ETHYLENE YIELD FROM A LARGE SCALE NAPHTHA PYROLYSIS CRACKING UTILIZING RESPONSE SURFACE METHODOLOGY

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DEDICATION

This thesis is dedicated to my late Abah (Zakria Mohamed), beloved Ummi (Rabiah Awang), Aboh (Jaafar Ali), Mama (Zakiah Ismail), supportive wife (Amirah Jaafar), and beloved children (Farhah Amni, Hanan Sufiyyah, Iffah Mardhiyyah, and Wafa Nadheera).

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ABSTRACT

It is desirable in industry to optimize the production yield from olefin plant, for instance, to achieve the highest profit from the yield of ethylene. However, there are gaps associated with the restricted usage of the proprietary simulation software and the lack of a specific model to correlate the relationship between variables that has a significant impact on the processing parameters. In this study, response surface methodology (RSM) was used to evaluate the impact of critical operating parameters from large scale naphtha pyrolysis cracking. Those parameters include hearth burner flow, integral burner flow, naphtha feed flow, dilution steam flow, and coil outlet temperature (COT), with the addition of propylene yield towards the ethylene yield. The data was collected at the steam cracker furnace using process information management system (PIMS) software, PI process book version 2015. The analysis was conducted for naphtha feedstock with paraffins content at 57.60 – 70.73 vol % to evaluate the impact of operating at different naphtha feedstock compositions on the ethylene yield. Propylene yield, hearth burner flow, and naphtha feed flow consistently showed a significant relationship with ethylene yield from surface response analysis with the interaction factor ranges at -10.07 to 192.3, -0.001698 to 0.01938, and -2.383 to 820, respectively. The final equation models were successfully concluded in the form of quadratic with 2-way interaction at the high paraffins content and linear relation at the lower paraffins content after the models' validation using probability plot, scatterplot, and Mann-Whitney hypothesis test. The maximum ethylene yield generated from response optimizer was observed dissimilar at 31.46 – 34.97 % for different paraffins content in naphtha feedstock, with the highest reading observed for the naphtha feedstock having the highest paraffins content. The best ethylene yield with consideration to the production cost for the naphtha with the highest paraffins content of 70.73 vol % was identified at the range 34.41 – 34.97 %, using the recommended process ranges at 12.22 – 12.25 % of propylene yield, 11033.90 – 11816.40 kg/hr of hearth burner flow, 66.67 – 67.05 t/hr of naphtha feed flow and 816.38 °C of COT. It is recommended for other large scale plants to adopt the same methodology that was proven successful in this study, for process monitoring and optimization.

ABSTRAK

Proses mengoptimumkan hasil pengeluaran daripada loji olefin adalah suatu keperluan di industri, antaranya untuk mendapatkan keuntungan tertinggi daripada hasil etilena. Walau bagaimanapun, terdapat kekangan disebabkan oleh keterbatasan pemilikan perisian simulasi, serta kekurangan model untuk menghubungkaitkan pembolehubah-pembolehubah yang mempunyai kesan ketara terhadap parameter proses. Kaedah tindak balas permukaan (RSM) telah digunakan dalam kajian ini untuk menilai kesan pembolehubah operasi kritikal daripada proses pemecahan pirolis nafta berskala besar. Parameter yang dimaksudkan adalah aliran penunu perapian, aliran penunu integral, aliran nafta, aliran wap pencairan, suhu salur keluar gegelung (COT) dengan penambahanan hasil propilena ke arah keberhasilan etilena. Data dikumpul di relau stim menggunakan perisian sistem pengurusan maklumat proses (PIMS), buku proses PI versi 2015. Analisis dijalankan kepada bahan mentah nafta pada kandungan parafin 57.60 – 70.73 vol % untuk menilai kesan operasi komposisi nafta yang berbeza terhadap hasil etilena. Hasil propilena, aliran penunu perapian, dan aliran nafta secara konsisten menunjukkan hubungan signifikan terhadap hasil etilena semasa analisis tindak balas permukaan dijalankan, dengan julat faktor interaksi masing-masing dalam -10.07 hingga 192.3, -0.001698 hingga 0.01938, dan -2.383 hingga 820. Model akhir berjaya diwujudkan dalam bentuk model persamaan kuadratik dengan interaksi 2 hala pada kandungan parafin tinggi, dan hubungan linear pada kandungan parafin rendah selepas pengesahan model dijalankan melalui plot kebarangkalian, plot serakan, dan ujian hipotesis Mann-Whitney. Hasil etilena maksimum yang dijana daripada tindak balas pengoptimum diperhatikan tidak sama pada kadar 31.46 – 34.97 % untuk kandungan parafin dalam nafta yang berbeza, dengan bacaan tertinggi dicatatkan oleh nafta yang mempunyai kandungan parafin tertinggi. Hasil terbaik etilena pada kandungan parafin tertinggi iaitu 70.73 vol % dengan mengambil kira kos pengeluaran dikenal pasti pada kadar 34.41 – 34.97 %, menggunakan julat proses yang disyorkan pada 12.22 – 12.25 % hasil propilena, 11033.90 – 11816.40 kg/j aliran penunu perapian, 66.67 – 67.05 t/j aliran nafta dan 816.38 °C COT. Adalah disyorkan kepada loji berskala besar lain untuk menggunakan metodologi yang telah terbukti berjaya dalam kajian ini, untuk pemantauan dan pengoptimuman proses.

