



Cairo University

**A SYSTEMATIC METHODOLOGY FOR RETROFIT  
ANALYSIS OF REFINERIES' PREHEAT TRAINS  
ACCOUNTING FOR VARIABLE HEAT CAPACITIES  
AND HEAT EXCHANGERS' FOULING**

By

**Haya Khaled Frez Hussein**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Chemical Engineering**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2020

**A SYSTEMATIC METHODOLOGY FOR RETROFIT  
ANALYSIS OF REFINERIES' PREHEAT TRAINS  
ACCOUNTING FOR VARIABLE HEAT CAPACITIES  
AND HEAT EXCHANGERS' FOULING**

By

**Haya Khaled Frez Hussein**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Chemical Engineering**

Under the Supervision of

**Prof. Dr. Fatma El-Zahraa Ashour**

**Prof. Dr. Mamdouh Ayad Gadalla**

.....  
Professor of Chemical Engineering  
Chemical Engineering Department  
Faculty of Engineering, Cairo  
University

.....  
Professor of Chemical Engineering  
Chemical Engineering Department  
Faculty of Engineering, Port Said  
University

**Prof. Dr. Osama Abd El-Baari  
Ibrahim**

.....  
Professor of Chemical Engineering  
Chemical Engineering Department  
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2020

**A SYSTEMATIC METHODOLOGY FOR RETROFIT  
ANALYSIS OF REFINERIES' PREHEAT TRAINS  
ACCOUNTING FOR VARIABLE HEAT CAPACITIES  
AND HEAT EXCHANGERS' FOULING**

By

**Haya Khaled Frez Hussein**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Chemical Engineering**

Approved by the  
Examining Committee

---

**Prof. Dr. Fatma El-Zahraa Ashour**, Thesis Main Advisor

---

**Prof. Dr. Mamdouh Ayad Gadalla**, Advisor

---

**Prof. Dr. Hanan Hassan El-Sersy**, Internal Examiner

---

**Prof. Ibrahim Hindi Alhajri**, External Examiner

- Associate Professor, Chemical Engineering Department, College of Technological Studies, Kuwait.

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2020

**Engineer's Name:** Haya Khaled Frez Hussein  
**Date of Birth:** 06 / 07 / 1991  
**Nationality:** Egyptian  
**E-mail:** [haya.khaled91@gmail.com](mailto:haya.khaled91@gmail.com)  
**Phone:** 00201099215404  
**Address:** 37 Rateb Street, Shoubra  
**Registration Date:** 01 / 03 / 2014  
**Awarding Date:** / / 2020  
**Degree:** Master of Science  
**Department:** Chemical Engineering  
**Supervisors:**



Prof. Fatma El-Zahraa Ashour  
Prof. Mamdouh Ayad Gadalla  
Prof. Osama Abd El-Baari Ibrahim

**Examiners:**

Prof. Fatma El-Zahraa Ashour (Thesis main advisor)  
Prof. Mamdouh Ayad Gadalla (Advisor)  
Prof. Hanan Hassan El-Sersy (Internal examiner)  
Prof. Ibrahim Hindi Alhajri (External examiner)  
- Associate Professor, Chemical Engineering  
Department, College of Technological Studies,  
Kuwait

**Title of Thesis:**

**A systematic methodology for retrofit analysis of refineries' preheat trains accounting for variable heat capacities and heat exchangers' fouling**

**Key Words:**

Heat Integration; Energy Saving; Fouling; Heat capacity; HEN Revamping

**Summary:**

Global demand for energy is growing, driven by increasing population and economic growth. Over the past three decades, world energy consumption has more than doubled. Oil refining is an energy consuming process, accounting for about half of all the energy consumed by the oil and gas industry. In order to decrease the energy consumption in the furnace and consequently decrease the overall energy consumption in the refinery, it is required to maximize the temperature of the crude oil before entering the furnace by increasing the efficiency of the preheat train.

Revamping can enhance the energy efficiency to improve productivity, lower the operating costs, and reduce the environmental impacts.

This study proposes a systematic methodology for analyzing the revamping of refinery's preheat train accounting for variable heat capacities and heat exchangers fouling. It introduces two modifications on the case study modification that was published in the article "A new graphical method for Pinch Analysis applications: Heat exchanger network retrofit and energy integration". The first modification, that the assumption of constant heat capacity is to be criticized and analyzed. The second modification is taking fouling into considerations. This will lead to a decrease in the cost of the furnace fuel by approximately 508,718.6 dollars/year.

