NEW GRAPHICAL METHODS FOR DIAGNOSIS AND PRAGMATIC RETROFIT OF HEAT EXCHANGER NETWORK

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

DECEMBER 2020

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Professor Ir. Ts. Dr. Zainuddin Abd Manan, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Professor Ir. Ts. Dr. Sharifah Rafidah Wan Alwi for her guidance, advice and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for funding my Ph.D study. Librarians at UTM also deserve special thanks for their assistance in supplying the relevant literature.

My sincere appreciation also extends to all my colleagues at Process Systems Engineering Centre (PROSPECT) UTM and others who have assisted at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

I would also like to express my sincere gratitude and love to my family and friends, who have always been the source of inspiration and encouragement for me to pursue study in my field of interest.

Besides, my appreciation goes to the Educational Technology Division under the Kedah State Education Department for providing an adequate place and infrastructure to conduct the online viva. Thank you especially to Mr. Ahmad Zahir, Mr. Idrus Mat and Mr. Ching for their time and effort in making arrangement to set up the place. With their help, the online viva was conducted successfully.

ABSTRACT

Manufacturing plants typically undergo retrofit several times throughout their lifetime to improve efficiency and profitability. Insight-based heat exchanger network (HEN) retrofit methodologies are preferred by industry because they typically provide clear visualised insights to systematically guide users to conduct plant retrofit. Over the years, research works have been done to improve the features of numerous graphical tools. However, there are still rooms for improvements. Conventional graphical visualisation tools such as composite curves contain very limited information about the properties and profiles of individual streams in an HEN that are important to be considered for generating practical retrofit solutions. Users need to undergo trial-and-error for stream matching and perform iterative calculations to check temperature feasibility and enthalpy balance before obtaining the network design that can achieve the maximum heat recovery. Capital-energy trade-off is usually considered in mathematical optimisation approaches and less so in graphical methodologies. Practical constraints especially the plant layout-based factors have not been a consideration in almost all of the insight-based methods. This research aimed to develop new graphical methods for HEN retrofit which incorporate systematic retrofit methodologies based on the individual stream concept that consider economics and various physical constraints. In this research, three retrofit methodologies were proposed. First, the individual stream temperature versus enthalpy plot (STEP) retrofit methodology that involves simultaneous diagnosis and retrofit of existing HEN was proposed. Second, the heat exchanger area versus enthalpy (A vs H) plot was then developed to be used together with STEP to enable capital-energy trade-off. Third, a three-dimensional coordinate representation was developed to incorporate plant layout-based factors that may hinder processes from achieving maximum heat recovery. Results of the first methodology applied on a fluid catalytic cracking plant demonstrated the advantages of STEP diagram in terms of the insights offered by the graphical tool, the flexibility to customise the methodology to achieve retrofit goals, and results comparability to those of established retrofit methods. Results of the second methodology applied on a sunflower oil production plant showed that the graphical tools and the cost screening technique can be used to perform capital-energy trade-off to result in comparable energy savings and 20% shorter payback period as compared to other established retrofit methodologies. Application of the third retrofit methodology on an illustrative industrial case study resulted in 18% higher in the total annualised costs for the retrofit design which does not consider plant layout-based factors and the one with plant layout-based factors. Implementation of all the new developed retrofit methodologies on literature and industrial case studies shows the applicability of the methodologies to cover different aspects of HEN retrofit, i.e. the simultaneous representation of the vital information, the economic aspect, and the practicability of HEN retrofit methodology.