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6σ - Six-sigma
λ - Lambda (for Box-cox transformation)
A1 - Propylene yield
B - Hearth burner flow
BCRE1 - Storage in Minitab (transformed value of response)
BFIT1 - Storage in Minitab (fitted value of original response)
C - Integral burner flow
C1 - Carbon group 1
C2 - Carbon group 2
C3 - Carbon group 3
C4 - Carbon group 4
C5 - Carbon group 5
C_nH_{2n} - Standard formulae for alkenes (olefins)
C_nH_{2n+2} - Standard formulae for alkanes (paraffins)
C-C - Carbon to carbon bond
C=C - Carbon double bond
C-H - Carbon to hydrogen bond
COEF1 - Storage in Minitab (coefficient)
D - Dilution steam flow
DFIT1 - Storage in Minitab (for DFIT)
E - Naphtha feed flow
F - Coil outlet temperature
FITS - Storage in Minitab (fitted values)
g - Geometric means (for Box-cox transformation)
H_0 - Null hypothesis
H_1 - Alternative hypothesis
N - Number of tests
RESI1 - Storage in Minitab (residuals)
X1 - Ethylene yield
vol % - Volume percent

wt % - Weight percent

LIST OF ABBREVIATIONS

2D	-	2-Dimensional
3D	-	3-Dimensional
AGO	-	Atmospheric Gas Oil
AHP	-	Analytic Hierarchy Process
AL	-	Arabian Light
ANN	-	Artificial Neural Network
ANOVA	-	Analysis of Variance
API	-	American Petroleum Institute
ASL	-	Arab Super Light
AXL	-	Arab Extra Light
BATH	-	Bio-acid Acetone to Hydrocarbon
BDU	-	Butadiene Unit
BFW	-	Boiler Feed Water
BFWP	-	Boiler Feed Water Preheat
CAPEX	-	Capital Expenditure
CC	-	Catalytic Cracking
CCD	-	Central Composite Design
CFD	-	Computational Fluid Dynamics
CGC	-	Charge Gas Compressor
CI	-	Confidence Interval
COP	-	Coil Outlet Pressure
COT	-	Coil Outlet Temperature
DCC	-	Deep Catalytic Cracking
DCS	-	Distributed Control System
DEACM	-	Data Envelopment Analysis Cross Model
DF	-	Degree of Freedom
DH	-	De-hydration Process
DoE	-	Design of Experiment
DOX	-	Disperse Oil Extraction
DS	-	Dilution Steam

