Cairo University

A NOVEL GRAPHICAL APPROACH FOR MASS EXCHANGE NETWORKS USING COMPOSITION DRIVING FORCE (CDF)

By

Nessren Mohamed Farrag Abou El-Ela

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Chemical Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019

A NOVEL GRAPHICAL APPROACH FOR MASS EXCHANGE NETWORKS USING COMPOSITION DRIVING FORCE (CDF)

By

Nessren Mohamed Farrag Abou El-Ela

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Chemical Engineering

Under the Supervision of

Prof. Dr. Mai Kamal Fouad

………………………………..

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

Prof. Dr. Mamdouh Ayad Gadalla

………………………………..

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

Dr. Ayat Ossama Ghallab

……………………………………

Associate Professor
Chemical Department
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019

A NOVEL GRAPHICAL APPROACH FOR MASS EXCHANGE NETWORKS USING COMPOSITION DRIVING FORCE (CDF)

By

Nessren Mohamed Farrag Abou El-Ela

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Chemical Engineering

Approved by the
Examining Committee

____
Prof. Dr. Mai Kamal Fouad **(Thesis main advisor)**

____
Prof. Dr. Mamdouh Ayad Gadalla **(Advisor)**
HOD of Chemical Engineering Department
Port Said University

____
Prof. Dr. Mahmoud Abdel Hakim El-Rifai **(Internal Examiner)**

____
Prof. Dr. Abeer Mahmoud Shoaib **(External Examiner)**
Professor at Faculty of Petroleum and
Mining Engineering, Suez Canal University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019

Engineer's Name:	Nessren Mohamed Farrag Abou El-Ela
Date of Birth:	19/2/1991
Nationality:	Egyptian
E-mail:	Nessren.farrag@bue.edu.eg
Phone:	0128 700 6 888
Address:	296 El-Narges-5th settlement

Registration Date:	1/10/2015
Awarding Date:	…./…./2019
Degree:	Doctor of Philosophy
Department:	Chemical Engineering

Supervisors:

Prof. Dr. Mai Kamal Fouad
Prof. Dr. Mamdouh Ayad Gadalla
HOD of Chemical Department
Faculty of Engineering, Port Said University
Dr. Ayat Ossama Ghallab

Examiners:

Prof. Dr. Abeer Shoaib (External examiner)
Professor at Faculty of Petroleum and
Mining Engineering, Suez Canal University
Prof. Dr. Mahmoud El-Rifai (Internal examiner)
Porf. Dr. Mai Kamal Fouad (Main advisor)
Prof. Dr. Mamdouh Gadalla (Advisor)
HOD of Chemical Engineering Department
Port Said University

Title of Thesis:

A Novel Graphical Approach for Mass Exchange Networks Using Composition Driving Force (CDF)

Key Words:
Mass integration; Composition driving force; Mass exchange networks; Equivalent lean stream composition; Graphical approach

Summary:

Mass integration is the most competent path to track in order to improve economical and environmental performance within the process industries, by minimizing both the amounts of external mass separating agents and waste disposal. This study presents a new graphical approach, taking into account the composition driving forces, to analyze the Mass Integration and exchange networks. The performance of mass exchanger networks is evaluated and analyzed in terms of composition driving force (CDF) inside the mass exchanger. This approach provides the maximum mass recovery network, as well as features minimum utility targets. Graphical insights for deciding location, size and mass load of mass exchangers are obtained from this plot as well as, quick decisions and analysis for mass networks.

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: Nessren Mohamed Farrag Date: / /2019

Signature:

Acknowledgments

Praise is to Allah, Lord of the world. I praise him for his favors and ask him to increase his grace and generosity. Without his willingness, this dissertation could not have been done.

I would like to express my deep thanks and gratitude to my supervisor **Prof. Dr. Mai Kamal Fouad**, Professor of Chemical Engineering in Cairo University and **Prof. Dr. Mamdouh Gadalla**, Head of Chemical Engineering department in Port Said University as well as **Dr. Ayat Ossama Ghallab**, Associate Professor of Chemical Engineering in Cairo University for giving me the honor to work under their supervision, their sincere guidance and reviewing.

I am also deeply indebted to **Dr. Dina Ahmed Kamel**, lecturer of Chemical Engineering in the British University in Egypt whose help, stimulating suggestions, encouragement, assistance and direction helped me in all the time of research. I would like to thank her for being such a tremendous source of inspiration.

Also, I would like to extend my sincere gratitude to **Prof. Dr. Abeer Mahmoud Shoaib**, Professor at Faculty of Petroleum and Mining Engineering, Suez Canal University and **Prof. Dr. Mahmoud Abdel Hakim El-Rifai**, Professor of Chemical Engineering in Cairo University for their valuable help, reviewing, commenting, supervision, and continuous helping all throughout this work.