ABSTRAK

Loji-loji pengeluaran biasanya menjalani beberapa pengubahsuaian sepanjang jangka hayatnya bagi meningkatkan kecekapan serta keuntungan. Kaedah pengubahsuaian rangkaian penukar haba (HEN) berasaskan grafik menjadi pilihan industri kerana kaedah ini dapat memberikan gambaran yang jelas dalam membimbing pengguna untuk mengubah suai HEN secara sistematik. Sejak beberapa tahun yang lepas, pelbagai kajian telah dijalankan untuk menambaik ciri-ciri kebanyakan kaedah grafik ini. Walau bagaimanapun, terdapat penambahbaikan yang masih boleh dilakukan. Kaedah grafik konvensional seperti lengkung rencam mengandungi maklumat yang sangat terhad mengenai sifat dan profil aliran individu di dalam HEN yang mana ianya penting untuk dipertimbangkan bagi menghasilkan reka bentuk pengubahsuaian yang praktikal. Pengguna perlu menjalani kaedah cuba-dan-jaya untuk kesepadanan aliran, dan membuat pengiraan berlelar bagi memastikan kesesuaian suhu dan keseimbangan entalpi sebelum mendapatkan reka bentuk rangkaian yang dapat mencapai perolehan haba maksimum. Keseimbangan antara modal dengan tenaga biasanya diambil kira dalam kaedah pengoptimuman matematik dan jarang digunakan dalam kaedah grafik. Kekangan praktikal terutamanya faktor berasaskan susun atur loji biasanya tidak dipertimbangkan dalam kaedah grafik. Matlamat kajian ini dilakukan adalah bertujuan untuk mencadangkan kaedah grafik baharu bagi pengubahsuaian HEN yang merangkumi kaedah-kaedah pengubahsuaian yang sistematik berdasarkan kepada konsep aliran individu yang mempertimbangkan aspek ekonomi dan pelbagai kekangan fizikal. Dalam kajian ini, tiga kaedah pengubahsuaian telah dicadangkan. Pertama sekali, kaedah pengubahsuaian yang berasaskan graf suhu aliran individu melawan entalpi (STEP) yang melibatkan diagnosis serentak dengan pengubahsuaian HEN telah dicadangkan. Kaedah kedua adalah graf keluasan penukaran haba melawan entalpi (A vs H) telah diwujudkan untuk digunakan bersama dengan STEP bagi mengimbangkan pelaburan modal kapital dengan kos tenaga. Ketiga, koordinat tiga dimensi diwujudkan untuk mempertimbangkan faktor-faktor susunatur loji yang boleh menghalang proses daripada mencapai perolehan haba maksimum. Aplikasi kaedah pertama terhadap loji pemecahan bermangkin bendalir menunjukkan kelebihan graf STEP dari segi gambaran yang diberi oleh alat grafik, fleksibiliti untuk menyesuaikan kaedah ini bagi mencapai matlamat pengubahsuaian, serta perbandingan keputusan dengan kaedah pengubahsuaian sedia ada. Aplikasi kaedah kedua terhadap loji pengeluaran minyak bunga matahari menunjukkan bahawa graf-graf yang dicadangkan dan teknik penyaringan kos boleh digunakan untuk mengimbangkan modal dengan tenaga bagi mencapai penjimatan tenaga dan 20% tempoh bayaran balik yang lebih pendek berbanding dengan kaedah pengubahsuaian yang lain. Aplikasi kaedah pengubahsuaian ketiga pada kajian kes ilustrasi industri menunjukkan perbezaan kos keseluruhan tahunan sebanyak 18% lebih tinggi bila dibandingkan antara reka bentuk pengubahsuaian yang mengambilkira faktor susun atur loji dengan yang tidak mengambilkira faktor susun atur loji. Pelaksanaan semua kaedah pengubahsuaian baharu yang dicadangkan pada kajian kes literatur dan perindustrian menunjukkan kemampuan kaedah tersebut untuk merangkumi aspek yang berbeza dalam pengubahsuaian HEN, iaitu pembentangan serentak maklumat penting, aspek ekonomi, dan kebolehlaksanaan metodologi pengubahsuaian HEN.

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LIST OF ABBREVIATIONS

ACC - Advanced Composite Curves
AHLC - Actual heat load curve
ART - Automated retrofit targeting
BCR - Benefit-cost ratio
CAT - Constant Approach Temperature
CC - Composite Curves
CDM - Cost Derivative Method
CGCC - Complement Grand Composite Curve
CLP - Constraint Logic Programming
CW - Cooling water
DCS - Distributed control systems
EECA - Energy Efficiency and Conservation Act
EHLC - Extreme heat load curve
ETD - Energy Transfer Diagram
EX - Heat exchanger
FG - Flue gas
FT - Correction factor
GA - Genetic algorithm
GCC - Grand Composite Curve
GDT - Grid Diagram Table
HEAT - HEat Allocation and Targeting
HELD - Heat-Exchanger Load Diagram
HEN - Heat exchanger network
HENs - Heat exchanger network synthesis
HENSM - Heat Exchanger Network Steam Matrix
HSDT - Heat Surplus-Deficit Table
HUC - Hot utility curve
IAS - Investment vs annual savings
ILP - Integer linear programming
LMTD - Logarithmic mean temperature difference

LP - Linear programming
MCS - Monte Carlo simulation
MHA - Maximum heat allocation
MHR - Maximum heat recovery
MER - Maximum energy recovery
METD - Modified Energy Transfer Diagram
MILP - Mixed-integer linear programming
MINLP - Mixed-integer nonlinear programming
NLP - Nonlinear programming
NPV - Net present value
PDI - Pressure drop index
PDM - Pinch Design Method
PTA - Problem Table Algorithm
ROI - Return on investment
RTD - Retrofit Thermodynamic Diagram
RTGD - Retrofit Tracing Grid Diagram
SA - Simulated annealing
SePTA - Segregated Problem Table Algorithm
SDGs - Sustainable Development Goals
SHARPS - Systematic Hierarchical Approach for Resilient Process Screening
SPTA - Simple Problem Table Algorithm
SRTD - Shifted Retrofit Thermodynamic Diagram
SRTGD - Shifted Retrofit Thermodynamic Grid Diagram
SRTGD-STR - Shifted Retrofit Thermodynamic Grid Diagram with Shifted Temperature Range of Heat Exchangers
ST-D - Supply-Target Diagram
STEP - Individual stream temperature versus enthalpy plot
TAC - Total annual cost
TCE - Total annual carbon dioxide emissions
TDF - Temperature Driving Force
THLC - Theoretical heat load curve
TPP - Total payback period
UN - United Nation

UTA - Unified Targeting Algorithm

LIST OF SYMBOLS

A - Heat exchanger area

d - Internal diameter of pipe

H - Enthalpy

h - Heat transfer coefficient

L - Pipe length

M - Mass flow rate

Re - Reynolds number

T - Stream temperature

U - Overall heat transfer coefficient

V - Volumetric flow rate

v - Fluid velocity

ΔH - Heat load

μ - Viscosity

ρ - Density of fluid

T^* - Shifted temperature

C_p - Specific heat capacity

FC_p - Heat capacity flow rate

f_m - Moody friction factor

P_{end} - Pressure at the end point of the stream

PP_i - Payback period for series i

PP_{set} - Desired payback period

P_{start} - Pressure at the starting point of the stream

Q_c - Cooling requirement

$Q_{c,min}$ - Minimum cooling requirement

Q_h - Heating requirement

$Q_{h,min}$ - Minimum heating requirement

$Q_{recovered}$ - Amount of heat recovery

TPP_{BS} - Total payback period required for the retrofit design before implementing SHARPS strategy