DSSH	-	Dilution Steam Superheat
DV	-	Decoke Valve
EBST	-	Ethane Buffer Storage Tank
EOEG	-	Ethylene Oxide Ethylene Glycol
EOR	-	End of Run
EPC	-	Engineering, Procurement, Construction
EPCC	-	Engineering, Procurement, Construction, and Commissioning
FCC	-	Fluidized Catalytic Cracking
FP	-	Flash Pyrolysis
FPH	-	Feed Preheat
FT	-	Fischer-Tropsch Synthesis
GA	-	Genetic Algorithm
GF	-	Gasoline Fractionator
GS	-	Gas Stream (Reactor Technology)
GSO	-	Group Search Optimization
HC	-	Hydrocarbon
HCR	-	Hydrocracker Residue
HDoE	-	Historical Design of Experiment
HEx	-	Heat Exchanger
HG	-	Hydrogenation
HHP	-	High Pressure (Super High Pressure)
HP	-	Hydro-pyrolysis (Specific to Figure 2.1)
HP	-	High Pressure
HPS	-	High Pressure Steam
HTUL	-	Hydro-thermal Upgrading Liquefaction
HVGO	-	Heavy Vacuum Gas Oil
IDF	-	Induced Draft Fan
I-MR	-	Individual – Moving Range
KTA	-	Kilo Tonne Per Annum
KTI	-	Kinetics Technology International
LCL	-	Lower Control Limit
LDV	-	Large Decoke Valve
LFPH	-	Lower Feed Preheat

LMP	-	Lower Mix Preheat
LPG	-	Liquefied Petroleum Gas
LSSH	-	Lower Steam Superheat
LSSVM	-	Least Square Support Vector Machine
LTHT	-	Lummus Technology Heat Transfer
MAPD	-	Methyl Acetylene Propadiene
MC	-	Management Committee
MINLP	-	Mixed-Integer Nonlinear Programming
MOC	-	Management of Change
MOO	-	Multi-Objective Optimization
MS	-	Mean of Square
MSSH	-	Medium Steam Superheat
MTO	-	Methanol to Olefins
MW	-	Molecular Weight
NBST	-	Naphtha Buffer Storage Tank
NLP	-	Nonlinear Programming
OA	-	Outer Approximation
OC	-	Oxidative Coupling
OM	-	Olefin Metathesis
OPEX	-	Operating Expenditure
OU	-	Olefins Upgrading
PD	-	Propane Dehydrogenation
PFD	-	Process Flow Diagram
PFO	-	Pyrolysis Fuel Oil
PGO	-	Pyrolysis Gas Oil
PI	-	Predictive Interval
PIMS	-	Process Information Management System
PIONA	-	n-Paraffins, Isoparaffins, Olefins, Naphthenes, Aromatics
PONA	-	Paraffins, Olefins, Naphthenes, Aromatics
PSA	-	Pressure Swing Adsorption
PSO	-	Particle Swarm Optimization
PWS	-	Process Water Stripper
QT	-	Quench Tower

RFCC	-	Residual Fluidized Catalytic Cracking
ROG	-	Refinery Off-Gas
RSM	-	Response Surface Methodology
RVP	-	Reid Vapor Pressure
SAS	-	Statistical Analysis Software
SC	-	Steam Cracking
SDV	-	Small Decoke Valve
SE	-	Standard Error
SH	-	Super High
SHPS	-	Super High Pressure Steam
SQP	-	Sequential Quadratic Programming
SR	-	Steam Reforming
SRN	-	Straight Run Naphtha
SRT	-	Short Residence Time
SS	-	Sum of Square
SSH	-	Steam Superheat
SSPS	-	Statistical Package for Social Sciences
TBP	-	True Boiling Point
TLE	-	Transfer Line Exchanger
TLV	-	Transfer Line Valve
TMT	-	Tube Metal Temperature
UCL	-	Upper Control Limit
UMP	-	Upper Mix Preheat
USA	-	United State of America
USD	-	United State Dollar
USSH	-	Upper Steam Superheat
UTM	-	Universiti Teknologi Malaysia
UTP	-	Universiti Teknologi PETRONAS
VFD	-	Variable Frequency Drive
VIF	-	Variance Inflation Factor
WRGO	-	Wide Range Gas Oil

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CHAPTER 1

INTRODUCTION

1.1 Preface

Olefins are unsaturated hydrocarbons comprised of a single double bond with a chemical formula of C_nH_{2n}. They are one of the most important chemicals in the petrochemical industry that form the basis for most of the essential applications such as pharmaceuticals, insulation, plastic, cosmetics product, and synthetic fiber (Bender, 2014; Fakhroleslam & Sadrameli, 2020; Rahimi & Karimzadeh, 2011; Sadrameli, 2015, 2016; Zhu et al., 2017).

