CONTINUOUS INDIVIDUAL PLOT CURVES TECHNIQUE FOR SIMULTANEOUS TARGETING AND DESIGN OF A MASS EXCHANGE NETWORK

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FOR SIMULTANEOUS TARGETING AND DESIGN OF
A MASS EXCHANGE NETWORK

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To my Beloved Parents

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ABSTRACT

In the last two decades, Mass Exchange Network (MEN) synthesis has been explored to design mass exchanger system to systematically minimize Mass Separating Agents (MSAs) and waste in process industries. Heuristic approach through pinch analysis is a convenient method to analysis mass-based separation network synthesis i.e. the mass transfer between rich and lean stream (process and external MSAs). This research introduces the notion of targeting and design of MEN simultaneously through a new pinch-based graphical technique. The new method aims to sort out the limitation of previous developed graphical approach such as Composite Curves (CC) and Grid Diagram (GD), where targeting and network design of MEN problem is done one at a time and independent of each other except being guided by the pinch point. The framework of this research consists of data specification, simultaneous MSA targeting and network design, and also impact of the design scenarios on capital. Continuous Individual Plot (CIP) approach has been developed to map continuous stream profiles of rich streams and lean streams involved in the MEN problem. Along with introduction of Mass Allocation Network (MAN) diagram, these new tools overcome sequential step practiced by current pinch-based approaches in synthesizing MEN.A set of heuristics are also produced to guide the procedure of these new tools. Systematic steps to analyze capital cost early during MSA targets of stream–matching are also provided. The research has demonstrated the ability of the new method with two industrial-based literature case studies for continuous system with single transferable component. The minimum MSA targets achieved are exactly the same as previous CC techniques while network design can now been translated directly from the targeting tool i.e. the CIP plot.

ABSTRAK

Dalam dua dekad yg terakhir, sintesis rangkaian pemisahan jisim telah digunakan untuk mereka bentuk sistem pemisahan jisim bagi meminimumkan agen pemisah jisim dan pembuangan bahan kimia dalam industri proses secara lebih sistematik. Pendekatan yang lebih heuristik menggunakan analisis jepit merupakan kaedah mudah untuk analisa perilaku sistem rangkaian pemisahan jisim, iaitu hubungan pindah jisim antara aliran kaya dan kurus. Kajian ini mengenengahkan idea-idea penetapan sasaran dan reka bentuk rangkaian pemisahan jisim berasaskan analisis jepit secara grafik. Kaedah ini bertujuan untuk menyelesaikan masalah yang terdapat pada pendekatan grafik sedia ada seperti keluk komposit dan rajah grid, di mana pensasaran dan reka bentuk rangkaian pemisahan jisim dilakukan satu persatu dan tidak bergantung antara satu sama lain kecuali hanya berpandukan kepada titik jepit. Rangkan asas kepada kajian ini terdiri daripada spesifikasi data, rangkaian agen pemisahan jisim serentak, dan kesan reka bentuk tersebut secara keseluruhan. Plot individu berterusan telah diterapkan dalam kajian ini untuk memetakan profil aliran kaya dan aliran kurus secara berterusan yang terlibat di dalam sistesis rangkaian pemisahan jisim. Rajah rangkaian peruntukan jisim dan pendekatan yang digunakan dalam kajian ini dapat mengatasi langkah berturutan yang telah digunapakai dalam kebanyakan analisa jepit dalam mensistesis rangkaian pemisahan jisim. Satu set pendekatan heuristik juga turut diperkenalkan sebagai manual kepada penggunaan kaedah ini. Langkah sistematik dalam menganalisa kos modal permulaan semasa pemadanan aliran bagi pensasaran agen pemisah jisim turut disertakan. Kajian ini telah menunjukkan kebolehan kaedah baru ini berdasarkan dua kajian industri untuk sistem berterusan dengan pemindahan komponen tunggal. Pensasaran agen pemisah jisim minima yang telah dicatatkan dalam kajian ini adalah sama dengan kaedah keluk komposit dengan reka bentuk rangkaian yang kini dapat dipindahkan secara langsung dari alat pensasaran iaitu plot keluk komposit