Z_E - Elevation of heat exchanger above the pump centre line

$\Delta P_{Additional}$ - Additional pressure drop incurred due to retrofit

ΔP_{cv} - Pressure drop across control valve

ΔP_{E} - Elevation pressure drop

$\Delta P_{Existing}$ - Existing pressure drop of the process stream

ΔP_{f} - Frictional pressure drop

$\Delta P_{f,retrofit}$ - Frictional pressure drop of the process stream after retrofit

ΔP_{HE} - Heat exchanger pressure drop

$\Delta P_{HE,retrofit}$ - Heat exchanger pressure drop after retrofit

$\Delta P_{Retrofit}$ - Pressure drop of the process stream after retrofit

ΔT_{min} - Minimum temperature approach

ρ_{l} - Density of liquid

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Over the last four decades, Malaysia's manufacturing sector has been rapidly growing. Manufacturing plants have been mushrooming in over 500 industrial estates and Free Zones throughout the country (Malaysian Investment Development Authority 2018). The strong performance of some of the sectors especially petrochemical and polymer industry has brought large income to the country. As nation industrialises, energy demand from fossil-based natural resources also increases. This results in an increased amount of gaseous emissions due to industrial activities such as the burning of fossil fuels to produce energy for manufacturing activities (Gaffey, 2017).

Depletion of natural resources has been a continuous threat to the sustainability of humankind. Non-renewable resources such as coal, oil, and natural gas are combusted to produce thermal energy and electricity. Human relies on non-renewable energy to sustain daily activities such as supplying power to electrical appliances, and industrial activities such as generating steam to fulfil the heating requirements of manufacturing processes. According to the BP's Statistical Review of World Energy 2016, the Earth has about 115 years of coal production and 50 years of oil and natural gas remaining before the fossil fuels are totally consumed by us (BP, 2016). Although it is mentioned that this prediction will vary with time, nonetheless, the possibility of extending the time for the fossil fuels to be fully depleted is small if we do not cut down on our fossil fuel consumption.

Besides the overexploitation of natural resources, the consumption of fossil fuels in industry results in environmental pollution. Burning of fossil fuels emits carbon dioxide which is one of the greenhouse gaseous that keeps the Earth warm. The world economy is developed at the cost of the environment. To mitigate this problem, authorities have begun to resort to political solutions. The United Nations (UN) had signed the Paris Agreement to keep the global temperature rise to below 2 ℃ and developed the UN Sustainable Development Goals (SDGs) and put them into effect since the year 2016. The main aim of all these efforts is to keep global warming and climate changes at bay.

Apart from the environmental challenges, energy wastage which translates into high utility bills and plant operating costs is also one of the reasons why retrofit is important. Talking about energy savings, usually the first thing that comes into mind is to save electricity. However, thermal energy has more savings potential as compared to electricity. According to the statistic from the UK Department of Business, Energy and Industrial Strategy in year 2016, 72% of the UK energy consumption is from industrial thermal processes and almost 20% from this (equivalent to 40 TWh/y) has the potential for waste heat recovery (Waters, 2017). This shows the importance of energy efficiency in helping industry save both energy and cost.

To reduce energy operating cost, energy efficiency improvement of industrial sites needs to be done. In June 2019, the Malaysian government approved the drafting of the Energy Efficiency and Conservation Act (EECA) that is expected to be put into effect by year 2021 (Chin, 2019). It is expected that energy efficiency measures can save the government nearly RM 47 billion by year 2030 (Kumar and Zainuddin, 2018). Usage of thermal energy in Malaysia which is not regulated by any existing law before this, will be monitored under EECA to ensure effective utilisation of energy in the country. One of the ways to improve thermal energy efficiency is by retrofitting the existing heat recovery system (or heat exchanger network (HEN)) in the manufacturing plant.

In a chemical plant, heat plays a major role in product manufacturing. Heat is required at the core of the process – the reactor, to carry out the main reaction to produce desired products as well as side products. The raw materials from the material tanks are heated up to the reaction temperature for the reaction to occur. The product coming out of the reactor is then purified using separation and recycle system to remove side products and impurities. For separation to occur at the separation units, the product needs to be heated up to the desired temperature. After the separation process, the temperatures of the desired product and recycle stream also need to be changed before they are sent to the storage tank or recycled. Throughout the production process, there are process streams that need to be heated up and process streams that need to be cooled down. During process design, heat integration between these streams will be performed before resorting to the use of external utilities. Linnhoff *et al.* (1982) represented the process design "layers" using the "Onion model" shown in Figure 1.1.

