ENERGY INTEGRATED DISTILLATION COLUMN SEQUENCE

MUNAWAR ZAMAN SHAHRUDDIN

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

This thesis is dedicated to parents and my elder sister that always be with me throughout this wonderful challenging journey.

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ABSTRACT

Recently, energy consumption has become a crucial consideration especially for energy-intensive distillation process. This issue becomes worse for a multi-component process which will involve a series of distillation columns for one process. Furthermore, the absence of a reliable process to cater for a big production with desired product purity would be the reason to maintain this distillation process. Hence, the only way to solve the issue is to improve the energy efficiency of the distillation process. For that, this study aimed to develop a new holistic, systematic and comprehensive framework for a feasible energy integrated distillation column sequence (EIDCS). The feasibility aspects in this study can be divided into process/design feasibility and economic feasibility. The proposed framework consists of six stages. It started from the formulation and extraction of the feed information in stage 1 before moving on to the step of column sequencing in stage 2 which is based on the number of the components; either in a manual energy analysis for all possible sequences for less than 5 components or straightaway to the implementation of the driving force method for the vice-versa case. In stage 3, simulations for the selected sequences were carried out and the results were brought to stage 4 for application of the thermal pinch analysis via problem table algorithm (PTA) for a range of ΔT_{min} from 5 to 40 °C. Then the total energy requirement (TER) was obtained and the heat exchanger network (HEN) in a form of a grid diagram (GD) was developed to meet the proposed design. The process/design feasibility was then obtained based on the value of the ft correction factor for each heat exchanger in the process. Then, the design(s) underwent an economic analysis in stage 5 involving the calculation of capital costs (CC) and annual operating costs (AOC). Lastly, an optimal solution in terms of the arrangement of the sequence and the ΔT_{min} was obtained from the calculation of the multi-objective functions in stage 6. Five case studies had been selected to evaluate and verify the proposed framework. It successfully recorded a range of energy saving from 30 to 42% compared to the existing sequence. The optimum sequence for case study 1 is split sequence with ΔT_{min} value from 5 to 30 °C. split-1D sequence from 5 to 20 °C is regarded as the optimum sequence for case study 2 and case study 3. For case study 4 and 5, the optimum sequences are split-1-split (ΔT_{min} from 5 to 25 °C) and split-1-D-split-2-D (ΔT_{min} from 5 to 20 °C). All optimum designs can be regarded as process feasible whereby all heat exchangers in the process recorded a value of ft correction factor of 1.0. Besides, the methods also reduced the CC and AOC of the process to \$870,000 and \$4.28 M for case study 3. The same costs have been reduced approximately 45% for the CC and 10% for the AOC for case study 4. Case study 5 also followed the same trend with a cost saving at \$476,000 for CC and around \$2.78 M for the AOC compared to the existing sequence. Overall, the results suggested that the framework has successfully produced a feasible EIDCS for all cases in a holistic, systematic and comprehensive manner.