## **Disclaimer**

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Haya Khaled Frez Hussein

Date: .../.../...

Signature:

## **Dedication**

*This thesis is dedicated to my mother.*

## Acknowledgments

I would like to express my deepest appreciation to many people, who have made this work possible. I wouldn't have finished this thesis without their help.

Firstly, I would like to express my sincere gratitude to my advisor Prof. Dr. Mamdouh A. Gadalla for his continuous support, patience, time, and great knowledge. His guidance helped me in all the time of research and working on this thesis.

Besides, my advisor Prof. Dr. Fatma-El Zahraa Ashour, I'm grateful for her endless support and motivation. She was always there for help whenever I needed.

I would like to thank Prof. Dr. Osama Abd El-Baari for his supervision, time and constructive comments throughout the stages of the thesis.

Also, I would like to thank all my professors, colleagues, and friends in the Chemical Engineering Department for their continuous encouragement especially Eng. Shady Fahim and Eng. Nora Hany.

Finally, I'm thankful for my family, especially my mother for providing me with her support, kindness, and continuous encouragement throughout my life and through the process of researching and writing my thesis. This accomplishment would not have been possible without her. Thank you.

# Table of Contents

<b>DISCLAIMER .....</b>	<b>I</b>
<b>DEDICATION .....</b>	<b>II</b>
<b>ACKNOWLEDGMENTS.....</b>	<b>III</b>
<b>TABLE OF CONTENTS .....</b>	<b>IV</b>
<b>LIST OF TABLES.....</b>	<b>VI</b>
<b>LIST OF FIGURES.....</b>	<b>VII</b>
<b>NOMENCLATURE .....</b>	<b>IX</b>
<b>ABSTRACT .....</b>	<b>X</b>
<b>CHAPTER 1 : INTRODUCTION .....</b>	<b>1</b>
<b>CHAPTER 2 : LITERATURE REVIEW .....</b>	<b>2</b>
2.1. INTRODUCTION .....	2
2.2. PROCESS INTEGRATION.....	3
2.2.1. Pinch technology.....	3
2.2.1.1. Pinch point.....	4
2.2.1.2. Pinch objectives .....	4
2.2.2. Composite curves.....	6
2.2.3. Grand composite curves.....	8
2.3. REVAMPING OF HEAT EXCHANGERS .....	10
2.4. HEAT CAPACITY .....	12
2.5. FOULING .....	13
2.5.1. Fouling mechanism.....	13
2.5.2. Parameters affecting the fouling .....	13
2.5.3. Rate of fouling .....	14
1. Linear fouling .....	14
2. Falling fouling .....	14
3. Accelerating fouling .....	14
4. Asymptotic fouling .....	15
5. Saw-tooth fouling .....	15
2.5.4. Removal of fouling deposits .....	16
2.6. COST.....	16
<b>CHAPTER 3 : STATEMENT OF THE PROBLEM.....</b>	<b>17</b>
<b>CHAPTER 4 : MODEL DEVELOPMENT.....</b>	<b>20</b>
4.1. HEN SIMULATION.....	21
4.2. HEN VALIDATION.....	22
4.3. HEN ANALYSIS.....	22
4.3.1. Analysis according to heat capacity.....	23
4.3.2. Analysis according to fouling .....	25
4.3.3. Analysis according to heat capacity and fouling .....	26
4.4. COST.....	26
4.4.1. Cost of energy savings.....	26
4.4.2. Cost of capital cost.....	26



<b>CHAPTER 5 : RESULTS AND DISCUSSION .....</b>	<b>28</b>
5.1.    HEAT CAPACITY CALCULATIONS.....	28
5.2.    FOULING CALCULATIONS .....	33
5.3.    COST CALCULATIONS.....	39
5.3.1.    Energy savings calculations.....	39
5.3.2.    Capital cost calculations .....	40
<b>CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS.....</b>	<b>43</b>
<b>REFERENCES .....</b>	<b>44</b>
<b>APPENDIX A: GRAPHICAL REPRESENTATION OF THE MODIFIED HEAT EXCHANGERS .....</b>	<b>46</b>
<b>APPENDIX B: GRAPHICAL REPRESENTATION OF THE MODIFIED HEAT EXCHANGERS CONSIDERING FOULING.....</b>	<b>52</b>