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LIST OF ABBREVIATIONS

AOC	-	Annual Operating Cost
ACC	-	Annual Capital Cost
BOD	-	Biochemical Oxygen Demand
CC	-	Composite Curves
CIP	-	Continuous Individual Plot
CIT	-	Composition Interval Table
COG	-	Coke Oven Gas
DCS	-	Distributed Control System
DFP	-	Driving Force Plot
DOE	-	Department of Environment
GCC	-	Grand Composite Curve
GD	-	Grid Diagram
HEN	-	Heat Exchange Network
HEAT	-	Heat Allocation and Targeting
IBMS	-	Interval Based MINLP Superstructure
LGO	-	Light Gas Oil
LP	-	Linear Programming
MAN	-	Mass Allocation Network
MEN	-	Mass Exchange Network
MEx	-	Mass Exchanger
MILP	-	Mixed Integer Linear Programming
MINLP	-	Mixed Integer Non-Linear Programming
MOC	-	Minimum Operating Cost
MSA	-	Mass Separating Agent
NAP	-	Number of Actual Plate
NLP	-	Non-Linear Programming

NTP	-	Number of Theoretical Plate
S&TBS	-	Supply and Target Based Superstructure
STEP	-	Stream Temperature over Enthalpy Plot
SWS	-	Stage-wise Superstructure
TAC	-	Total Annual Cost
T&SBS	-	Target and Supply Based Superstructure

LIST OF SYMBOLS

α	-	Volume efficiency
b_j	-	Constant for the j^{th} lean stream
C_{min}	-	Minimum removal cost for each MSA
C_{msa}	-	MSA cost ($/kg)
D	-	Column Diameter
ε	-	Minimum composition difference
G	-	Rich stream flowrate (kg/s)
G_i	-	Rich stream flowrate for the i^{th} stream (kg/s)
G_m	-	Gas flowrate (kg/second)
H	-	Packed column height
HTU_x	-	The overall height of transfer units (lean phase)
HTU_y	-	The overall height of transfer units (rich phase)
L	-	Lean stream flowrate (kg/s)
L_j	-	Lean stream flowrate for the j^{th}stream (kg/s)
L^c_j	-	Maximum lean stream flowrate (kg/s) for the j^{th} stream
m_j	-	Mass transfer coefficient for the j^{th} lean stream
ΔM	-	Pollutant mass load (kg/s)
N_i	-	Number of independent synthesis sub problem
N_R	-	Number of rich streams
N_S	-	Number of lean streams
N_e	-	Number of equilibrium stages
$[N_e]$	-	Rounded up number of equilibrium stages
N_r	-	Number of real stages
$[N_r]$	-	Rounded up number of real stages
NTU_x	-	The overall number of transfer units (lean phases)
NTU_y	-	The overall number of transfer units (rich phases)

R	-	Rich stream
η_o	-	Overall Exchanger Efficiency
ρ_l	-	Liquid density (kg/m^3)
ρ_v	-	Gas density (kg/m^3)
S	-	Lean stream
S	-	Tray spacing (m)
t	-	Operating time (year)
u_{max}	-	Maximum allowable gas velocity
U_{min}	-	Minimum number of units
u_v	-	Actual gas velocity
x_{lim}	-	Limiting lean stream composition
x_j	-	j^{th} lean stream composition
$x_{s,j}$	-	Lean stream supply composition forthe j^{th} stream
$x_{t,i}$	-	Lean stream target composition for the j^{th} stream
x^{max}	-	Maximum achievable solute composition in MSAs
x^*_j	-	Attainable composition of the lean stream (MSA) for the j^{th} stream
$x^c_{t,j}$	-	The maximum permissible lean stream (MSA) target composition for the j^{th} stream
y	-	Rich stream composition (scale)
$y_{s,i}$	-	Rich stream supply composition for thei^{th} stream
$y_{t,i}$	-	Rich stream target composition for the i^{th} stream
y^*	-	Modified rich stream composition
Δy_{min}	-	Minimum rich stream composition difference

CHAPTER 1

INTRODUCTION

1.1. Process Integration for Industrial Wastes

Industrial activities have been playing important roles in increasing the quality of human life by utilizing natural resources to provide multitude of basic chemical, industrial, and consumer products. These include petroleum, gas, chemical, petrochemical, pharmaceutical, food, fertilizer, and forestry product (El-Halwagi and Manousiouthakis, 1989). However, these activities also produce wastes from by-product, unconverted material, and pollutant because of undesired raw materials and process limitations.