ABSTRAK

Kebelakangan ini, penggunaan tenaga menjadi pertimbangan yang amat mustahak terutama untuk proses tenaga intensif penyulingan. Isu ini bertambah buruk untuk proses pelbagai komponen untuk siri turus penyulingan bagi sesuatu proses. Tambahan pula, ketiadaan proses yang mampu untuk menghasilkan produk secara besar-besaran bersama ketulenan produk yang dikehendaki menjadi sebab untuk proses penyulingan ini terus dikekalkan. Oleh itu, hanya satu cara menyelesaikan isu ini adalah dengan memperbaiki kecekapan tenaga bagi proses penyulingan ini. Untuk itu, kajian ini menyasarkan kepada pembangunan kerangka baharu yang holistik, sistematik dan komprehensif bagi turutan turus penyulingan terintegrasi-tenaga (EIDCS) yang boleh dilaksanakan. Aspek kebolehlaksanaan dalam penyelidikan ini dapat dibahagikan kepada kebolehlaksanaan proses/rekabentuk dan kebolehlaksanaan ekonomi. Kerangka yang dicadangkan ini mempunyai enam peringkat. Ianya bermula daripada formulasi dan pengekstrakan maklumat masukan pada peringkat 1 sebelum beralih kepada langkah menghasilkan turutan pada peringkat 2 yang ditentukan oleh bilangan komponen, sama ada tenaganya dianalisis secara manual bagi komponen kurang daripada 5 atau terus sahaja kepada kaedah pelaksanaan daya pacu untuk kes sebaliknya. Pada peringkat 3, simulasi untuk turutan terpilih telah dijalankan dan hasilnya dibawa ke peringkat 4 bagi aplikasi analisis jepit termal melalui algoritma jadual masalah (PTA) untuk julat ΔT_{min} dari 5 °C ke 40 °C. Kemudian, jumlah keperluan tenaga (TER) diperolehi dan rangkaian penukar haba (HEN) dalam bentuk rajah grid (GD) dibangunkan untuk menyesuaikannya dengan rekabentuk yang dicadangkan. Kebolehlaksanaan dari segi proses/rekabentuk diperoleh berdasarkan kepada nilai faktor pembetulan ft untuk setiap penukar haba dalam proses tersebut. Seterusnya, rekabentuk dinilai secara ekonomi di peringkat 5 yang mana melibatkan pengiraan kos modal (CC) dan kos operasi tahunan (AOC). Akhir sekali, penyelesaian optimal berdasarkan kepada penyusunan turutan dan ΔT_{min} diperoleh daripada pengiraan fungsi multi-objektif pada peringkat 6. Lima kajian kes dipilih untuk menilai dan mengesahkan kerangka yang dicadangkan. Ia telah berjaya merekodkan penjimatan tenaga antara 30% hingga 42% berbanding turutan sedia ada. Turutan optimum untuk kajian kes 1 ialah turutan split dengan nilai ΔT_{min} daripada 5 °C ke 30 °C. Turutan split-1D daripada 5 °C ke 20 °C disimpulkan sebagai turutan optimum bagi kajian kes 2 and kajian kes 3. Untuk kajian kes 4 dan 5, turutan optimum adalah split-1-split (ΔT_{min} daripada 5 °C ke 25 °C) dan split-1-D-split-2-D (ΔT_{min} daripada 5 °C ke 20 °C). Kesemua rekabentuk optimum boleh dianggap sebagai berkebolehlaksanaan secara proses di mana kesemua penukar haba di dalam proses tersebut mencatatkan nilai faktor pembetulan ft bersamaan 1.0. Selain itu, kaedah-kaedah tersebut juga menurunkan CC dan AOC kepada $870,000 dan $4.28 juta untuk kajian kes 3. Kos-kos yang sama juga diturunkan kepada sekitar 45% untuk CC dan 10% untuk AOC bagi kajian kes 4. Kajian kes 5 turut mengikut trend yang sama dengan penjimatan kos sebanyak $476,000 untuk CC dan anggaran $2.78 juta untuk AOC berbanding turutan asal. Secara keseluruhan, hasil penyelidikan menunjukkan bahawa kerangka tersebut berjaya menghasilkan EIDCS yang boleh dilaksanakan untuk semua kajian kes secara holistik, sistematik dan komprehensif.

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LIST OF ABBREVIATIONS

AOC - Annual Operating Cost
CC - Composite Curve
CPS - Conceptual Process Synthesis
CW - Cooling Water
DCS - Distillation Columns Sequence
DED - Double Effect Distillation
DWC - Divided Wall Column
EEDC - Energy Efficient Distillation Column
EIDCS - Energy Integrated Distillation Columns Sequence
FUG - Fenske, Underwood and Gilliland
FUGK - Fenske-Underwood-Gilliland-Kirkbride
GCC - Grand Composite Curve
GD - Grid Diagram
HEN - Heat Exchanger Network
HIDiC - Internally Heat Integrated Distillation Column
HPS - High Pressure Steam
LIES - Locally Integrated Energy Sector
LPS - Low Pressure Steam
MER - Maximum Energy Recovery
MINLP - Mixed Integer Non-linear Programming
MP - Mathematical Programming
MPS - Medium Pressure Steam
PTA - Problem Table Algorithm
SDM - Sequential Design Method
TAC - Total Annual Cost
TER - Total Energy Requirement
VCD - Vapor Compression Distillation
VRC - Vapor Recompression Column

