DESIGN OF HEAT EXCHANGER NETWORK USING PINCH METHOD

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A dissertation submitted as partial fulfillment of the requirement for the award of the Master's Degree in Mechanical Engineering

Department of Mechanical Engineering
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NOVEMBER 2006

"I declare that this thesis entitled 'Design of Heat Exchanger Network Using Pinch Method' is the result of my own work except as cited in references".

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For my family,
who offered me unconditional love and support throughout this long journey. And dedicated to all those who believe in the richness of learning.

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ABSTRACT

Chemical or oil refinery processes utilize huge amounts of energy in their routine operations. Therefore, it is vital for such industries to find ways of maximizing the use of energy and make the system more efficient through reduction in energy, water and raw material consumption. Waste energy can be transferred to another process and that will increase the profitability of the industries. When the use of a heat exchanger network (HEN) is considered for these tasks, the framework developed in this study can be implemented to make a cost-benefit analysis.

This thesis represents a framework for generating the HEN over a specified range of variations in the flow rates and temperature of the streams. So that the heat exchanger area, number of heat exchange units and load on the heat exchangers can be estimated. The proposed method to analyze and design the HEN is called pinch method, which is one of the most practical tools and used to improve the efficiency of energy usage, fuel and water consumption in industrial processes. This method investigates the energy flows within a process and identifies the most economical ways of maximizing heat recovery. This method consists of five major steps to follow, which will finally lead to HEN design. The steps are: (1) choose a minimum temperature approach temperature (DTmin), (2) construct a temperature interval diagram, (3) construct a cascade diagram and determine the minimum utility requirements and the pinch temperature, (4) calculate the minimum number of heat exchangers above and below the pinch and (5) construct the heat exchanger network.

The emphasis of this work has been on the designing of the HEN. However, to demonstrate the practical implications of pinch analysis, DTmin and the heat exchanger costs, it is necessary to estimate the heat transfer area of the HEN, which will help in arriving at the total cost including capital and running costs of the designed HEN. The effect of changing the DTmin gave a good indication on the overall costs.

ABSTRAK

Industri pemprosesan kimia atau penapisan minyak banyak menggunakan tenaga dalam rutin harian mereka. Maka industri-industri sebegini perlu mencari alternatif untuk memaksimumkan penggunaan tenaga dan memastikan sistem yang digunakan adalah efisyen melalui pengurangan dalam penggunaan tenaga, air dan juga bahan mentah. Haba buangan daripada proses yang dijalankan boleh dikitar dan diguna semula untuk digunakan di dalam proses yang lain. Jadi, bila alat penukar haba digunakan di dalam proses yang disebutkan di atas, maka kerja di dalam tesis ini boleh digunakan untuk mengurangkan penggunaan kos untuk industri tersebut.

Tesis ini mempersembahkan jalan kerja untuk merekabentuk 'Rangkaian Penukar Haba'. Hasilnya, kawasan yang diperlukan untuk membina alat-alat penukar haba ini boleh dikira, begitu juga bilangan unit yang diperlukan dan bebanan yang dikenakan kepada alat penukar haba boleh dianggarkan. Rangkaian yang diusulkan ini menggunakan kaedah yang dikenali sebagai Kaedah Pinch. Kaedah ini merupakan kaedah yang paling praktikal dan digunakan untuk meningkatkan penggunaan tenaga, air dan bahan mentah secara efisyen. Kaedah ini mengenalpasti tenaga yang boleh dialirkan dari buangan kepada proses yang berguna dan seterusnya dapat memaksimumkan penggunaan tenaga. Kaedah ini mengandungi lima langkah yang perlu diikuti: (1) pilih suhu rendah yang dibenarkan, (2) bina diagram jarak-suhu, (3) bina diagram Cascade dan tentukan keperluan tenaga minimum, (4) kira bilangan alat penukar haba yang diperlukan dan (5) bina rangkaian alat penukar haba.