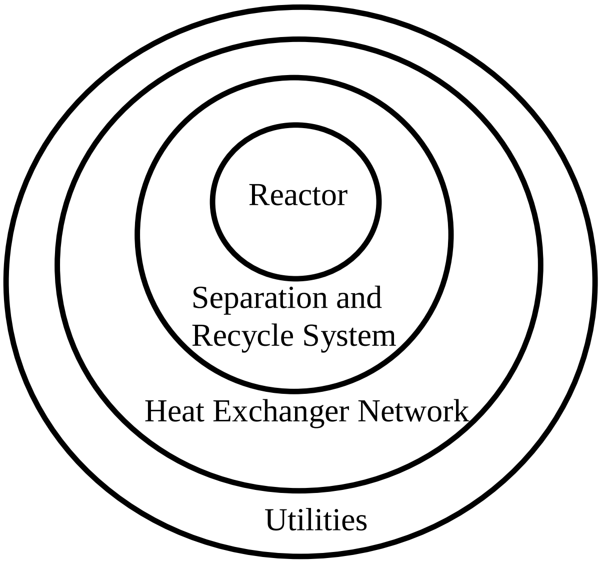

Figure 1.1 The Onion model representing layers of process design (Linnhoff *et al.*, 1982)

Heat integration recovers heat released from chemical processes to be reused in the part of the process that requires heat via HEN. It is established for minimising heat consumption, environmental emissions, operating and utility costs needed for chemical processes that require heating and cooling. Instead of outsourcing hot and cold utilities such as fuel oil, steam, and cooling water to fulfil all the heating (Q_h) and cooling requirement (Q_c), HEN enables heat to be transferred from the part of the process that releases heat to the part of the process that requires heat. This can reduce the operating and utility costs of a plant as less utility is to be outsourced. By minimising the heat consumption, burning of fossil fuel to sustain industrial operation can be reduced, hence the environmental problem such as carbon dioxide emission, natural resource depletion, and global warming can be reduced. As manufacturing plants continue to operate over the years, the plants' energy efficiency tends to deteriorate due to the change of operating conditions to meet the quantity and quality requirement of the product. From time to time, process plants may need to undergo process retrofit or modifications especially to improve its productivity and efficiency. Low process efficiency may result in wastage of resources, including energy, and increase operating and utility costs.

HEN retrofit and grassroots designs have some similarities and differences. HEN retrofit and grassroots designs both involve data collection, targeting, and network design. However, there are still some significant differences between retrofit and grassroots HEN design. Rangaiah (2016) has compared retrofit and grassroots projects. Some of the points that are applicable to the case of HEN are listed in Table 1.1.

Table 1.1 Comparison between retrofit and grassroots projects (Rangaiah, 2016)

Item	Grassroots Projects	Retrofit Projects
Design constraints	Fewer design options and constraints	More constraints due to reuse and modifications of existing plant equipment within limited available space and project execution time
Available space	Sufficient space available	Limited available space constrained by maintenance access, fire, safety and emergency handling requirements
Equipment installation	Can be installed any time following the project planning	Installation may be constrained by shutdown period
Project cost	More as compared with the retrofit project	Less as compared with the grassroots project
Conceptual design	Conceptual design can be performed as there is no restriction by existing HEN	Conceptual design has to be calibrated with the plant's performance. The design shall be able to perform within existing equipment constraints
Review of existing HEN	Not required as all equipment needed is in the new design	Required as HEN retrofit may require more auxiliary equipment such as pumps and valves

HEN retrofit involves more constraints as compared to grassroots design due to reuse and modifications of existing HEN with limited available space and project execution time. Sufficient space is normally available for grassroots design as there is no existing HEN. For HEN retrofit, space is constrained by existing HEN, maintenance access, fire, safety and emergency handling requirements. Retrofit design is usually implemented during plant shutdown and has to be completed within this period. Grassroots design on the other hand can be installed at any time following the project planning. The retrofit cost is generally less than the grassroots project.

In terms of HEN design, retrofit design needs to be calibrated with the existing heat exchangers in the plant to ensure the feasibility of the design to perform within existing equipment constraints, for example existing heat exchanger area and construction material. The retrofit design also has to be reviewed to identify if there is extra equipment (e.g. pumps and valves) required to sustain the operability of the HEN.

Due to the limitations of existing HEN, limited available space, project execution time and retrofit cost, retrofit design can hardly achieve the thermodynamic target. It is impossible to completely revamp the existing HEN as this may impose a very high retrofit cost. Plant owner might have just build a new HEN if the retrofit cost is too high. Usually, HEN retrofit can only achieve utility reduction through HEN modifications. Thermodynamic targets are usually unachievable.

HEN retrofit methods can be categorised into three groups, namely the graphical-based methods, mathematical-based methods, and hybrid methods. The graphical-based methods use visualisation tools to assist in generating retrofit solutions; Mathematical-based methods involve mathematical programming to solve the retrofit problems; Hybrid methods combine the advantages of graphical-based methods and mathematical based methods to retrofit existing HEN. Among the retrofit techniques, graphical-based retrofit methods are preferable by the industry as they can give clear insights to the users. A few examples of the latest graphical-based retrofit methods are the Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) (Yong *et al.*, 2015a), the Temperature Driving Force (TDF) curve (Kamel *et al.*, 2018) and the T-H diagram (Li *et al.*, 2019). The current development of HEN retrofit methods focuses on improving the representation of the stream profiles, but there is still a lack of clarity on the important information that is required to retrofit existing HEN. The limitations of HEN retrofit which include the retrofit cost and space constraint have yet to be addressed in the state-of-the-art graphical-based retrofit methods.

1.2 Problem Statement

The global economy has been developing rapidly. To ensure sustainable resource consumption, industries have the responsibility to cut down on their energy consumption to ensure that the manufacturing activities are still able to be carried out. The initiative can be achieved by improving thermal energy efficiency. One of the most effective ways to improve energy efficiency is through retrofit of existing HEN. Insight-based HEN retrofit methods utilise graphical and algebraic tools to cope with different retrofit stages. These tools often require iterative calculations to result in HEN retrofit designs which are thermodynamically and economically feasible.