LIST OF SYMBOLS

A - Area of heat exchanger

β_{ij} - Separability factor

C_{cw} - Cost of cooling water

C_{steam} - Cost of steam

CP - Heat capacity flowrate

D - Diameter of vessel

ΔT_{min} - Minimum temperature difference

ΔT_{LMTD} - Log mean temperature difference

F_c - Correction factor

F_d - Design factor

F_m - Material factor

F_p - Pressure factor

F_{ij} - Driving force

H - Height of vessel

J - Multi-objective function

$M\&S$ - Marshall and Swift cost index

N_S - No. of sequences

p - No. of products

P_i - Objective function i

P_a/P_b - Vapor pressure for component a/b

Q_c - Cooling requirement before pinch analysis

Q_{cmin} - Minimum cooling requirement

Q_h - Heating requirement before pinch analysis

Q_{hmin} - Minimum heating requirement

Q_i - Enthalpy of interval *i*

Q_{total} - Total energy requirement before pinch analysis

$Q_{totalmin}$ - Total energy requirement

S - Shifted temperature for the interval i

T - Temperature

$T_{c,in}$ - Inlet cold stream temperature

$T_{c,out}$ - Outlet cold stream temperature

$T_{h,in}$ - Inlet hot stream temperature

$T_{h,out}$ - Outlet hot stream temperature

U - Overall heat transfer coefficient

w_i - Weightage for objective function i

x_i - Liquid composition

y_i - Vapour composition

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Distillation is a well-known process and considered as a mature technology in a chemical and petrochemical processing plant. It is simply because it can accommodate for mass production of the intended products (Bisgaard *et al.*, 2017). However, two distinctive issues could arise from the distillation process whereby both of it involves energy usage: 1) environmental issues and the increase in stringency of the government environmental policy pertaining the carbon dioxide (CO_2) emissions, and 2) the efficiency of the process itself which ultimately determines the plant economic and business profitability (Halvorsen and Skogestad, 2011). The latter statement was strengthened by the fact that the distillation process accounted for more than 50 % of plant operating cost and 3 % of world energy consumption (Cui *et al.*, 2016). This has paved a way for several options to overcome the issues.

The term “Energy-Efficient Distillation” has been used by Jobson (2014) to emphasize the methods that can be employed for energy saving in a distillation process. The methods listed are: 1) conceptual design of simple columns, 2) operation and control, 3) advanced and complex column configurations, 5) evaluation of energy requirements and 5) heat integration of distillation.

The simplest method to achieve the energy-efficient distillation process is the conceptual design of the column which involved several design parameters such as degree of freedom for column design, column operating pressure, number of stages, feed condition, feed stage location and types of utilities and auxiliary equipment

(Jobson, 2014). All the parameters mentioned have the influence in determining the energy consumption in the distillation column. However, it is mostly suitable for a single column scenario whereby it cannot cater for more complex separation processes such as multi-component distillation columns sequence.

The role of column operation and process control are essential towards the energy-efficient distillation columns since it is related to the reflux, production capacity and purity of the product(s). In the economic perspective, the trade-off between those three parameters needs to be well managed, i.e. the higher the reflux, the higher the purity of the products but in return also demand higher energy consumption and can also become a hindrance in terms of the production capacity itself. Furthermore, the column condition needs to be in a good shape during operation especially the important column conditions such as temperature, pressure, flowrate, etc. (namely process set points in process control) and to compensate for any related disturbances as well. This explains why monitoring, control, maintenance, and operational management (dynamic studies) become a key to operate the distillation column efficiently (Jobson, 2014). The outcome of one particular research (Li *et al.*, 2017) showed that the improved dynamic configuration has been successfully compensated the process disturbances which are flowrate and composition in the extractive distillation columns for the separation of 2-methoxy ethanol/toluene.

Both methods for energy-efficient distillation columns explained previously involved a simple and conventional distillation column. There is also a method namely advanced column or complex column configuration which increasingly become an attractive way to save energy specifically for distillation processes. For instance, the Double Effect Distillation (DED) column has been proposed by Bessa *et al.* (2012) for the multi-component alcohol mixture. It resulted in a 54 % reduction in terms of steam usage compared to the conventional distillation column. Meanwhile, Díaz and Tost (2016) further investigation on the advanced column configuration has been done including DED and Vapor Compression Distillation (VCD) for ethanol and isobutanol separation. The study proved that both methods successfully reduced the energy consumption although the latter performs better at 25 to 30 % and 39 to 40 % lower than DED for isobutanol and ethanol, respectively. Internally Heat Integrated

Distillation Column (HIDiC) is an extended version of VCD and the research on it has been started as early as 1977 (Olujic *et al*., 2003). In a recent study by Li *et al*. (2016), HIDiC has been modified with the addition of a heat pump and being called intensified-HIDiC (int-HIDiC). The researchers have demonstrated that the performance of int-HIDiC is more superior compared to the conventional HIDiC and VCD itself and of course conventional distillation column in such a way that the system did not require a reboiler and low-pressure steam anymore.