Olefin plants utilizing steam cracking in the steam cracker furnace are often defined as the core of the petrochemical industry (Fan et al., 2015; Nikolaidis et al., 2018). Its plant performance is important in indicating the development of the chemical industry in the country and region (Gong et al., 2017) due to its significant contribution to the industry.

Ethylene and propylene are examples of the most important olefins produced widely in the olefin plants to meet the demands in the petrochemical industry. Their yield monitoring from the steam cracker furnace is therefore essential as their values translate to the profit generation and sustainability of the olefin plant, especially to the steam cracker furnace performance (Díaz & Bandoni, 1996; Gholami et al., 2021; Khor et al., 2014; Lashkajani et al., 2016; Leo et al., 2018; Luo et al., 2015; Petracci et al., 1993; Ruckaert et al., 1978).

Previous studies had been established to utilize various process simulations to improve the olefins' yield (Geng et al., 2016; Leo et al., 2018; Song & Tang, 2018; Yu et al., 2018). These simulation studies were successfully developed and significantly improve the olefins' yield by controlling various controlled variables in the olefin process. The effort to enhance the olefin process continues, targeting various operating parameters for steam cracking utilizing gaseous and liquid feedstocks. Most of the studies were carried out using olefin simulation software, with some being verified at the lab or small pilot plant.

Besides the well-utilized simulation software for olefin process evaluation and improvement, there is also a bright prospect to utilize statistical software that was proven robust such as Minitab (Arminian & Ozgur, 2020; Martin & Roberts, 1996; Ozgur, 2019), Stata (Fuad et al., 2015; Shim et al., 2016), SSPS (Cuesta-Lozano et al., 2020; Ozgur, 2019; Sahud Alotaibi, 2020), SAS (Gunst, 2012; Ozgur, 2019; Sullivan & Greenland, 2012), and GraphPad Prism (Mavrevski et al., 2018; Mitteer et al., 2019) as they seem more practical to be practiced by Operation personnel compared to the complex and expensive simulation software equipped by Olefin Licensors that come with a high price and restricted access to safeguard the proprietary design knowledge by Olefin Licensors.

ABB Lummus, KTI-Technip, Linde AG (Pyrocrack), Stone and Webster, M.W. Kellogg (Brayden et al., 2008; Sadrameli, 2015), and Sinopec (Pu & Shi, 2013; Wang et al., 2021) are examples of the established Olefin Licensors which having mature, reliable, and proven olefin technologies. There are also various available simulation software from Olefins Licensors and simulation companies that is currently available such as SPYRO (Dente et al., 1979; Van Goethem et al., 2001), SHAHAB (Toufighi et al., 2004), CRACKER (Joo et al., 2000; Joo & Park, 2001), CHEMKIN (Kee et al., 2006; Reyniers et al., 2017; Van Cauwenberge et al., 2017) and CRACKSIM (Hillewaert et al., 1988; Van Geem et al., 2008; Willems & Froment, 1988).

Surface response analysis is an example of established mathematical and statistical approaches used for modeling and analyzing a process (Haladu et al., 2022; Montgomery, 2017) that may utilize the available statistical software in the market. In surface response analysis, the response of interest is affected by the number of variables (Braimah et al., 2016) in multi-relations. The recent studies conducted for various normal type furnaces utilizing surface response analysis (Ganesh et al., 2018; Sun, Yang, et al., 2016; Sun, Zhang, et al., 2016) had also successfully improved the related process. However, the surface response implementation towards the ethylene yield from special type furnaces, such as steam cracker furnace in the actual fluctuating large scale olefin plant with non-normal data, is not found in the literature.

This study was conducted with a focus on ethylene yield at the newly commissioned olefin plant with the design capacity to produce 1,100 KTA of polymer grade ethylene from the steam cracker furnace, Short Residence Time (SRT) VII type. The feedstock used in the studied plant is a straight run naphtha (SRN) from the upstream plant and is cracked in the SRT VII with the operating tube metal temperature (TMT) of 1,050 °C - 1,180 °C. Conducting the study in actual olefin plant conditions is challenging, resulting from various process fluctuations (Feli et al., 2017; Lin et al., 2021; Zakria, 2018; Zakria et al., 2016) and variations in the upstream process, downstream readiness, utility shortage, and frequent changes in the feedstock compositions. Figure 1.1 shows the configuration of the SRT VII furnace with its support auxiliaries at the studied plant.