These wastes can be huge sources of water, air and land pollution which are harmful to human and environment because of the toxic components. Industrial wastes often give rise to contaminant with heavy metals and persistent organic compounds. According to Industrial Development Organization (UNIDO), industrial activities produce 300-500 million tons of heavy metals, solvent, toxic sludge and other wastes each year (UNWATER, 2012). Some examples of these wastes are wastewater containing benzene, hydrocarbons sludge, phenolic wastewater and spent caustic solution from a petroleum refining industry (Cheremisinoff and Rosenfeld, 2009). In Chemical Industries, typical wastes generated are acids and bases, spent solvents, reactive waste, and wastewater containing organic. (Safewater.org, 2012).

According to UNESCO (2012) industrial activities consume as much as 59% of total water use in high-income countries whereas low and middle-income countries consume 10% of total water use (Figure 1.1). However, in developing countries, 70% of industrial wastes are dumped untreated into waters where they pollute the usable water supply (UNWATER, 2012).

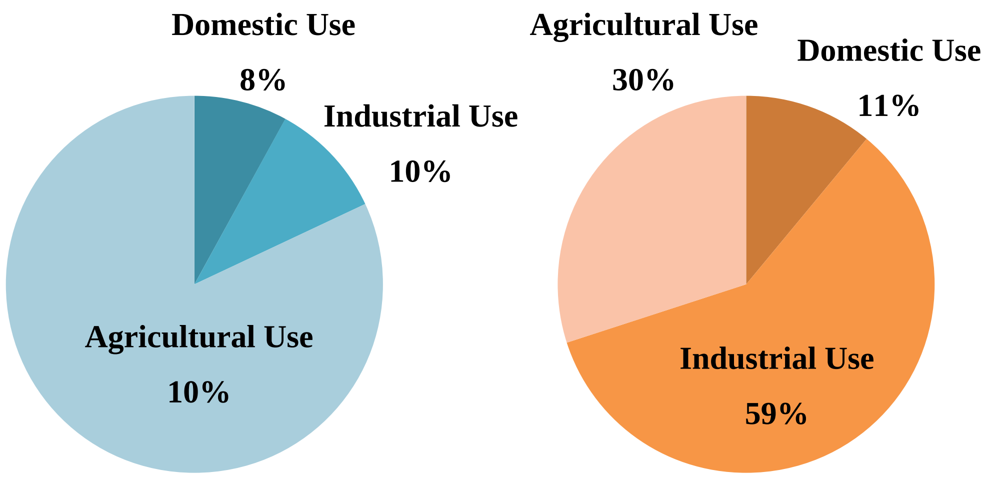

Figure 1.1 Water uses for (a) Low income countries (b) High income countries (UNESCO, 2012)

In Malaysia, the common forms of industrial pollution are suspended particulate emissions that cause air pollution, Biochemical oxygen demand (BOD) discharges which cause water pollution, and toxic waste discharges. Over 40% of the total volume of wastewater discharge in Malaysia originates from manufacturing activities (Figure 1.2).

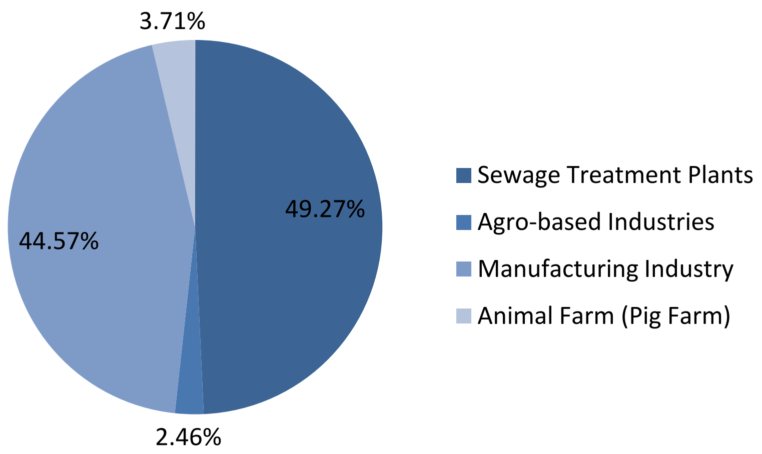

Figure 1.2 Malaysia: composition of wastewater by sector (DOE, 2010)

The staggering magnitude of industrial waste coupled with the growing awareness of the consequences of discharging effluents into natural resources have spurred the process industry to become more environmentally conscious. Hence, the objectives of preventing pollution, conserving resources, increasing productivity, and enhancing profitability are among the top priorities of the process industries. This can be done through a sound systematic technique known as process integration.