State-of-the-art study of the literature on HEN retrofit shows that there are a few drawbacks of the graphical methods that have remained unsolved. The conventional HEN retrofit methods employ several graphical tools during the retrofit. For instances, Composite Curves (CC) is used to determine energy target and Pinch point, while Grid Diagram is used to diagnose and design the HEN. CC represents the temperature intervals of composite instead of individual streams. Because the CC does not represent pairs of individual streams, the Grid Diagram is used to generate HEN retrofit designs. As Grid Diagram is not drawn to any temperature or enthalpy scale, HEN diagnosis needs to be accompanied by iterative calculations to check enthalpy balance, temperature feasibility and area implications of every single heat exchanger match.

Apart from graphical tools that are based on CC, a few recent graphical tools are used to represent process streams individually. These include the plot of hot process streams temperatures versus cold process streams temperatures that was introduced by Gadalla (2015a) and the TDF curve by Kamel *et al.* (2018). Most of the graphical tools quantitatively represent individual stream temperature (T) to scale, but not the heat loads (ΔH) exchanged for individual heat exchangers. Besides stream profiles, existing retrofit graphical tools also do not represent network configuration of the HEN which is important for network design, except for the graphical tools that are derived from the Grid Diagram.

A graphical tool known as the individual stream temperature versus enthalpy plot (STEP) was introduced for simultaneous targeting and design of grassroots HEN (Wan Alwi and Manan, 2010). STEP represents continuous hot and cold stream profiles in which the information is important for HEN design. STEP diagram has been extended to form the HEat Allocation and Targeting (HEAT) diagram that represents HEN network configuration. STEP and HEAT diagram include representation of individual T, ΔH and HEN network configuration that address the aforementioned limitations of existing HEN retrofit graphical tools. This makes them possible to be used for HEN retrofit. However, unlike the original STEP diagram for grassroots design that is constructed from scratch based on the thermodynamic profile of process streams, the STEP diagram for retrofit needs to be modified so that it can represent existing HEN. A systematic retrofit methodology is also required to complement the graphical tools and enable diagnosis and retrofit existing HEN.

HEN retrofit methodology which is solely based on process stream's thermodynamic profile can sometimes produce complex retrofit solutions that could be practically and economically infeasible to implement. The amount of investment available can limit the amount of heat recovery ($Q_{recovered}$) that can be achieved. Capital-energy trade-off has typically been the main objective in mathematical-based HEN retrofit methods, but not in the case of graphical-based methods. In fact, HEN retrofit graphical methodologies have the advantage of providing useful visualisation insights to designers especially from among practitioners, and therefore allowing better control of retrofit solution space. For example, selective units can be selectively eliminated in order to reduce the fixed cost required to install new heat exchanger, and retrofit can be directed to focus on the parts of HEN that can achieve the largest and most cost-effective heat recovery. The type of utilities applied also contributes to the utility cost besides the amount of utility needed. The number and size of additional heat exchangers, as well as the information of the utilities, need to be visualised simultaneously. Hence, a systematic cost screening graphical methodology for HEN retrofit is needed to guide users to achieve the desired payback period (PP_{set}) for investment.

HEN retrofit is complex as compared to grassroots design due to the existing HEN in the plant. Conventional graphical HEN retrofit methodologies solve retrofit problems by observing the thermodynamic profiles of process streams without considering the practical aspects which may hinder a given process system from achieving maximum heat recovery (MHR). This is because a pair of thermodynamically-matched process streams may be located far away from each other. Extra pumping and piping costs will be required to overcome the pressure drop caused by the long piping. The on-site space limit also needs to be considered for the installation of additional equipment. The aforementioned issues underscore the urge to develop a graphical HEN retrofit methodology which considers the physical distance between process streams, pressure drop, as well as available space for additional equipment.

1.3 Objectives of Study

The objectives of this research are:

(a) To develop a new graphical HEN retrofit methodology based on individual stream concept.
(b) To develop a new graphical HEN retrofit methodology to incorporate the economic aspect of HEN retrofit.
(c) To establish a new graphical HEN retrofit methodology that incorporates physical constraints in HEN retrofit.

1.4 Scope of Study

This study focuses on the development of new graphical HEN retrofit methodologies based on individual stream concept built upon the principles of Pinch Analysis. The proposed graphical methodologies include new and existing retrofit heuristics that have been developed or applied to guide the retrofit design process. The scope for each of the objectives is as listed below.

(a) Objective 1: To develop a new graphical HEN retrofit methodology based on individual stream concept

The STEP diagram which is established for simultaneous targeting and design of HEN is modified and adapted to introduce the individual stream concept for HEN retrofit. Pinch rules are applied for diagnosis while retrofit heuristics which are related to T, heat capacity flow rate (FC_p), ΔH, and stream splitting are used to guide the stream matching. All process conditions are kept constant while all process and physical constraints in the existing HEN are assumed to be negligible.

(b) Objective 2: To develop a new graphical HEN retrofit methodology to incorporate the economic aspect of HEN retrofit

The economic aspect of HEN retrofit is incorporated into the graphical methodology by proposing a new graphical tool to graphically represent the heat exchanger area distribution across the network. A new framework for capital-energy trade-off is proposed by combining the new graphical tool with STEP, and a cost-screening technique to guide the decision-making process. In this framework, the process conditions are kept constant while all process and physical constraints in the existing HEN are assumed to be negligible.