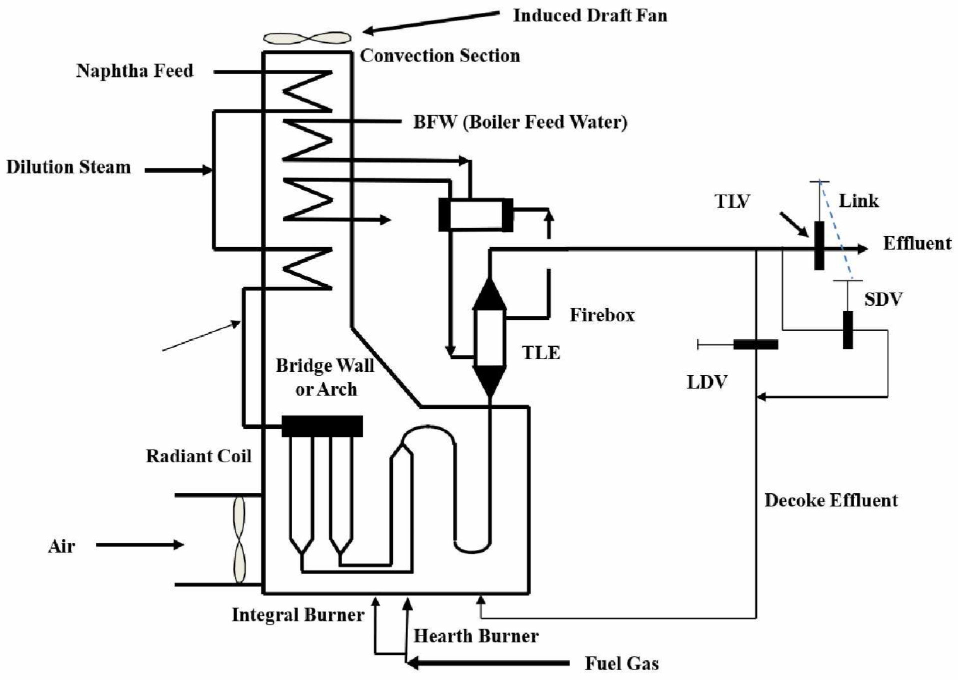

Figure 1.1 Configuration of SRT VII in the studied plant

This study is essential as a baseline and provides the guidelines to the Operations personnel in the actual olefin plant to systematically monitor and improve the ethylene yield. It adopts practical statistical software from both academic and industrial perspectives, providing a reliable alternative to the simulation software offered by Olefin Licensors.

1.2 Problem Statement

Surface response analysis is the established statistical multi-response analysis proven successful in improving the process (Ganesh et al., 2018; Sun, Yang, et al., 2016; Sun, Zhang, et al., 2016). However, it is not widely discussed at the large scale olefin process as the olefin plant often relies on the Olefin Licensors to run their proprietary simulation software should there is any process upset. This causes process troubleshooting and evaluation to become longer and more challenging, especially for the fluctuating process with non-normal data that is frequently observed at the large scale olefin plant (Feli et al., 2017; Lin et al., 2021; Zakria, 2018; Zakria et al., 2016). No surface response analysis study was found from the literature on the steam cracker furnace in the large scale olefin plants to find various variables' significant and interaction factors towards the ethylene yield focusing on non-normal data from fluctuating plant conditions. Besides, the output provided from Olefins Licensor's simulation software is in the form of a few operating cases which require further interpretation, without a specific linear or quadratic equation model with coefficient factors that can directly correlate the relationship of controlling variables for faster decision by Operations personnel. In addition, due to the dynamics of naphtha feedstock compositions in the olefin plant, a fast but reliable analysis tool to handle the evaluation of different naphtha feedstock compositions, especially on the paraffins content towards ethylene yield, is also required. Furthermore, previous studies on improving the olefins process mostly focused on increasing the olefin yield (Berreni & Wang, 2011; Khor et al., 2014; Riverol & Pilipovik, 2007; Song & Tang, 2018) via increasing the Coil Outlet Temperature (COT) with less focus to the operating cost at the large scale application. However, operating a large scale steam cracker furnace at the highest COT is impractical where it may cause a higher fuel gas consumption and, therefore largely increase the production cost. The practical guideline to be established for Operations personnel at the large scale olefin plant to monitor and improve the ethylene yield effectively and economically.

