OPTIMAL HEAT EXCHANGER NETWORK SYNTHESIS WITH OPERABILITY AND SAFETY CONSIDERATION

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A dissertation submitted in partial fulfilment of the

requirements for the award of the degree of

Master of Engineering (Chemical)

Faculty of Chemical Engineering

Universiti Teknologi Malaysia

SEPTEMBER 2015

ACKNOWLEDGEMENTS

I would like to express my most sincere gratitude to my supervisor, Assoc. Prof. Ir. Dr. Sharifah Rafidah bt Wan Alwi for guiding and supervising of this dissertation. Her patience, tolerance and helping character really help me towards the dissertation accomplishment. Without her guidance, I believe this research would not be completed in time.

My sincere appreciation also extends to all my friends whom always encourage and support me all the long ways that I had walked through. Last but not least, I am deeply indebted to my family for their endless support. At the same time, being close hand to render love, comfort and support to achieve and succeed.

ABSTRACT

Heat exchanger network (HEN) in the industries is very complex as it considers many problems and situations. Quantitative part such as cost of the heat exchanger and external utilities as well as the qualitative part such as safety, operability and flexibility are part of the design objective. This study presents a method for optimal HEN design which considers the inherent safety and operability aspects in the design. Data will be extracted for pinch study and safety assessment. The construction of continuous hot and cold Stream Temperature vs Enthalpy Plot (STEP) prioritized the inherent safety index than the heat capacity flowrate (FCp). The high ISI of hot and cold streams are matched together and vice versa. Thus, the focus of safety can centralized on a particular heat exchanger. The pinch temperature and minimum utility can be determined from STEP. The disturbance propagation path through the HEN and the affected streams are analysed. The modification of network by downstream path concept is performed in order to reduce the disturbance propagation path and affected streams. The ΔT_{min} violation and energy penalty is determined due to the changes of network. The flexibility and the structural controllability of each of the alternative network are determined and compared. Highest percentage of changes in every streams of the network and index of structural controllability near to 1 indicates that network is the most flexible and controllable. The application of this method on Case Study 2 shows alternative network 3 is the most flexible and controllable with 22% and 0.917 respectively.

ABSTRAK

Rangkaian penukar haba (*HEN*) di dalam industri adalah sangat kompleks kerana ia mempertimbangkan pelbagai masalah dan situasi. Bahagian kuantitatif seperti penukar haba dan kegunaan luaran serta bahagian kualitatif seperti keselamatan, kebolehkendalian dan fleksibiliti merupakan sebahagian daripada objektif reka bentuk. Kajian ini membentangkan kaedah untuk reka bentuk HEN yang optimal yang mempertimbangkan aspek-aspek keselamatan dan kebolehkendalian di dalam reka bentuk. Data akan diambil untuk kajian jepit dan penilaian keselamatan. Pembentukan aliran panas dan sejuk yang berterusan yang dipanggil Plot Aliran Suhu dan Entalpi *(STEP)* mengutamakan indeks keselamatan yang wujud daripada kadar aliran kapasiti haba (*FCp*). *ISI* yang tinggi bagi aliran panas dan sejuk akan dipadankan bersama dan begitu juga sebaliknya. Oleh itu, fokus keselamatan boleh berpusat hanya pada penukar haba tertentu. Suhu jepit dan utiliti minimum boleh ditentukan daripada *STEP*. Laluan penyebaran gangguan menerusi *HEN* dan aliran yang terjejas akan dianalisis. Pengubahsuaian rangakaian boleh dilakukan dengan menggunakan konsep laluan aliran dibawah untuk mengurangkan laluan penyebaran gangguan dan aliran terjejas. Pelanggaran ΔT_{min} dan penalti tenaga dikenalpasti kerana berlaku perubahan rangkaian. Fleksibiliti dan pengawalan struktur setiap rangakaian alternatif dikenalpasti dan dibandingkan. Perubahan aliran dalam setiap aliran sesuatu rangkaian yang mempunyai peratusan tertinggi dan indeks pengawalan struktur yang hampir dengan nilai 1 merupakan rangkaian yang paling fleksibel dan terkawal. Aplikasi kaedah ini terhadap *Kes Kajian 2* menunjukkan rangakaian alternatif 3 adalah yang paling fleksibel dan terkawal dengan masing-masing bernilai 22% dan 0.917.