The other method for energy-efficient distillation columns is the energy evaluation by employing several methods such as: 1) distillation column modelling, 2) thermodynamic analysis in the column and 3) thermal driving force method. For distillation column modelling, it can be a single column modelling and need to be synchronized with a sequence model to link it from one column to another in the case of multi-component system or a complex column configuration. The former is being called the shortcut method whereby it consists of a simple model such as Fenske, Underwood and Gilliland models that can be used to determine the estimation of reflux ratio, numbers of stages and feed location at a given process condition. It can also be used for early-stage of energy analysis for the proposed distillation columns sequence. Meanwhile, the latter is a rigorous method that is a stage by stage modelling and involves with more complex equation (mass and energy balance) and it can be a very good way to model the sequence of the distillation column as being explained in the literature (Rev *et al*., 2001). The authors employed the shortcut method to study the energy loss in the distillation column sequence and emphasized the potential of the Petlyuk Column for energy-saving via a rigorous simulation environment. Thermodynamic analysis can be a part of the energy evaluation as well mainly on the reversible distillation (Olujic *et al.*, 2003). The ideal case for reversible distillation is as simple as a binary column whereby it can be very challenging when involved with multi-component system. The main point in the study is the emergence of HIDiC as one of the attractive ways to conserve energy. As for the thermal driving force, it refers to the exergy analysis for measuring the irreversibility of the process.

The method suggested that the thermal profile of the process in the feed condition will largely affect the energy consumption of the process. Therefore, it will involve the addition of a pre-heater/cooler or side condenser/reboiler in the distillation process.

The last method enlisted by Jobson (2014) in the energy-efficient distillation column is a quite familiar process; heat integration. The concept of heat integration is very popular and is classified as one of the methods for process intensification (Stankiewicz and Moulijn, 2000). The concept involves the determination of heat exchange and heat recovery; heat sink and heat source; heating load and cooling load; and other related terms used in the literature (Jobson, 2014). By studying the available process flowsheet e.g. conventional distillation column, the pinch analysis can be used as a method to determine the energy requirement of the distillation process. Then, the possible energy saving will be generated using the heat exchanger network (HEN) grid diagram. This will trigger the question; can this method be combined with other suitable methods in the earlier paragraph? If yes, how much energy can be saved? This is one of the questions that needs to be answered in this study.

1.2 Problem Statement

Distillation is an energy-intensive process in chemical and petrochemical industry. There are two perspectives to establish the real energy-related issue behind the distillation process: 1) the energy usage of the distillation which accounted for 50 % of energy demand in the plant and 3 % of global energy consumption, and 2) the multi-component distillation process which further increases the energy consumption. Basically, both scenarios have been pointing in the same direction which is a huge amount of energy consumption. Despite that, distillation remains an option for the separation process in the chemical and petrochemical industry due to its versatility in terms of production and quality of the product itself. Therefore, it is not easy to replace the distillation process with other technology especially when dealing with retrofitting scenarios. The key to continually employ distillation column is to improve the efficiency of the process, specifically the distillation columns sequence. It will then lead to the ultimate goal in terms of economy, and environmental sustainability.

According to Rathore et al. (1974), a good chemical process should address these two sub-problems: 1) sequence of the process and 2) heat recovery system. The sequence of the process is related to the arrangement of distillation columns. There will be a superstructure of distillation sequence needed to be addressed prior to determine the optimal distillation columns sequence (sequence with lowest energy consumption) via mathematical programming. This will lead to complexity especially for the multicomponent distillation process whereby much tedious mathematical programming works are required. On the other hand, the heat recovery system for a distillation column can be regarded as the energy integration in the process. The process can be done with the background process namely process-to-process energy integration. Nevertheless, since the energy consumption of distillation column is huge, which originated from the condenser and reboiler of the column, there is also an opportunity for a utility-to-utility energy integration which led to the energy integration within the distillation process.