I particularly wish to thank my dear husband **Eng. Mohamed Refaat** for his devotion, patience and understanding throughout this study. I also want to thank my dear son Hazem and my lovely daughter Rala for being such a motive.

This work would not have been possible without the love and support from my mother (Dr. Azza Abdel Hamed), my father (Eng. Mohamed Farrag), sisters (Yasmine and Logien). I owe deep debts of gratitude to my mother in law (Mrs. Fatma Ahmed) for all her help and support. This cannot adequately be acknowledged. Finally, I would like to thank everyone who helped me in the department.

Thanks to Allah at the end as well as it was in the beginning.

Eng. Nesreen Farrag

2019

Table of Contents

List of Tables

List of Figures

Nomenclature

MEN	Mass Exchange Network
CDF	Composition Driving Force
MSA	Mass Separating Agent
PM	Pinch Methodology
PA	Pinch Analysis
PoPA	Power Pinch Analysis
HYPS	Hybrid Power System
HI	Heat Integration
WENs	Water-Energy Networks
WEI	Water Energy Integration
Net_G	Net Generation
T_{BMI}	Terminal Load before Mass Integration
F_{BMI}	Fresh Load before Mass Integration
Y	Rich Stream Composition
y*	Equilibrium Rich Stream Composition
X	Lean Stream Composition
M	Equilibrium Dependency Constant
GCC	Grand Composite Curve
HEN	Heat Exchange Network
CIT	Composition Interval Table
TAC	Total Annual Cost
CIT	Composition Interval Table
ε	Minimum allowable composition difference
$x_{equ.jmax}$	Maximum achievable lean stream composition
y_i	Rich stream composition
y_{imin}	Minimum composition in the rich stream
$x_{equ.j}$	Given equivalent lean stream composition
x	Lean stream composition
m	Equilibrium dependency constant
ΔC	Driving force

$\Delta C_{rich\ end}$	Rich end driving force
$\Delta C_{lean\ end}$	Lean end driving force
x_{eqv}^{target}	Target equivalent lean stream composition
x_{eqv}^{supply}	Supply equivalent lean stream composition
y^{supply}	Supply rich stream composition
y^{target}	Target rich stream composition
x^{f}	Feasible lean stream composition
ΔC_{min}	Minimum driving force
ΔM	Mass load transferred within the exchanger
L	Lean Stream flow rate
G	Rich stream flow rate
x_{eqv}^{out}	Exit equivalent lean stream composition
x_{eqv}^{in}	Inlet equivalent lean stream composition
S	Slope of the exchanger line
NTP	Number of theoretical plates
EMSA	External mass separating agent

Abstract

The abundance of essential raw material is critical to the success of both chemical and process industries. Additionally, by-products of such industries may act themselves as raw materials for other industries instead of being disposed of. The goal of conservation of natural resources dictates efficient utilization of raw materials. Mass integration insures the best possible process performance at both the economic and environmental levels, and leads to the minimization of both the amounts of external mass separating agents used and waste disposal needed.

This study presents a new graphical-approach method of analyzing mass integration and exchange networks; one designed to take into account composition driving forces. This proposed approach can be applied to both existing mass networks as well as new ones. The performance of mass-exchange networks (MENs) is evaluated and analyzed in terms of composition driving forces (CDF) inside mass exchangers. In this graphical approach, the x-axis represents the equivalent lean stream compositions, whilst the y-axis represents the difference in compositions for each stream in the exchanger. Pinch Analysis principles are embedded within the graphical representation.

The composition driving forces are the main driver aiding in the relocation of target materials from richer to leaner streams. Additionally, postulating the number of theoretical plates depends mainly on it. Considering the composition driving force is related to estimates of total cost. Such considerations are also beneficial in screening matches. Moreover, the composition driving force graphical approach is valuable in sizing mass exchanger equipment. This approach insures the largest possible mass recovery network, and the least utility targets. Each mass exchanging unit is represented as a straight line with a slope related to the mass flows of both rich and lean streams and length proportional to the mass load transferred within the exchanger. The new plot is divided into five design regions. The principles of Pinch Analysis are used to analyze and optimally locate mass exchangers.

Two case studies were considered for the application of the new approach; a copolymerization plant and a scrap-tires-to-fuel plant. Both plants were designed with mass integration targets in consideration. In both plants, optimum matches were selected based on maximum driving force and minimum flow. In the scrap-tires plant, however, matches with minimum costs were selected. In general, this approach can help synthesize mass networks and achieve targets, whilst maintaining maximum driving force - and thus minimum equipment size and minimum flow.