## List of Tables

Table 5.1: Temperatures of Hysys vs. previous case study .....	28
Table 5.2: Stream data for the previous case study [1].....	30
Table 5.3: Heat capacities .....	31
Table 5.4: Clean overall heat transfer coefficient ( $U_C$ ) values .....	33
Table 5.5: Fouling $0.003 \text{ ft}^2 \cdot ^\circ\text{F}\cdot\text{hr}/\text{Btu}$ .....	34
Table 5.6: Fouling $0.002 \text{ ft}^2 \cdot ^\circ\text{F}\cdot\text{hr}/\text{Btu}$ .....	35
Table 5.7: Fouling $0.001 \text{ ft}^2 \cdot ^\circ\text{F}\cdot\text{hr}/\text{Btu}$ .....	35
Table 5.8: Fouling with interval difference $0.0002 \text{ ft}^2 \cdot ^\circ\text{F}\cdot\text{hr}/\text{Btu}$ .....	36
Table 5.9: Outlet temperatures after considering heat capacities and fouling.....	38
Table 5.10: Outlet temperatures considering the heat capacities and fouling separately .	38
Table 5.11: Heat exchangers cost estimate for existing area (Estimated cost in 2014)....	40
Table 5.12: Heat exchangers cost estimate for required area (Estimated cost in 2014)...	41

## List of Figures

Figure 2.1: World primary energy demand, 1980–2035 [2].....	2
Figure 2.2: Onion diagram for process synthesis [8].....	5
Figure 2.3: Financial benefits of using pinch technology [9].....	6
Figure 2.4: Formation of hot composite curve [8].....	7
Figure 2.5: Hot vs. cold composite curves [7].....	8
Figure 2.6: Grand composite curve [9].....	9
Figure 2.7: Different cost as function of $\Delta T_{min}$ [7].....	9
Figure 2.8: Heat capacity vs. temperature [12].....	12
Figure 2.9: Time dependence of fouling resistance [16].....	15
Figure 3.1: Refining plant for crude oil distillation [1].....	17
Figure 3.2: An existing HEN including crude oil stream from the well to the distillation column [1].....	18
Figure 3.3: A modified HEN for energy savings [1].....	19
Figure 4.1: A Systematic methodology for retrofit of refinery's HEN.....	20
Figure 4.2: HEN simulation on Hysys.....	21
Figure 4.3: HEN validation.....	22
Figure 4.4: Heat exchanger's temperatures diagram.....	23
Figure 4.5: Graphical representation for heat capacity versus temperature.....	24
Figure 4.6: Illustrating figure for calculating LMTD.....	25
Figure 5.1: Graphical presentation for the modified heat exchanger E-1.....	29
Figure 5.2: Illustrating figure for $C_p$ versus temperature.....	32
Figure 5.3: Graphical presentation for the modified heat exchanger E-1 considering fouling.....	37
Figure A. 1: Graphical presentation for the modified heat exchanger E-1.....	46
Figure A. 2: Graphical presentation for the modified heat exchanger E-20.....	47
Figure A. 3: Graphical presentation for the modified heat exchanger E-3.....	47
Figure A. 4: Graphical presentation for the modified heat exchanger E-6.....	48
Figure A. 5: Graphical presentation for the modified heat exchanger E-5.....	48
Figure A. 6: Graphical presentation for the modified heat exchanger E-4.....	49
Figure A. 7: Graphical presentation for the modified heat exchanger E-9.....	49
Figure A. 8: Graphical presentation for the modified heat exchanger E-10.....	50
Figure A. 9: Graphical presentation for the modified heat exchanger E-8.....	50
Figure A. 10: Graphical presentation for the modified heat exchanger E-11.....	51
Figure A. 11: Graphical presentation for the modified heat exchanger E-12.....	51
Figure B. 1: Graphical presentation for the modified heat exchanger E-1 considering fouling.....	52
Figure B. 2: Graphical presentation for the modified heat exchanger E-6 considering fouling.....	53
Figure B. 3: Graphical presentation for the modified heat exchanger E-3 considering fouling.....	53
Figure B. 4: Graphical presentation for the modified heat exchanger E-8 considering fouling.....	53
Figure B. 5: Graphical presentation for the modified heat exchanger E-5 considering fouling.....	53

Figure B. 6: Graphical presentation for the modified heat exchanger E-9 considering fouling.....	53
Figure B. 7: Graphical presentation for the modified heat exchanger E-4 considering fouling.....	53
Figure B. 8: Graphical presentation for the modified heat exchanger E-10 considering fouling.....	53
Figure B. 9: Graphical presentation for the modified heat exchanger E-11 considering fouling.....	53
Figure B. 10: Graphical presentation for the modified heat exchanger E-12 considering fouling.....	53