Process Integration can be defined as a holistic approach to process design and optimization, which exploits the interactions between different units in order to employ resources effectively and minimize costs. Pinch analysis has been a widely-used technique in process integration. In the late 1970s, the technique was developed by Linhoff and Flower (1978) for energy minimization in an oil refinery. Later it has been adapted and lead other pioneer works for various applications such as mass (El-Halwagi and Manousiouthakis, 1989), water recovery problems (Castro *et al.*, 1999), wastewater minimization (Wang and Smith, 1994), hydrogen (Alves, 1999), and carbon planning (Tan and Foo, 2007).

Pollution prevention and industrial waste reduction can be obtained from process integration techniques. In general, there are four main approaches for pollution prevention (El-Halwagi, 1997):

(i). Source reduction, it includes any in-plant actions to reduce the quantity or the toxicity of the waste at the source.

(ii). Recycle/reuse, this approach involves the use of pollutant-laden streams within the process. Typically, separation technologies are key elements in a recycle/reuse system to recover valuable materials such as solvents, metals, inorganic species, and water.

(iii). End-of-pipe treatment, it refers to the application of chemical, biological, and physical processes to reduce the toxicity or volume of downstream waste.

(iv). Disposal involves the use of post-process activities that can handle waste, such as deep-well injection.

This dissertation will focus at the second approach which aims to reduce the amount of waste such as solvent or recover valuable material in order not to be excessively discharged. Process integration through mass-pinch analysis will be used as the fundamental approach in designing a set of mass-based separation system to meet the goal.

During process synthesis, an engineer is usually provided with various process technologies, alternatives, configurations, and operating conditions. These will usually lead to high number of process alternatives. Hence, it is difficult to be certain that a solution will be regarded as the best potential configuration practically and economically. Even until today, design is geared toward previous experiences (Figure 1.3(a)) and corporate preference which could miss opportunity to meet the best among the alternatives.

Because the vast amount of alternatives, it is necessary to have a systematic process synthesis technique that is able to extract the optimal solution(s) among numerous design candidates. This is where pinch analysis has a major advantage. Pinch applications begin with the setting up of the true baseline targets based on the thermodynamics of a process under study. Mass pinch analysis aims to set a minimum mass separating agent (MSA) target e.g. solvent use and predict a minimum number of mass exchange unit target for a set of mass-based separation equipment which is known as mass exchange network (MEN) synthesis problem (El-Halwagi and Manousiouthakis, 1989).

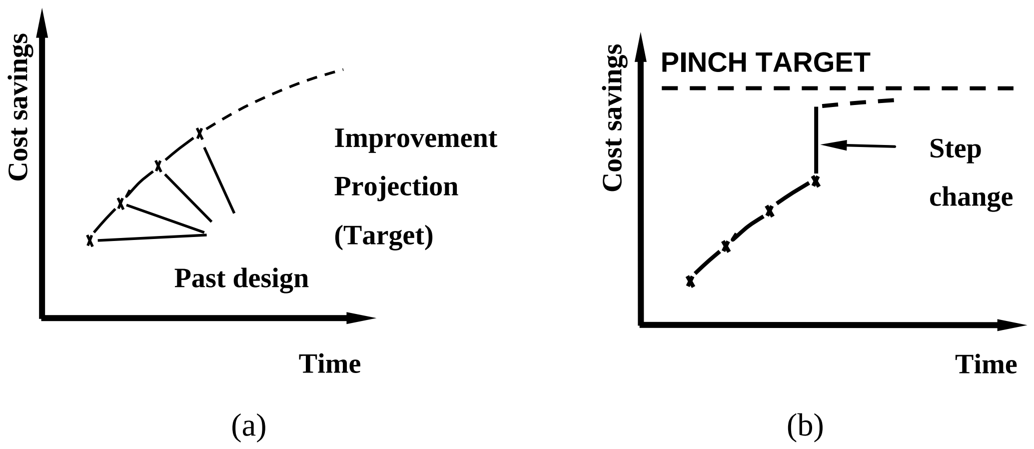

Figure 1.3 Comparison of conventional and pinch technique. a) Design/Retrofit based on past. b) Design/Retrofit based on pinch technique (Wan Alwi, 2005)

