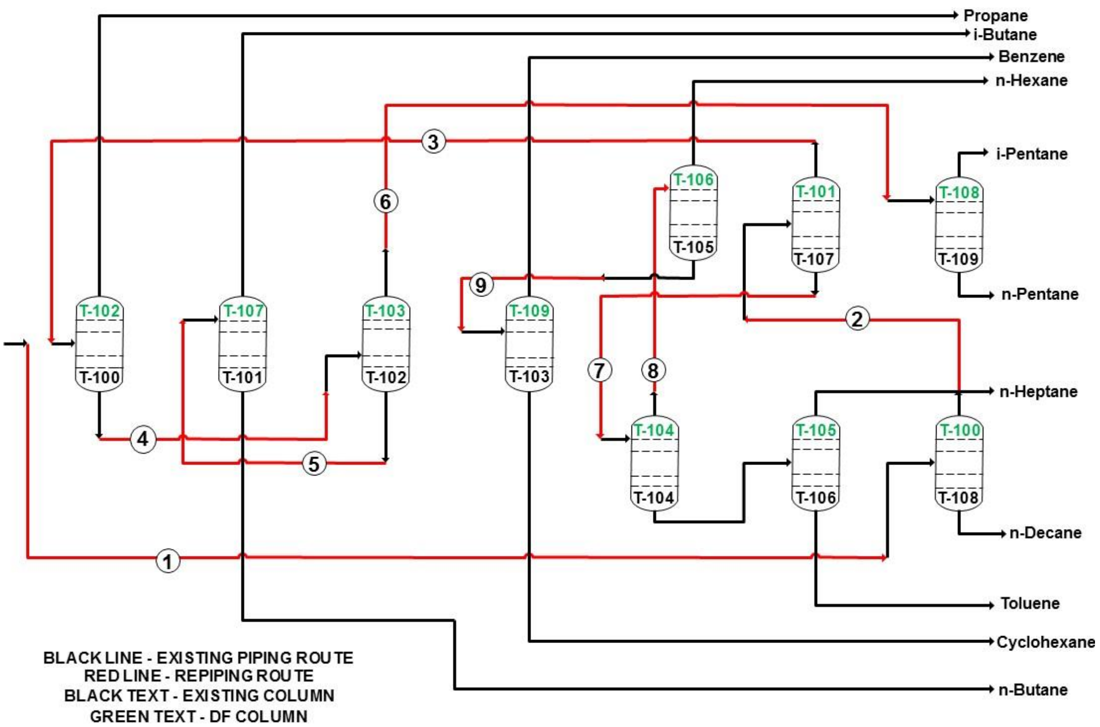

Figure 5: Simplified flow sheet illustrating the repiping modification from indirect sequence into driving force sequence

Based on calculation regarding the economic analysis, the return of investment (ROI) generated with amount of 1.92. The total energy saving was estimated about 2,198,230 $/y. The payback period for the modification of the process from indirect sequence method into the driving force method is about six months. Table 3 summarized all the economic analysis of the modification process of the hydrocarbon mixtures separation plant.

Table 3: Summary of economic analysis for the sustainable hydrocarbon mixtures separation plant

Repiping Cost ($)	69,328
Total Modification Cost ($)	1,146,363
Total Energy Saving ($/y)	2,198,230
Return of Investment (ROI)	1.92
Payback Period	6 months

4. Conclusion

The study and analysis of the energy saving and sustainability improvement for the hydrocarbon separation process by using driving force method has been successfully performed. The existing hydrocarbon mixture separation process consists of eleven compounds (propane, i-butane, n-butane, i-pentane, n-pentane, n-hexane, benzene, cyclohexane, n-heptane, toluene, and n-decane) with ten indirect sequence distillation columns was simulated using a simple and reliable short-cut method within Aspen HYSYS environment with a total of 157.96 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 150.63 MW of energy was used for the same product recovery. The results show that the maximum of 4.78 % sustainability index 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 hydrocarbon mixture separation process in an easy, practical and systematic manner.

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