For utility-to-utility energy integration, there will be many possibilities for the exchangeable heat of the utility streams resulting the emerging of another superstructure to determine the optimal heat exchanger network within the distillation process. Furthermore, the problem will also be amplified if the sequence superstructure is to be considered as well to meet the definition of a good process as suggested by Rathore et. al (1974).

Therefore, this study will utilize the graphical methods to solve the complexity from both superstructure scenarios. This can be done by employing a driving force method, one of the recent conceptual process synthesis approaches that has been introduced by Bek-Pedersen et al. (2000). This will ensure at least a nearly optimal sequence could be achieved despite of using the mathematical programming. This will eliminate the issue pertaining the sequence superstructure. For the integration superstructure (based on forward and backward integration by Masoumi & Kadkhodaie (2012)), the thermal pinch analysis will be employed to complement the former method just now. The well-established method (Klemeš, 2013) with the graphical feature of thermal pinch analysis will be expected to further the energy saving of the process. The framework that integrates these two graphical methods has yet to be explored so far in terms of the feasibility either by the process feasibility or economic feasibility. Furthermore, the effect of ΔT_{min} in the heat integration within the distillation process has not been addressed as well particularly when involving the optimal distillation columns sequence. Therefore, this study proposes a sequential framework of graphical methods namely Energy Integrated Distillation Columns Sequence (EIDCS) for a systematic energy saving approaches for the distillation process. The ultimate goal for the proposed framework is the determination of the optimal sequence with the optimal ΔT_{min}.

1.3 Objective of the Study

Based on the research background and problem statement discussed earlier, the main objective of this study is to develop a new holistic, systematic and comprehensive framework for the energy integrated distillation columns sequence (EIDCS) by taking into account process feasibility, as well as the economic analysis in designing an optimal EIDCS in an easier, efficient and systematic manner.

There are some specific objectives that have to be fulfilled in achieving the main objective, which are:

1. To develop the new framework for designing optimal energy integrated distillation columns sequence problem.
2. To apply the sequencing method of manual analysis and the driving force method in determining the optimal solution to the energy integrated distillation columns sequence synthesis problem.
3. To apply the thermal pinch analysis method in determining the optimal solution to the energy integrated distillation columns sequence synthesis problem.

4. To verify the capability of the newly developed framework in solving energy integrated distillation columns sequence problem by considering into account the process feasibility and economy criteria using the case studies.

1.4 Scopes of the Study

To achieve the intended research objectives, the scope of research has been outlined as followed:

(a) Studying the state-of-the-art development and technologies related to energy integrated distillation columns (EIDCS) sequence synthesis, design, process feasibility and identify gaps and potential improvement for EIDCS sequence design and analyses.

(b) Developing a new holistic and comprehensive framework for designing a feasible EIDCS sequence. The development includes process feasibility and economic analyses to the established EIDCS sequence methodology. Specific scopes include:

    (i) Using commercial process simulator such as ASPEN HYSYS V10 to simulate the distillation columns sequence and analyze the energy requirement for each analyzed sequence.

    (ii) Extending the established EIDCS sequence methodology according to the number of chemical/petrochemical components/products in the system.

    (iii) Extending the established EIDCS sequence by including process feasibility and economic analyses for improving further the potential of energy saving.

(c) Applying the manual energy analysis and driving force-based distillation column sequence design concept in determining the optimal solution to the feasible EIDCS sequence synthesis problem. The specific scope is to determine the optimal sequence of distillation columns that requires less energy.

(d) Applying the thermal pinch analysis method in determining the optimal solution to the EIDCS sequences synthesis. Specific scopes are:

  (i) Applying the method of thermal pinch analysis in determining the optimal heat exchanger network within the existing and driving force sequences for improving further the potential of energy saving.

  (ii) Selecting the optimal value of ΔT_{min} starting from 5 to 40 ^{o}C which satisfying design (energy saving), process feasibility and economy criteria.

  (iii) Applying the Problem Table Analysis (PTA) and Grid Diagram (GD) for designing heat exchanger network within the existing and driving force sequences.

(e) Verifying the capability of the newly developed framework in solving complex EIDCS sequence problem by considering into account the process feasibility and economy criteria using case studies. In addition the multi-objective calculation or parametric analysis is used to obtain the optimal EIDCS.