A targeting approach has been done in a sequential manner, in which design targets are determined in subsequent stages ahead of any final design and without commitments to final network configuration. As a result, the problem dimensionality is reduced into more manageable size. In addition, valuable insights for the system performance and characteristic can be accessed. With the notion of the design targets, a designer will avoid a combinatorial design alternatives problem. By knowing the minimum MSA targets guidelines ahead of any detail design, the best possible design that can yield the most efficient network will indeed be produced. As a result, a step change in process design improvement will be likely achieved (Figure 1.3(b)).

1.2. Research Background

Mass Separating Agent (MSA) for separation systems such as solvents, adsorbents (e.g. activated carbon), stripping agents (e.g. steam, air), and ion-exchanges are very important resources in process industry. Over the last 20 years, many design techniques have been developed for MEN synthesis to optimize the use of these MSAs in mass-based separation system (Figure 1.4) based on pinch technology similar with heat exchanger network (HEN) synthesis approach. Generally, MEN problem is approached by using graphical, algebraic, and mathematical programming method.

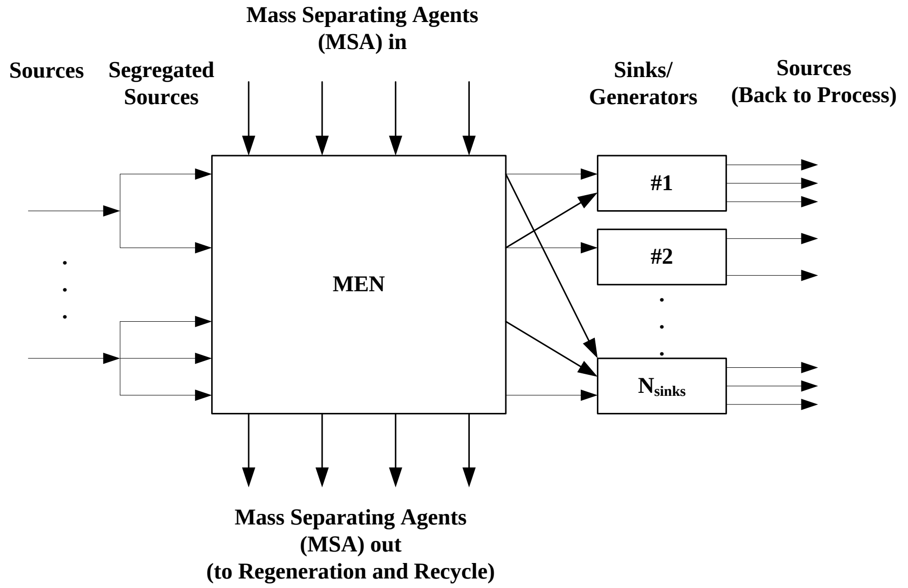

Figure 1.4 A mass-based separation system from a species viewpoint with MSAs for interception (El-Halwagi, 2006)

First attempt to solve MEN problem is to perform separated task of targeting stage and design stage. Minimum amount of MSA can be targeted through pinch analysis by means of mass composite curve and composition interval diagram (CIT) method (El-Halwagi and Manousiouthakis, 1989) analogous to HEN. Minimum number of units targeting is performed using number of streams information according to pinch regions. Finally, the network is designed to meet or closely approach these targets using several rules to ensure feasible mass transfer between rich and lean streams. These initial works have provided fundamental and triggered other development of MEN synthesis. First mathematical programming approach has also been presented through separated targeting and design stage which is an automated version (El-Halwagi and Manousiouthakis, 1990).

In recent years, pinch analysis for MEN has contributed in industrial application and been brought to the same level in comparison to pinch analysis by HEN. Capital cost target, super targeting, and retrofit targeting have given significant contribution to this achievement. Different approach in graphical technique is also presented. In spite of the contribution, the synthesis tasks are still performed sequentially, i.e. setting the target and designing the network.