Chapter 1 : Introduction

The abundance of raw materials and enough supply of energy are both indispensable parts of the success of chemical industries and their plant processes, allowing them to produce those chemicals that have become crucial to the economics of both industrialized and developing countries. A key element in effect utilization of raw materials is the notion of *mass integration*, which takes place in mass exchange networks or MENs. Such integration leads to the reduction of waste disregarded streams as well as the minimum utilization of external utilities and services. Numerous procedures have been proposed in order to best synthesize mass networks, presented together with numerical and graphical solutions. This research embeds a new graphical method of studying and investigating mass integration design problems and MENs. The proposed technique applies the rules of Pinch Analysis and its guidelines into a graphical plot of design problems as the difference in compositions between rich and lean streams against the equivalent compositions of lean streams [1].

1.1. Basic definitions

Chemical and industrial processes are complicated structures of unit operations, machines, instruments, turbines, and material streams. These components implement the essential operations for the plant within the reactions, heaters, coolers, compressors, and even separators. Generally, the integration operations for mass and energy are vital for network synthesis and design particularly when the environment is of great concern [1].

Mass integration ensures mass exchange within two or more process streams. It is defined by El-Halwagi as:

"a systematic methodology that provides fundamental understanding of the global flow of mass within a process and employs this understanding in identifying performance targets and optimizing the generation and routing of species throughout the process" [2].

Mass integration is necessary to coordinate the flow in process streams, which may pass through purification and separation stages or as well as cleaning operations prior to discharge. During such steps, valued species may be recovered from process streams rich in these components (thus called rich streams). These streams can transfer these components to other streams requiring the same components, which are labeled as lean streams. Mass integration allows for the elimination of pollutants from process streams as well as the retention of precious resources within such streams [3].

Mass integration is a key component in the planning of recycling plants, working on waste minimization or even decreasing the amounts of external separating agents. MENs are then the structure developed using this tool in order to be implemented in processing facilities [1].

El-Halwagi and Manousiouthakis, in their research, presented the basics of MENs and the systematic procedures for MEN design and analysis [4]. Several researchers have conceived devices and worked to improve approaches in order to prefect the designs of MENs. Azeez et al. [5] proposed novel mathematical scheme whereby inlet temperatures or the various compositions of streams could be utilized to produce heat or in the design of MENs. In their study, Liu et al. [6] incorporated both mass and energy, presenting an orderly technique for cascaded synthesis. In their calculations, they used the pinch with mass networks and numbers from the pseudo-temperature–enthalpy with heat networks. Same investigators also developed a superstructure-based model to synthesize mass networks for several constituents; using programming for optimization.

A limited number of researchers have dedicated their research to particular aspects of mass integration, examining, for the example, how best to handle H_2 and pollutant streams [7]. Hallale and Fraser [8] concentrated on embedding Pinch Analysis into estimations of total costs of running water networks. For current systems, Fraser and Hallale [9] used novel Pinch tools principles to design networks aiming at decreasing waste produced through absorption, stripping and other processes. Their research results were successfully used decrease disposal from gold solvent extraction procedures by 40%. Primary studies dealing with mass integration were generally designed to target the maximum utilization of raw materials in chemical process industries [1].

Specific criteria have been created to be used when attempting to decide on mass integration targets. Mass exchange pinch diagrams, developed by El-Halwagi and Manousiouthakis, are now used to guide design [4]; implementing the well-established principles of Pinch Analysis, firstly used in planning energy integration [10]. Foo et al. [11] in a study of mass network design, set up the utility targets ahead of batch MEN design. Chen and Hung [12] investigated flow disturbances and recommended a new approach to design. Isafiade and Fraser introduced another approach, to the synthesis of MENs, basing it on the limits of inlet and exit compositions. Their research adjusted an MINLP, and extended the use of cascaded processes with external mass separating agents.

Recently, Liu et al. [6] reported on a formulation of super-structure for the synthesis of MENs, focusing on multiple components. In these later cases, mathematical programming and optimization techniques were mainly used to synthesize MENs for large problems with complex applications. El-Halwagi [2], and Klemeš et al. [14] provided a comprehensive review for mass integration problems and summarized the most recent studies and milestones with regards to MEN design and revamping. Before this study, graphical representation of MENs had not been considered, with the exception of graphical representation through retrofit approaches grounded on mathematical programming.

The current work aims to introduce a novel graphical technique to be used in the evaluation of performance of present MENs as well as to design new ones. This graphical technique depends on the depiction of the particular mass integration problem on a novel graph designed to link the variance in compositions of constituents in all streams against the equivalent composition of lean streams. The technique helps to define present networks through new illustrator technique that should help facilitate performance assessment of the transfer operations. By applying this method, plants should be able to improve revamping and overall performance. In addition, the mass pinch design technique could be integrated into this new approach, allowing for the design of novel constructions of MENs that would be designed to satisfy targets suggested by the Pinch Analysis. Moreover, the number of plates required for mass separation between the two distinct streams can be obtained directly from the graph.