(c) Objective 3: To establish a new graphical HEN retrofit methodology to incorporate physical constraints in HEN retrofit

The physical constraint in HEN retrofit is considered by graphically representing the plant layout using a new three-dimensional graphical tool. Retrofit heuristics which are related to the physical distance between pipelines, volumetric flow rate (V), viscosity (μ), pumping head limit and existing pressure drop ($\Delta P_{Existing}$) of the individual process streams are proposed to guide the stream matching and heat exchanger placement in the existing plant. In this methodology, the process conditions are kept constant while the process constraints are assumed to be negligible.

The proposed methodologies are applied to literature and industrial case studies. Thermodynamic and economic feasibility studies are performed for each of the case study to ensure the practicability of the methodologies. Performance of the new retrofit methodologies is also compared with the existing methodologies.

1.5 Significance and Contributions of Study

This research proposes three new graphical HEN retrofit methodologies to overcome the limitations of existing graphical tools. The significance and contributions of each methodology are described below.

(a) The first graphical HEN retrofit methodology adapted the STEP diagram to provide insights of individual stream profile which is required for HEN retrofit. Use of STEP diagram which was established solely for grassroots design of HEN has been extended to represent existing HEN. A retrofit methodology based on STEP diagram has been proposed to solve retrofit problems newly developed, and existing retrofit heuristics.

(b) The second graphical HEN retrofit methodology is a new framework which enables capital-energy trade-off in HEN retrofit. The framework employs a new graphical tool known as the heat exchanger area versus enthalpy (A vs H) plot which is proposed to be used together with STEP diagram to provide economic insights for consideration in the retrofit design. A cost-screening technique is also adapted to guide the decision-making process in the framework.

(c) The third graphical HEN retrofit methodology is a three-dimensional coordinate representation which visualises the plant layout-based factors. The methodology is proposed together with five retrofit heuristics for stream matching and heat exchanger placement to guide the retrofit with consideration of the physical constraints at the plant site.

1.6 Thesis Outline

Chapter 1 of the thesis introduces the background, problem statement, objectives, scope and significance of the study. Chapter 2 explains the basic concept of heat integration, reviews the state-of-the-art HEN retrofit approaches which include the graphical and mathematical optimization approaches, and concludes aspects that can be improved from the current approaches. Chapter 3 elaborates on the methodology to conduct the study. Chapters 4-6 summarise the research findings and contribution of the published journal articles which answer the objectives of this study. Figure 1.2 shows the journal articles in each of the chapter that correspond to the objectives of the study. Chapter 7 concludes the outcome of the study and provides recommendations for future work.