Objektif utama tesis ini adalah merekabentuk rangkaian alat penukar haba, namun sebagai pelengkap kepada keperluan ekonomi, tesis ini turut mendemonstrasi kesan daripada penggunaan kaedah pinch ini dengan suhu minimum yang dipilih dan juga kos untuk membina rangkaian alat penukar haba. Kos-kos ini termasuk kos untuk membina kawasan, kos pembuatan alat penukar haba dan lain-lain. Kos ini disebut

sebagai kos utama yang melibatkan kos permulaan untuk memulakan operasi. Manakala *kos tahunan atau kos yang perlu ditanggung sepanjang industri ini menjalankan operasi* mereka termasuk kos untuk membeli tenaga, minyak, air dan lain-lain. Dengan menukar nilai suhu minimum yang dipilih di dalam langkah (1), kos-kos yang disebutkan akan berubah dan di sini akan wujud titik optimum yang boleh diaplikasi oleh pihak industri.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	Heat Exchangers Area
A_s	Shell-Side or Tube Outside Surface Area
Cp	Specific Heat Capacity
d_o	Tube Diameter
$DP_{s\text{-}actual}$	Actual Pressure Drop in the Shell-Side
$DP_{s\text{-}id}$	Ideal Pressure Drop in the Shell-Side
D_s	Shell Diameter
DT_{int}	Temperature Difference at Each Interval
DTmin	Minimum Allowable Temperature Difference
F	LMTD Correction Factor
F_1	Correction Factor for the Tube Outside Diameter and Tube Layout
F_2	Correction Factor for the Number of Tube Passes
F_3	Correction Factor Various Rear-End Head Designs
h	Heat Transfer Coefficient
HDD	Humidification–Dehumidification Desalination
HEN	Heat Exchanger Network
h_{id}	Ideal Heat Transfer Coefficient
h_s	Shell-Side Heat Transfer Coefficient
J_b	Correction Factor for Bundle
J_c	Correction Factor for Baffle Configuration
J_l	Correction Factor for Baffle Leakage Effects
J_r	Correction Factor for Any Adverse Temperature Gradient
J_s	Correction Factor for Larger Baffle Spacing
k	Thermal Conductivity
L	Tube Length
L_{eff}	Effective Tube Length

LMTD	Logarithmic Mean Temperature Difference
LP	Linear Programming
m	Flow Rate
mCp	Heat Capacity Flow Rate
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MO-MILP	Multi-Objective Mixed-Integer Linear Programming
N_b	Number of Baffles
NLP	Nonlinear Programming
$N_{r,\ cc}$	Number of Tube Rows Crossed During Flow Through One Crossflow in the Exchanger
$N_{r,\ cw}$	Number of Tube Rows Crossed in Each Baffle Window
N_t	Number Of Tubes
Nu	Nusselts No.
PDM	Pinch Design Method
P_s	Temperature Effectiveness
Q	Heat Supply/Demand
$Q_{available}$	Heat Available
QC	Cold Enthalpy
QH	Hot Enthalpy
Q_{int}	Heat for Each Interval
R_s	Heat Capacity Ratio
STHX	Shell-and-Tube Heat Exchanger
TEMA	Tubular Exchanger Manufacturers' Association
T-H	Temperature-Enthalpy
T-I	Temperature Interval
T_{in}	Supply Temperature
T_{out}	Target Temperature
U	Overall Heat Transfer Coefficient
U_s	Overall Shell-Side Heat Transfer Coefficient
W	Work Done

ΔH	Enthalpy Change
ΔP	Pressure Drop
$\Delta P_{b,id}$	Ideal Pressure Drop in the Central Section
ΔP_{cr}	Pressure Drop in the Central (Crossflow) Section
$\Delta P_{i\text{-}o}$	Pressure Drop in the Shell-Side Inlet And Outlet Sections
ΔP_{w}	Pressure Drop in the Window Area
ζb	Correction Factor for Bypass Flow
ζ_{l}	Correction Factor for Tube-to-Baffle and Baffle-to-Shell Leakage Streams
ζs	Correction Factor for Inlet and Outlet Sections
η	Viscosity
ρ	Density

LIST OF APPENDIXES

CHAPTER I

INTRODUCTION

The transfer of thermal energy is one of the most important and frequently used processes in engineering. The transfer of heat is usually accomplished by a heat exchanger. As a heat transfer device, it is the function of a heat exchanger to transfer heat as efficiently as possible. This makes it the ultimate device of choice, for instance, when it comes to saving energy by recovering wasted heat and making it useful again. When there is a waste of energy or a hot stream that is not recovered, a pre-heater or recuperator can convert that hot stream into a useful source of heat in other applications.