Recently, the notion of MEN synthesis has been dominated by mathematical programming approach. This is mainly attributed to the ability to tackle large and complex MEN problems. Although it can be used for small scale problem in terms of streams number, it is computationally extensive and once the mathematical program is formulated, the designer is essentially removed from the design process. His or her insights and inputs therefore need to be included in the problem formulation and this can be a difficult task (Hallale and Fraser, 2000a).

Until now, pinch analysis by graphical method for MEN synthesis has been solely done in two steps i.e. targeting and network designing steps. So far, the targeting stages cannot represent clearly the match between each rich and lean stream because of its composite nature. Hence, the network should be design separately with feasibility criteria such as stream population and operating line versus equilibrium line criteria. Graphical technique is considered as practical method and can give visual representation of the streams involved directly; hence this gives more insight regarding changes of streams properties throughout the process.

The importance of MEN and the urge for an interactive, practical, direct and non-sequential systematic MEN synthesis approach have motivated this work. The research is geared towards development of a new graphical technique by pinch analysis to perform targeting stage and network designing simultaneously. In the new targeting stage, it is expected that matches between each rich and lean streams can directly represents the final configuration of the network. Hence, designing the network that meets the targets will not require feasibility criteria checking to be done because the network structure can be translated from the targeting plot.

1.3. Problem Statement

Industrial waste can be harmful to human and environment. Mass-based separation system is an example inside a chemical plant which deals and produces industrial waste materials. Mass-pinch composite curves (CC) and grid diagram (GD) have been available as a graphical tool in order to synthesize cost effective mass-based separation system also termed as Mass Exchange Network (MEN). In MEN synthesis, waste material is transferred from a set of rich streams (undesired species laden streams) to lean streams also known as Mass Separating Agent (MSA). The idea is to achieve minimum MSA targets in CC and to design the network in GD. Because of composite nature of CC, both stages cannot be performed simultaneously which means that targets in CC cannot be directly translated into network design. Hence, a designer must deal with a set of feasibility criteria checking and repetitive calculation must be involved through the process. It is very clear that there is a need to develop a systematic graphical tool that can perform targeting and network design simultaneously.

The mass exchange network synthesis problem for simultaneous target and design is summarized as follows:

"Given a set of rich streams and a set of lean streams (MSA), it is desired to synthesis mass exchange network by targeting minimum MSA use, minimum number of units and designing the network simultaneously."

1.4. Research Objectives

The main aim of this research is to develop a new graphical approach for simultaneous targeting and network design of a cost-effective mass exchange network for mass-based separation systems. It is envisioned for such approach to be able to provide better alternative for the current graphical approaches.

1.5. Scope of Research

Four tasks have been identified to achieve this research study. The scope of research study includes:

(i). Analysis of the state-of-art MEN synthesis techniques using pinch-based graphical approaches.

(ii). Development of new graphical MEN synthesis technique to simultaneously target and design single component problem using pinch analysis.

(iii). Application of the new technique to two continuous process MEN examples from literature to study the effectiveness of this approach.

(iv). Comparison of the new graphical method with previous graphical approach and identification of possible future works.

1.6. Research Contribution

(i). The new graphical technique termed as Continuous Individual Plot (CIP) curves approach has established an advanced approach in MEN synthesis that can show individual stream profiles and eliminate feasibility design criteria checking for MEN synthesis problem

(ii). The CIP curves provide cost effective, practical solution and is less time consuming because of its capacity to simultaneously target and design network.

(iii). The CIP curves are able to be applied in various MSA and mass-based separation system design, pertaining to single component and continuous problem.

(iv). The CIP curves can conveniently be used to calculate equipment cost using simple correlation during targeting and design since it contains individual stream profiles.

(v). The graphical approaches in MEN synthesis has been brought to the same level as HEN synthesis in terms of simultaneously targeting and design using pinch-based graphical approach.

1.7. Summary of Dissertation

In this dissertation, a set of new systematic simultaneous targeting and design techniques for mass exchange network (MEN) synthesis has been developed. The basic concept of pinch technology utilized for mass exchange network (MEN) using composite curve has been extended for simultaneous targeting and design of MEN. Hence, a new advanced technique is added for MEN synthesis area.