1.3 Objective of Study

This study focuses on evaluating the ethylene yield from steam cracking using naphtha as a feedstock at the actual plant condition with various process fluctuations. The study is conducted at the newly commissioned steam cracker furnace, SRT VII type, with the objectives as follows:

i) To analyze the significance and interaction factors for the controlled variables in the SRT VII furnace.

ii) To establish the linear or quadratic equation model with two-way interactions between significant variables for the ethylene yield from the actual fluctuating plant condition using surface response analysis.

iii) To investigate the impact of operating the SRT VII furnace at different naphtha feedstock compositions towards ethylene yield.

iv) To evaluate the process condition in achieving the best ethylene yield with consideration to the production cost through the proposed operating parameters in Response Optimizer.

1.4 Scope of Study

The scope of study mainly focuses on developing the ethylene yield model using surface response analysis at one dedicated SRT VII furnace in the studied plant. The study also will cover the following scopes:

i) Analysis of the significance and interaction factors for the selected operating variables towards the ethylene yield. The process range for data analysis was limited to the actual plant operating condition for the studied variables during the study duration with hearth burner flow (10.08 – 12.19 t/hr), integral burner flow (0.61 – 0.74 t/hr), dilution steam flow (40.59 – 40.79 t/hr), naphtha feed flow (61.33 – 72.89 t/hr), COT (809.27 – 816.38 °C) and propylene yield (10.63 – 12.25 %). The analysis proceeded regardless of the non-normal data was extracted from PI Process Book to represent the actual large scale operating plant condition using the Box-cox data transformation approach throughout the data analysis.

ii) Establishment of final equation model based on the linear or quadratic equation model for the ethylene yield. The data validation for the final model utilized the existing plant data used for the analysis and also the new data. For existing data, the validation covered a full range of ethylene yield using Probability Plot of residuals and Scatterplot with the support of Mann-Whitney hypothesis test for actual versus predicted ethylene yield. For model validation using the new data, the analysis is limited to only 1.5 days (36 hours) of actual plant data, established after the surface response analysis was completed. This was due to the studied SRT VII limitation resulting from coke continuous built-up in the coils which may interfere on the validation of the established model.

iii) Investigation of ethylene yield from different naphtha feedstock compositions at 3 cases based on the main component, which was paraffins, ranging from 57.6 – 70.7 vol %. Only paraffins content was studied for comparison as this study did not intend to evaluate the full aspect of naphtha feedstock composition towards ethylene yield. The analysis of the relationship between identified significant variables towards the ethylene yield was presented using the available graphical tools in Minitab, which are Interaction Plot, Surface Plot, and Response

Optimizer. In this step, the maximized ethylene yield comparison between these cases was established using Response Optimizer without considering the production cost.

iv) Evaluation of ethylene yield considering the production cost, limited to the proposed operating conditions in Response Optimizer. The actual costs for the significant variables were inserted into the evaluation table and calculated based on the previously validated final equation model to see the impact of the production cost from the identified significant variables on the ethylene yield. The range of most profitable process conditions at the studied SRT VII was determined from the evaluation table, limited to the identified significant variables in the validated final equation model.

1.5 Significance of Study

Analyzing the non-normal process data is practical to be applied at the large scale olefin plant due to frequent process fluctuation (Feli et al., 2017; Lin et al., 2021; Zakria, 2018; Zakria et al., 2016) observed at the steam cracker furnace, such as SRT VII. It will also significantly reduce the time from excessive data clearance, which is not practical to be conducted due to time-consuming. Besides, deleting the vast non-normal data to make the data normal may also unnecessarily remove the essential actual process variability at the actual plant condition. Minitab software version 21 can run the analysis to find the significance and interaction factors of the studied variables in the SRT VII directly by transforming the non-normal data using the Box-cox transformation approach (Minitab, 2022).

Besides, the established equation model using surface response analysis will show the impact of each significant variable in the form of the coefficient factors on the linear or quadratic equation model. The coefficient factors on this equation model may guide Operations personnel to focus on which controlled variables to be given closer attention to in generating a better ethylene yield. Besides, the capability of surface response analysis in Minitab to establish the multiple response relationships in the form of the equation model is practical and may help Operations personnel to act fast and avoid unnecessary opportunities lost for the studied plant compared to waiting for the response from Olefins' Licensor on their proprietary simulation result.