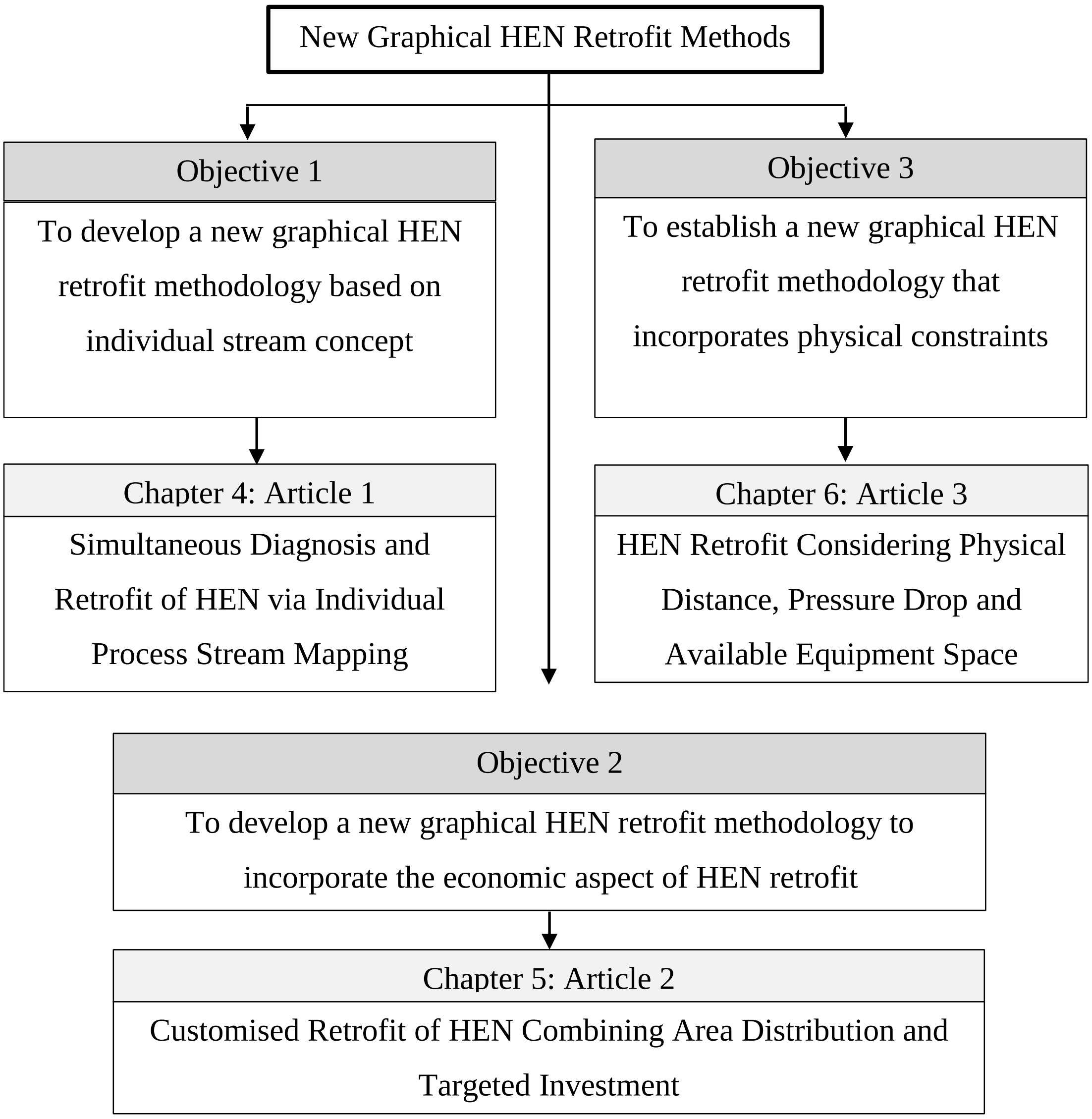

Figure 1.2 Journal articles mapped to the corresponding research objectives

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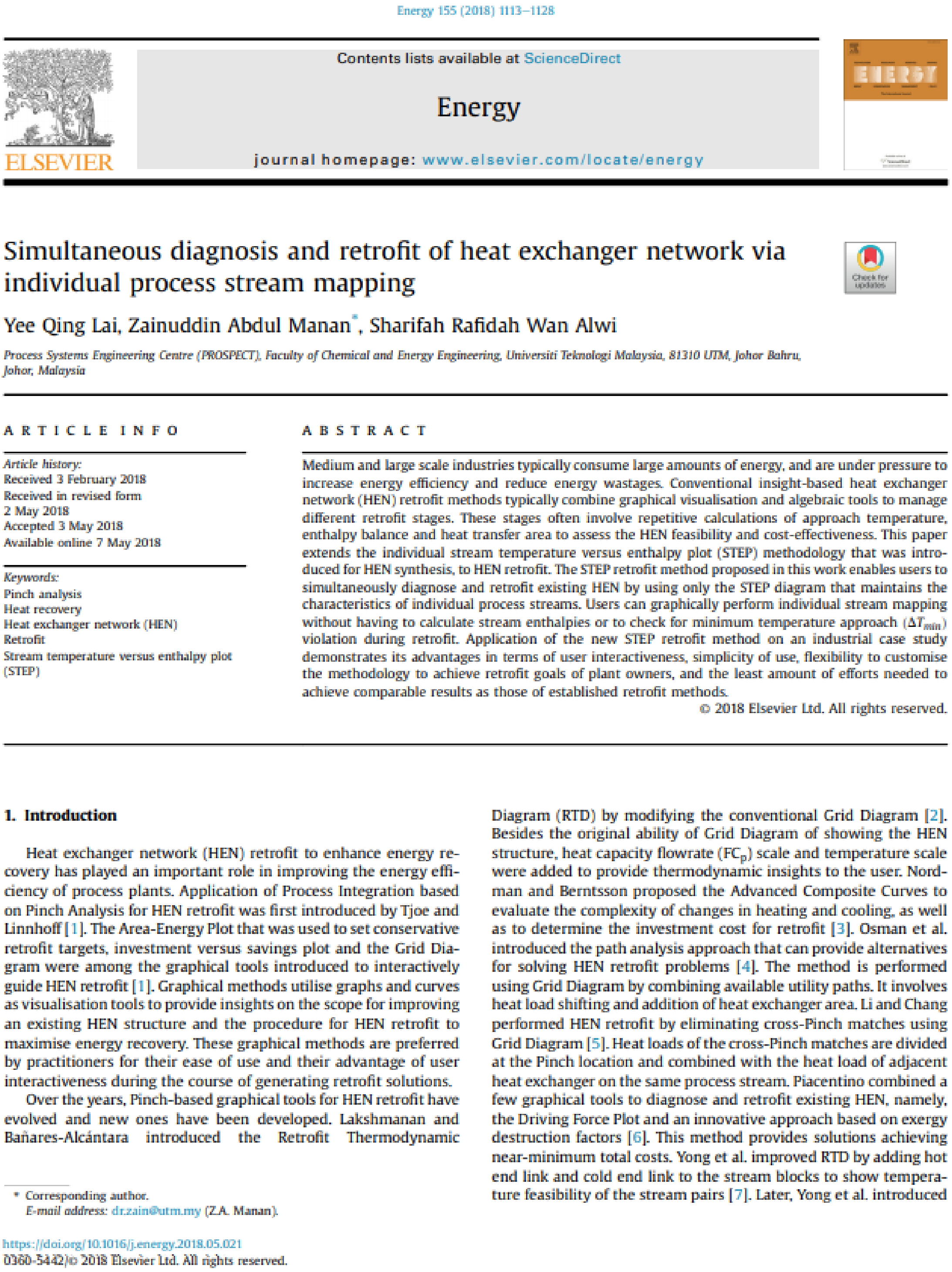
Appendix A Article 1



Energy 155 (2018) 1113–1128

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Simultaneous diagnosis and retrofit of heat exchanger network via individual process stream mapping

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A R T I C L E I N F O

Article history:
Received 3 February 2018
Received in revised form
2 May 2018
Accepted 3 May 2018
Available online 7 May 2018

Keywords:
Pinch analysis
Heat recovery
Heat exchanger network (HEN)
Retrofit
Stream temperature versus enthalpy plot (STEP)

A B S T R A C T

Medium and large scale industries typically consume large amounts of energy, and are under pressure to increase energy efficiency and reduce energy wastages. Conventional insight-based heat exchanger network (HEN) retrofit methods typically combine graphical visualisation and algebraic tools to manage different retrofit stages. These stages often involve repetitive calculations of approach temperature, enthalpy balance and heat transfer area to assess the HEN feasibility and cost-effectiveness. This paper extends the individual stream temperature versus enthalpy plot (STEP) methodology that was introduced for HEN synthesis, to HEN retrofit. The STEP retrofit method proposed in this work enables users to simultaneously diagnose and retrofit existing HEN by using only the STEP diagram that maintains the characteristics of individual process streams. Users can graphically perform individual stream mapping without having to calculate stream enthalpies or to check for minimum temperature approach (ΔT_{min}) violation during retrofit. Application of the new STEP retrofit method on an industrial case study demonstrates its advantages in terms of user interactiveness, simplicity of use, flexibility to customise the methodology to achieve retrofit goals of plant owners, and the least amount of efforts needed to achieve comparable results as those of established retrofit methods.