Chapter 2 provides a review of the relevant literatures related to the development in pinch technology for mass exchange network. Overview of current mathematical programming approach for MEN synthesis is also mentioned. Overview of simultaneous Heat Exchange Network (HEN) using pinch analysis is also highlighted to support the idea of this study.

A review of the relevant theories underlying pinch analysis for mass exchange network is provided in Chapter 3. Detailed explanation in basic concept of pinch analysis application in MEN is also covered.

Chapter 4 gives an overview of the methodologies for Continuous Individual Plot (CIP) technique in this work. Six heuristic step has been provided which include (1) Rich and lean streams data specifications, (2) CIP construction, (3) Minimum MSA targeting, (4) Network design using MAN from CIP, (5) Network evolution, and (6) Economic evaluations.

The application of the methodology as well as the analysis of the results in two different case studies is presented in Chapter 5.

Chapter 6 concluded the dissertation by summarizing the main points and contributions discussed and exploring the potential area for future development of MEN synthesis through CIP curves technique.

REFERENCES

Alves, J. (1999). *Analysis and Design of Refinery Hydrogen Systems*. Doctor of Philosophy, UMIST, Manchester.

Azeez, O. S., Isafiade, A. J., and Fraser, D. M. (2012). Supply and Target BasedSuperstructure Synthesis of Heat and Mass Exchanger Networks. *Chemical Engineering Research and Design.* 90(2), 266-287.

Castro, P., Matos, H., Fernandes, M. C., and Pedro Nunes, C. (1999). Improvements for Mass-Exchange Networks Design. *Chemical Engineering Science.* 54(11), 1649-1665.

Chen, C.-L., and Hung, P.-S. (2005). Simultaneous Synthesis of Mass Exchange Networks for Waste Minimization. *Computers andChemical Engineering.* 29(7), 1561-1576.

Cheremisinoff, N. P., and Rosenfeld, P. (2009). *Handbook of Pollution Prevention and Cleaner Production - Best Practices in The Petroleum Industry*. Oxford: William Andrew Publishing.

Comeaux, R.G., 2000. *Synthesis of Mass Exchange Networks with Minimum Total Cost*. Mphil, UMIST, Manchester.

Coulson, J. M., Richardson, J. F. and Sinnott, R. K. (1993). *Chemical Engineering. Vol. 6*, 2nd ed. U. K.: Pergamon Press.

Department of Environment (DOE). 2010. *Malaysia Environmental Quality Report 2010*. Petaling Jaya: Sasyaz Holdings Sdn Bhd.

El-Halwagi, M. M. (1997). *Pollution Prevention through Process Integration*. San Diego: Academic Press.

El-Halwagi, M. M. (2006). In M. E.-H. Mahmoud (Ed.), *Process Integration* (Vol. Volume 7, pp. vii-x): Academic Press.

El-Halwagi, M. M., and Manousiouthakis, V. (1989). Synthesis of Mass Exchange Networks. *AIChE.* 35(8), 1233-1242.

El-Halwagi, M. M., and Manousiouthakis, V. (1990). Automatic Synthesis of Mass-Exchange Networks with Single-Component Targets. *Chemical Engineering Science.* 45(9), 2813-2831.

Emhamed, A. M., Lelkes, Z., Rev, E., Farkas, T., Fonyo, Z., and Fraser, D. M. (2007). New Hybrid Method for Mass Exchange Network Optimization. *Chemical EngineeringCommunications.* 194(12), 1688-1701.

Fraser, D. M., Harding, N., and Matthews, C. (2001). *Retrofit of Mass Exchange Networks*. In G. Rafiqul and J. Sten Bay (Eds.), *Computer Aided Chemical Engineering* (Vol. Volume 9, pp. 991-996): Elsevier.

Fraser, D. M., Howe, M., Hugo, A., and Shenoy, U. V. (2005). Determination of MassSeparating Agent Flows Using The Mass Exchange Grand Composite Curve. *Chemical Engineering Research and Design.* 83(12), 1381-1390.

Hallale, N., and Fraser, D. M. (1998). Capital Cost Targets for Mass Exchange Networks A special case: Water minimisation. *Chemical Engineering Science.* 53(2), 293-313.

Hallale, N., and Fraser, D. M. (1999). Optimum Design of Mass Exchange Networks Using Pinch Technology. *Computers and Chemical Engineering.* 23, Supplement(0), S165-S168.