# Nomenclature

HEN	Heat Exchanger Network
C <sub>p</sub>	Specific Heat Capacity
ΔT <sub>min</sub>	Minimum Temperature Approach
T	Temperature
H	Flow Enthalpy
ΔH	Change in Flow Enthalpy
CC	Composite Curve
GCC	Grand Composite Curve
Q	Heat Duty
Q <sub>h</sub>	Minimum Hot Utility
Q <sub>c</sub>	Minimum Cold Utility
T <sub>s</sub>	Supply temperature
T <sub>t</sub>	Target temperature
PFD	Process Flow Diagram
HPS	High Pressure Steam
MPS	Medium Pressure Steam
LPS	Low Pressure Steam
BFW	Boiler Feed Water
ADU	Atmospheric Distillation Unit
VDU	Vacuum Distillation Unit
LP	Linear Programming
LMTD	Logarithmic Mean Temperature Difference
U <sub>D</sub>	Design Overall Heat Transfer Coefficient
U <sub>C</sub>	Clean Overall Heat Transfer Coefficient
f	Fouling factor
T <sub>ho</sub>	Outlet Temperature of Hot Stream
T <sub>co</sub>	Outlet Temperature of Cold Stream
A	Area of Heat Flow

## Abstract

Global demand for energy is growing, driven by increasing population and economic growth. Over the past three decades, world energy consumption has more than doubled. Oil refining is an energy consuming process, accounting for about half of all the energy consumed by the oil and gas industry. Raw crude oil is heated initially in a preheat train and then enters the furnace, where most of the energy is consumed. In order to decrease the energy consumption in the furnace and consequently decrease the overall energy consumption in the refinery, it is required to maximize the temperature of the crude oil before entering the furnace by increasing the efficiency of the preheat train.

Retrofitting or revamping of existing chemical engineering plant is essential for improving the performance of existing heat exchanger network. Revamping can enhance the energy efficiency to improve productivity, lower the operating costs, and reduce the environmental impacts.

Heat capacity is a function of temperature, which means that it isn't constant, and changes with the change of temperature. Fouling also is important factor in revamping, as adding area without considering the fouling might not give the required duty. Most of retrofit studies in literature ignored the impact of heat capacities and fouling. Consequently, their modifications might not lead to a practical solution as the solution is not accurate as a result of ignoring the heat capacity and fouling effect.

This study proposes a systematic methodology for analyzing the revamping of refinery's preheat train accounting for variable heat capacities and heat exchangers fouling. It introduces two modifications on the case study modification that was published in the article **"A new graphical method for Pinch Analysis applications: Heat exchanger network retrofit and energy integration"** [1]. The first modification, that the assumption of constant heat capacity is to be criticized and analyzed. This will result a temperature difference in the inlet temperature to the furnace from 275.7 °C to 281.2 °C. The second modification is taking fouling into considerations, this will affect the temperature, as it will be 281.1 °C. However, the furnace duty will be decreased by 2 MW. This will lead to a decrease in the cost of the furnace fuel by approximately 508,718.6 dollars/year.

# **Chapter 1 : Introduction**

Energy efficiency has become one of the major factors to consider in the chemical processes design because of the trending energy prices, the fossil fuel limited resources and environmental restrictions being applied worldwide to reduce greenhouse gas emissions which account for climate changes. Therefore, different companies are started to raise the awareness of energy conservation and improve the energy efficiency for their plants to remain sustainable and competitive in the challenging global market.

Heat integration plays an important role in enhancing energy efficiency and reducing operational costs in the process industry. Several methodologies have been developed for heat exchanger network synthesis. Heat integration considers industries and intends to re-use all heat outputs of certain processes, if they can be usable in the moment or later.

Chapter 2 presents a detailed literature review of the energy savings and its importance. On the other hand, the heat integration in preheat train networks, pinch analysis, composite and grand composite curves, retrofit of heat exchangers, heat capacities, and fouling in heat exchangers including the types of fouling and types of fouling rates.

Chapter 3 summarizes the importance of the integration of heat, scope of work, and a statement of the present work.

Chapter 4 focuses on the description of the analysis for the developed model of preheat train in refinery considering the heat capacities and the fouling.

Chapter 5 presents the results of the present work compared with the proposed retrofit in the previous work.

Chapter 6 summarizes the conclusion and the recommendations for this work.