1.5 Research Contributions

Through the work conducted in this study, several key contributions have been identified as follows:

(a) A new holistic and comprehensive EIDCS sequence framework

The new holistic and comprehensive framework for designing a feasible EIDCS sequence developed in this study can be applicable for any numbers of chemical/petrochemical components.

(b) Utility-to-utility heat integration

In the field of energy integration, many efforts have been done to integrate the energy stream based on process-to-process integration or so called the process integration with the background process. Therefore, this research will look at the potential for the process integration within the distillation process since the higher availability of the exchangeable heat particularly from condenser and reboiler.

(c) Solving the superstructure complexity

The determination of the optimal distillation columns sequence (the sequence with less energy consumption) requires vast analysis of the sequence superstructure. In addition to that, for the purpose of the energy integration, the integration superstructure should also need to be considered for further energy saving. This will lead to the complexity of the process and requires a tedious analysis works. Therefore, by employing the two-step sequential graphical method, it will solve both sequence and integration superstructure of the problem.

(d) Enhance energy saving

The energy saving for the distillation process can be enhanced in two steps, 1) the determination of the optimal sequence with less energy consumption compared to the existing sequence and 2) further energy saving via utility-to-utility energy integration. This will ensure higher energy saving for the distillation process.

(e) Better feasibility with regards to the value of ΔT_{min}

The EIDCS framework can be more feasible compared to the existing sequence since it promotes more exchangeable heat so that the process will maintain the energy saving throughout a range of ΔT_{min}.

Several publications have been successfully published from this study as a part of the intellectual contributions. The lists of publications and achievements that have been accomplished during the study period and the key contribution of the knowledge can be referred in the List of Publications.

1.6 Thesis Organization

There are five chapters in this thesis. The first chapter includes the background of the studies and the problem statements that lead to the formulation of EIDCS framework. Then the objectives and related scopes are outlined including the research contributions. Chapter 2 explains in details the development of the conceptual process synthesis and the thermal pinch analysis over the years to be associated with the formulation of EIDCS. The methodological framework is then proposed and explained in Chapter 3. It consists of the process categorization, driving force plot, shortcut and rigorous simulations, thermal pinch analysis, process feasibility analysis and economic analysis and the calculation of multi-objective functions. Chapter 4 details-out the results and discussion on the application of the EIDCS framework to the selected case studies. The effect of the value of ΔT_{min} towards the final output of the EIDCS framework is also discussed. Finally, the listed objectives are answered and concluded in Chapter 5. Besides, future works are also be suggested in the same chapter.

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LIST OF PUBLICATIONS

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1. **Shahruddin, M. Z.**, Asri , M. H., Mohd Zin, R., Rahimi, A. N., Zubir, M. A., Zahran, M. F. I., Ibrahim, N. & Abd. Hamid, M. K. 2020a. The Feasibility Study of Driving Force and Thermal Pinch Analysis Methods for Energy Saving of Natural Gas Liquid (NGL) Distillation Process. *Malaysian Journal of Chemical Engineering & Technology,* 3**,** 18-24.
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7. **Shahruddin, M. Z.**, Xinyi, T., Rahimi, A. N., Zubir, M. A., Zahran, M. F. I., Ibrahim, K. A. & Abd. Hamid, M. K. Thermal Pinch Analysis Application for Driving Force Distillation Columns Sequence of 5-Component Alcohol Mixture. International Graduate Conference on Engineering, Science and Humanities (IGCESH), 13-15 August 2018 2018c UTM Skudai, Johor Bahru.
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1. **Shahruddin, M. Z.,** Mokhtar, N. S., Mohd Zin, R., Rahimi, A. N., Zubir, M. A., Zahran, M. F. I., Ibrahim, N., Abd. Hamid, M. K. The Optimum Value of Minimum Temperature Gap in The Energy Targeting of Distillation Columns Sequence by Thermal Pinch Analysis. International Conference on Applied Energy 2020 (ICAE2020), 1-10 December 2020, Bangkok, Thailand (Virtual)
2. **Shahruddin, M. Z.**, Xinyi, T., Rahimi, A. N., Zubir, M. A., Zahran, M. F. I., Ibrahim, K. A. & Abd. Hamid, M. K. Thermal Pinch Analysis Application for Distillation Columns Sequence of 5-Component Alcohol Mixture. International Graduate Conference on Engineering, Science and Humanities (IGCESH), 13-15 August 2018 2018b UTM Skudai, Johor Bahru.
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