1. Introduction

Heat exchanger network (HEN) retrofit to enhance energy recovery has played an important role in improving the energy efficiency of process plants. Application of Process Integration based on Pinch Analysis for HEN retrofit was first introduced by Tjoe and Linnhoff [1]. The Area-Energy Plot that was used to set conservative retrofit targets, investment versus savings plot and the Grid Diagram were among the graphical tools introduced to interactively guide HEN retrofit [1]. Graphical methods utilise graphs and curves as visualisation tools to provide insights on the scope for improving an existing HEN structure and the procedure for HEN retrofit to maximise energy recovery. These graphical methods are preferred by practitioners for their ease of use and their advantage of user interactiveness during the course of generating retrofit solutions.

Over the years, Pinch-based graphical tools for HEN retrofit have evolved and new ones have been developed. Lakshmanan and Bañares-Alcántara introduced the Retrofit Thermodynamic Diagram (RTD) by modifying the conventional Grid Diagram [2]. Besides the original ability of Grid Diagram of showing the HEN structure, heat capacity flowrate (FC_p) scale and temperature scale were added to provide thermodynamic insights to the user. Nordman and Berntsson proposed the Advanced Composite Curves to evaluate the complexity of changes in heating and cooling, as well as to determine the investment cost for retrofit [3]. Osman et al. introduced the path analysis approach that can provide alternatives for solving HEN retrofit problems [4]. The method is performed using Grid Diagram by combining available utility paths. It involves heat load shifting and addition of heat exchanger area. Li and Chang performed HEN retrofit by eliminating cross-Pinch matches using Grid Diagram [5]. Heat loads of the cross-Pinch matches are divided at the Pinch location and combined with the heat load of adjacent heat exchanger on the same process stream. Piacentino combined a few graphical tools to diagnose and retrofit existing HEN, namely, the Driving Force Plot and an innovative approach based on exergy destruction factors [6]. This method provides solutions achieving near-minimum total costs. Yong et al. improved RTD by adding hot end link and cold end link to the stream blocks to show temperature feasibility of the stream pairs [7]. Later, Yong et al. introduced

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https://doi.org/10.1016/j.energy.2018.05.021
0360-5442/

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Lai, Y. Q.**, Manan, Z. A. and Wan Alwi, S. R. (2018) 'Simultaneous Diagnosis and Retrofit of Heat Exchanger Network via Individual Process Stream Mapping'. *Energy*, 155, pp. 1113-1128. **(Q1, IF: 6.082)**

2. **Lai, Y. Q.**, Wan Alwi, S. R. and Manan, Z. A. (2019) 'Customised Retrofit of Heat Exchanger Network Combining Area Distribution and Targeted Investment'. *Energy*, 179, pp. 1054-1066. **(Q1, IF: 6.082)**

3. **Lai, Y. Q.**, Wan Alwi, S. R. and Manan, Z. A. (2020) 'Graphical Customisation of Process and Utility Changes for Heat Exchanger Network Retrofit Using Individual Stream Temperature Versus Enthalpy Plot'. *Energy,* pp. 117766. (**Q1. IF: 6.082**).

Indexed Journal

1. **Lai, Y. Q.**, Manan, Z. A. and Wan Alwi, S. R. (2017) 'Heat Exchanger Network Retrofit Using Individual Stream Temperature vs Enthalpy Plot'. *Chemical Engineering Transactions*, 61, pp. 1651-1656. **(Indexed by SCOPUS)**

2. **Lai, Y. Q.**, Manan, Z. A. and Wan Alwi, S. R. (2018) 'An Enhanced Tool for Heat Exchanger Network Retrofit Towards Cleaner Processes'. *Chemical Engineering Transactions*, 63, pp. 487-492. **(Indexed by SCOPUS)**

3. **Lai, Y. Q.**, Wan Alwi, S. R. and Manan, Z. A. (2018) 'A New Graphical Approach for Heat Exchanger Network Retrofit Considering Capital and Utility Costs'. *Chemical Engineering Transactions*, 70, pp. 1867-1872. **(Indexed by SCOPUS)**

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1. **Lai, Y. Q.**, Wan Alwi, S. R. and Manan, Z. A. (2017) 'Retrofit of Heat Exchanger Network with Process Changes Using Individual Streams Heat Curves'. In *2017 6th Conference on Emerging Energy & Process Technology (CONCEPT)* (pp. 51-52). Centre of Hydrogen, Universiti Teknologi Malaysia.

2. **Lai, Y. Q.**, Wan Alwi, S. R. and Manan, Z. A. (2018) 'Simultaneous Retrofit and Process Changes of Heat Exchanger Networks'. In *2018 13th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES)* (pp. 46). Faculty of Mechanical Engineering and Naval Architecture, Zagreb.