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LIST OF SYMBOLS

C	-	Control Vector
c_j	-	Element in Vector C
C_R	-	Reduced Vector C
d	-	Changes in inlet stream
D	-	Disturbance Vector
d_i	-	Element in Vector D
D_R	-	Reduced Vector D
E_{tot}	-	Overall effects on the output variables
$E_{tot,min}$	-	Minimum overall effects on the output variables
$E_{tot,max}$	-	Maximum overall effects on the output variables
$E_{tot, R}$	-	Reduced overall effects on the output variables
I_{SC}	-	Index of structural controllability
N	-	Number of Streams Affected by Disturbances
FCp	-	Heat capacity flowrate
F	-	Flexibility
$\delta\dot{Q}_i$	-	Change of heat duty
P	-	Disturbance propagation matrix
$p_{i,j}$	-	Element in matrix P
P_R	-	Reduced matrix P
T'_c	-	Shifted cold temperature
T'_h	-	Shifted hot temperature

T_c	-	Cold stream temperature
T_h	-	Hot stream temperature
T_{pinch}	-	Shifted pinch point temperature

LIST OFABBREVIATIONS

AHI	-	Atmospheric Hazard Index
CC	-	Cumulative Curve
EHI	-	Environmental Hazard Index
EURAM	-	European Union Risk Ranking Method
GA/SA	-	Genetic/Simulated Annealing Algorithms
GCC	-	Grand Composite Curve
GD	-	Grid Diagram
HEN	-	Heat Exchanger Network
HI	-	hazard Index
ISI	-	Inherent Safety Index
IS-KPIs	-	Inherent Safety Key Performance Indicators
ISPI	-	Inherent Safety Potential Index
I2PI	-	Integrated Inherent Safety Index
PA	-	Pinch Analysis
PTA	-	Problem Table Algorithm
RISI	-	Risk-based Inherent Safety Index
SPTA	-	Simple Problem Table Algorithm
STEP	-	Stream Temperature vs. Enthalpy Plot
SWeHI	-	Safety Weighted Hazard Index
TRI	-	Toxic Release Inventory

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Heat exchanger network (HEN) is a key aspect of chemical process design (Linnhoff and Hindmarch, 1983). The improvement of HEN can save the energy about 20-30% together with the capital saving. During the last two decades, a lot of researches on the development of HEN synthesis have been done especially on the development of heat recovery pinch method and utilization of maximum energy recovery, minimum area and unit targets and minimum global total cost. However, less consideration of operability and safety of HEN may lead to the undesired condition in a process such as the failure of heat exchanger. In most cases, the operating condition of heat exchanger network synthesis and design are assumed fixed at nominal conditions. Nevertheless, HEN in the industries is very complex as it considers many problems and situations. For instance, fouling, changes in feedstock, changes in specifications, catalyst deactivation, changes in product demand and varied seasonal operations (Shenoy, 1995). It is possible that these frequent changes create variations in the plant operation which are difficult to predict (Verheyen and Zhang, 2006). The deviation of the supply temperature and heat capacity flowrate from the nominal values is the most significant variations with high potential to occur (Tellez *et al*., 2006).

Linnhoff and Flower (1978) have developed Pinch Analysis technique for maximum energy recover targeting and network integration. Setting energy target is the main point of Pinch Analysis in which the target is important for the energy reduction before a detailed design is conducted. The application of Pinch Analysis in industries has been widely spread since then. Pinch Analysis is a systematic and holistic approach in improving the process stream and maximising heat recovery (Manan and Wan Alwi, 2006). The application of Pinch Analysis in industries gives some benefits as the process heating and cooling requirement can be minimised. Other than that, the number of heat exchanger, cooler and heater can also be minimised. Wan Alwi and Manan (2010) has proposed a new graphical method known as Stream Temperature vs. Enthalpy Plot (STEP) in order to overcome the limitations of composite curves (CC). At the same time, targeting and design of HEN can be ascertained from STEP as it is mapped on individual hot and cold streams using a shifted temperature versus enthalpy diagram. The Pinch point, maximum heat allocation (MHA) and energy target are simultaneously shown from STEP. MHA from the STEP diagram is then translated into Heat Allocation and Targeting (HEAT) diagram. Chan *et al*. (2014) has proposed STEP that considers inherent safety of heat exchanger network. Inherent safety is focusing in reducing hazard in the early phase design. The area of hazard in the heat exchanger network can be reduced by matching the unsafe hot and cold stream together. Furthermore, it is important to select a process network that will lead towards inherently safer design because the inherent safety of the whole design is affected by the choice of network selection.