Hallale, N., and Fraser, D. M. (2000a). Capital and Total Cost Targets for Mass Exchange Networks: Part 1: Simple Capital Cost Models. *Computers and Chemical Engineering*. 23(11–12), 1661-1679.

Hallale, N., and Fraser, D. M. (2000b). Capital and Total Cost Targets for Mass Exchange Networks: Part 2: Detailed Capital Cost Models. *Computers and Chemical Engineering.* 23(11–12), 1681-1699.

Hallale, N., and Fraser, D. M. (2000c). Supertargeting for Mass Exchange Networks: Part I: Targeting and Design Techniques. *Chemical Engineering Research and Design*. 78(2), 202-207.

Hallale, N., and Fraser, D. M. (2000d). Supertargeting for Mass Exchange Networks: Part II: Applications. *Chemical Engineering Research and Design.* 78(2), 208-216.

Isafiade, A. J., and Fraser, D. M. (2008). Interval Based MINLP Superstructure Synthesis of Mass Exchange Networks. *Chemical Engineering Research and Design.* 86(8), 909-924.

Linnhoff , B., Flower J.R. (1978). Synthesis of Heat Exchanger Networks. Part i. SystematicGeneration of Energy Optimal Networks. *AIChE Journal*. 24 (4) 633–642.

Msiza, A. K., and Fraser, D. M. (2003). *Hybrid Synthesis Method for Mass Exchange Networks*. In K. Andrzej and T. Ilkka (Eds.), *Computer Aided Chemical Engineering* (Vol. Volume 14, pp. 227-232): Elsevier.

Papalexandri, K. P., Pistikopoulos, E. N., and Floudas, C. A. (1994).Mass exchange Networks for Waste Minimisation: A Simultaneous Approach. *Transactons IChemE*, 72, 279–294.

Perry, R. H., and Green, D.W. (1997) *Perry's Chemical Engineer's Handbook*. 8th Ed. New York: McGraw Hill.

Safewater website. *http://www.safewater.org/PDFS/knowthefacts/IndustrialWaste.pdf*. Accessed on May, 1 2012.

Smith, R. (1995). *Chemical Process Design*. New York: McGraw Hill.

Szitkai, Z., Farkas, T., Lelkes, Z., Fonyo, Z., Kravanja, Z., (2006). Fairly Linear Mixed Integer Nonlinear Programming Model for The Synthesis of Mass Exchange Networks. *Ind. Eng. Chem. Res*. 45, 236–244.

Szitkai, Z., Msiza, A. K., Fraser, D. M., Rev, E., Lelkes, Z., and Fonyo, Z. (2002). Comparison of Different Mathematical Programming Techniques for Mass Exchange Network Synthesis. In g. Johan and s. Jan van (Eds.), Computer Aided Chemical Engineering (Vol. Volume 10, pp. 361-366): Elsevier.

Tan, R. R., and Foo, D. C. Y. (2007). Pinch Analysis Approach To Carbon-Constrained Energy Sector Planning. *Energy*. 32(8), 1422-1429.

Treybal, R. E. (1981). *Mass Transfer Operations* (3rd ed.). Singapore:McGraw–Hill.

UNESCO website. *http://webworld.unesco.org/water/wwap/facts_figures/water_industry.shtml*. Accessed on May, 1 2012.

UNWATER website. *http://www.unwater.org/statistics_pollu.html*. Accessed on May, 1 2012.

Wan Alwi, S. R. (2005). *A Holistic Framework for Minimum Water Design for Urban and Industrial Sectors.* Doctor of Philosophy, UTM, Skudai

Wan Alwi, S. R., and Manan, Z. A. (2010). STEP—A New Graphical Tool for Simultaneous Targeting and Design of A Heat Exchanger Network. *Chemical Engineering Journal*. 162(1), 106-121.

Wang, Y. P., and Smith, R. (1994). Wastewater Minimisation. *Chemical Engineering Science*. 49(7), 981-1006.

Yee, T. F., and Grossmann, I. E. (1990). Simultaneous Optimization Modelsfor Heat Integration. I. Area and energy Targeting and Modeling ofMulti-Stream Exchangers. *Computers and Chemical Engineering*, 14,1151.