Surface response analysis may also investigate the ethylene yield under various conditions, including the different paraffins content in naphtha feedstock using a large amount of data. This flexibility ensures various conditions at the studied steam cracker furnace can be analyzed using the surface response analysis without the need for integration with other methods. Besides, the graphical tools in the Minitab, such as Interaction Plot, Surface Plot, and Response Optimizer, are effective in evaluating the impact of operating the steam cracker furnace at different naphtha feedstock compositions towards the ethylene yield. These graphical representations are also practical for Operation personnel to directly assess the effect of each studied naphtha composition towards the ethylene yield through the graphical representation without the complex evaluation through the calculations and additional detailed analysis.

The evaluation of ethylene yield with consideration to the production cost is important in the actual plant condition. Achieving the maximum olefins yield is usually the goal for any operating olefin plant, as the higher olefins yield typically translates to higher profit generation (Díaz & Bandoni, 1996; Gholami et al., 2021; Khor et al., 2014; Lashkajani et al., 2016; Leo et al., 2018; Luo et al., 2015; Petracci et al., 1993; Ruckaert et al., 1978). The actual large scale olefin plant depends on various operating parameters to remain profitable. Therefore, the operational process evaluation based on profit generation is essential. This study also will evaluate the ethylene yield with consideration to the production cost from the established significant variables using the validated final equation model. This approach is necessary to achieve the best olefins' yield with consideration to the production cost to keep a healthy financial flow to the studied plant.

1.6 Thesis Outline

The thesis is organized into six chapters. Chapter 1 starts with a brief introduction about the olefins, information on the steam cracker furnace, and the background of the surface response analysis. Besides, this chapter also presents the problem statement, objectives, scope of work, and significance of the study. Chapter 2 discusses the detailed literature taken from previous, current, and future works in improving ethylene yield. This chapter presents the information on the olefins production, reaction mechanism, steam cracker furnace, statistical analysis focusing on surface response, and previous olefin yield improvement studies. Chapter 3 describes the detailed research methodology, starting from selecting controlled variables, data transformation from non-normal data, and methods used to illustrate the impact of the process on the production cost. This chapter also discusses the basic procedure for data analysis using surface response analysis with the validation steps for the final equation model. Chapter 4 discusses the detailed analysis results of the study's significant factors and equation model establishment. This chapter critically explains one-by-one variable elimination using surface response analysis for all studied cases: Case 1, Case 2, and Case 3. Chapter 5 focuses on the ethylene yield relationship from the final equation model validated in Chapter 4. It explains the investigation findings on the relationship between the significance variables assisted by graphical tools in Minitab for the maximized and optimized condition (further evaluation considering production cost). Finally, Chapter 6 summarizes the research conclusion and responds to all the objectives planned for the study. It also provides recommendations for future studies on ethylene yield valuation at the end of the chapter.

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LIST OF PUBLICATIONS

1. **Zakria, M. H.**, Mohd Ghazali, M. N., & Abdul Rahman, M. R. (2021). Ethylene Yield from a Large Scale Naphtha Pyrolysis Cracking Utilizing Response Surface Methodology. *Pertanika Journal of Science & Technology*, *29*(2), 791-808. https://doi.org/10.47836/pjst.29.2.06 **(Indexed by WOS ESCI & SCOPUS)**

2. **Zakria, M. H.**, Mohd Ghazali, M. N., Abdul Rahman, M. R., & Saudi, M. A. (2021). Ethylene yield in a large scale olefin plant utilizing regression analysis. *Polyolefins Journal*, *8*(2), 105-113. https://doi.org/10.22063/poj.2021.2795.1169 **(Indexed by SCOPUS)**

3. **Zakria, M. H.**, Mohd Nawawi, M. G., & Abdul Rahman, M. R. (2021a). Ethylene Yield from Pyrolysis Cracking in Olefin Plant Utilizing Regression Analysis. *E3S Web of Conference*, *287*, 1-6. https://doi.org/10.1051/e3sconf/202128703004 **(Indexed by WOS CPCI & SCOPUS)**

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