Operability of HEN refers to the ability of the network to remain in steady state even when some of the stream parameters such as inlet or outlet temperatures and heat capacity flowrates vary within the specified bound (Calandranis and Stephanopoulos, 1988). The optimal HEN should not only exhibits the trade-off between the capital and operating cost, but it also must have the operability characteristics that allow this economic performance to be achievable in practical operating environment (Glemmstad, 1997). Linnhoff and Kotjabasakis (1987) introduced the concept of downstream paths to identify the disturbance propagation path through the network which gives engineers much insight for the flexibility design. The modification of the network is done to reject the disturbances from the plant.

On the other hand, in 1989, Huang and Fan (1989) has introduced a distributed strategy for integration of process design and control based on the principles of knowledge engineering. This method is able to generate an effective process with a high degree of structural controllability. It also can deal with different degrees of disturbance and various level of control precision. As it can develops a high degree of structural controllability network, thus, the repeated modification of the network can be prevented as well as simplified the design of process control system.

The disturbances that propagate severely through HEN makes it difficult to be operated and uncontrollable. This problem gave the realisation and great attention in introducing the integrated process design and control (IPDC) (Seferlis and Georgiadis, 2004). The IPDC and decomposition based solution strategy for HEN has been introduced by Abu Bakar *et al*. (2012). The IPDC formulation has the performance objective in terms of design, control and cost is optimised subject to a set of constraints.

However, based on all the literatures, there are no work which integrates all the components of maximising energy recovery, safety, design and operability together for heat exchanger network design. Hence this is the motivation of this research.

1.2 Problem Statement

In an industry, the heat exchanger network is typically designed only based on maximising heat recovery potentials. Safety element is only considered through HAZOP analysis after the design of network. It is possible for contamination, explosion, fouling and leakage of heat exchanger to occur in plant industries. Besides that, in most cases, the operating condition of heat exchanger network synthesis and design are assumed at steady state and non-variable. However in reality, changes and disturbances of operating condition may occur especially the supply temperature and heat capacity flowrate.

Matching of heat exchangers without considering the streams chemical and physical properties may lead to high cost at the later stage of the design. The consideration of safety elements of network selection at the early phase is more desirable in order to reduce the area of hazard and the need for extensive safety design in the later stage. In the meantime, a network with many connected heat exchangers within its path and split streams may also cause controllability problem. Heat exchangers also need to be able to cater flexibility where when there are disturbance in the streams, the system can still delivers the heat requirement. STEP method which can simultaneously target and design heat exchanger network has been extended to consider inherent safety by Chan et al (2014). However, the method has not been extended to include operability issues mainly flexibility and controllability. Following is the problem statement of this research:

Given a set of hot streams that needs to be cooled down, a set of cold streams that needs to be heated up, it is desired to design a heat exchanger network which maximise the heat recovery potentials. At the same time, the final network design should consider inherent safety and operability of the network. In this work, a new framework to design a heat exchanger network that maximise heat recovery, minimise material construction cost, flexible and with less operability problem is proposed by using the STEP method.

1.3 Objectives of the Study

The main objective of this research is to develop a new framework for optimal heat exchanger network (HEN) design considering maximum energy recovery (MER), inherent safety and operability.

Following are the sub-objectives:

1) To determine the inherent safety index score of each streams involved.
2) To determine the total number of streams affected in which a disturbance propagates through a heat exchanger network.
3) To modify heat exchanger network and determine the flexibility and controllability to the disturbance.
4) To compare and select the optimal heat exchanger network design.

1.4 Scope of Study

The scope of the study includes:

1) State of the art review of inherent safety and operability in heat exchanger network (HEN).
2) Developing a framework for designing a heat exchanger network considering heat recovery, inherent safety and operability based on STEP method.
3) Designing the MER heat exchanger network based on inherent safety index score instead of heat capacity flowrate (FCp).
4) Analysing the impact of operability disturbance on the heat exchanger network design through the downstream path concept.
5) Developing a heat exchanger network design that is more flexible and structural controllable to the disturbances of the operating condition.
6) Demonstrating the new framework with illustrative case study of a grassroots design.

1.5 Significance of the Study

The benefits of this study are:

1) The consideration of inherent safety index score at the early stage of heat exchanger network can minimise the risk of contamination, accidents and explosion occurs in the industries.
2) The modification of heat exchanger network allows the design of a less sensitive control structure with the minimisation of disturbance propagation path and affecting streams.
3) The development of flexible and controllable heat exchanger network toward the variations in the operating conditions allows it to meet the design requirement at new operating condition.

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