When designing heat exchangers and other unit operations, limits exist that constrain the design. These limitations are imposed by the first and second laws of thermodynamics. In heat exchangers, a close approach between hot and cold streams requires a large heat transfer area. Whenever the driving force for heat exchange is small, the equipment needed for transfer becomes large and it is said that the design has a "pinch". When considering systems of many heat exchangers, it is called a heat exchanger network (HEN). There will exist somewhere in the system a point where the driving force for energy exchange is minimum. This represents a pinch or pinch point. The successful design of these networks involves discovering where the pinch exists and using this information at the pinch point to design the whole network. This design process is called pinch technology.

The HEN synthesis has been one of the most well studied in process synthesis during the last three decades and has been widely applied, especially in the petroleum refining and petrochemical industry. To illustrate the role of HEN in the overall process design, consider the "onion diagram" (Linhoff et. al., 1982) as shown below. The design of a process starts with the reactors in the "core" of the onion. Once feeds, products, recycle concentrations and flowrates are known, the separators (the second layer of the onion) can be designed. The basic process heat and material balance is now in place, and the HEN (the third layer) can be designed. The remaining heating and cooling duties are handled by the utility system (the fourth layer). The process utility system may be a part of a centralised sitewide utility system.

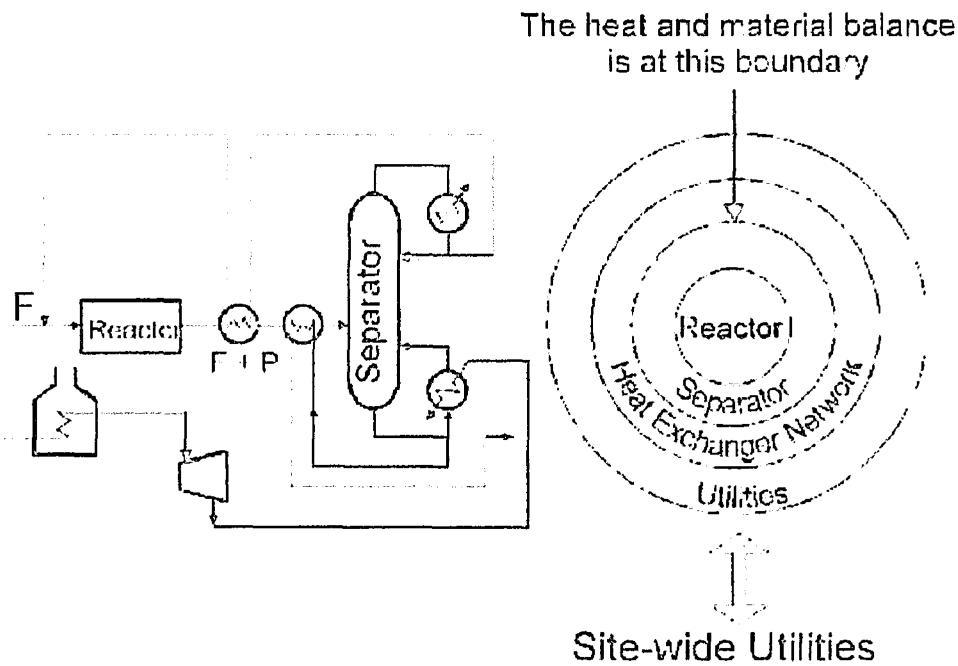

Figure 1.1: Onion Diagram of Hierarchy in Process Design

The pinch analysis starts with heat and material balances for the process. Using pinch technology, it is possible to identify appropriate changes in the core process conditions that can have an impact on energy savings (onion layers one and two). After the heat and material balance is established, targets for energy saving can be set prior to the design of the heat exchanger network. The pinch design method ensures that these targets are achieved during the network design.

Process integration using pinch technology offers a chronicle approach to generate targets for minimum energy consumption before heat recovery network design. Heat recovery and utility system constraints are then considered in the design of the core process. Interactions between the heat recovery and utility system are also considered. The pinch design can reveal opportunities to modify the core process to improve heat integration. The pinch approach is unique because it treats all processes with multiple streams as a single, integrated system. This method helps to optimize the heat transfer equipment during the design of the equipment.

1.1 Background of the Problem

As the heat exchanger consumes energy vastly, it is vital to find a method to improve the use of energy and reduce capital and utilities cost. Finding ways to reduce and conserving energy are always a smart way to cut cost. Reduced energy usage is a big selling point for end users. If the functionality of a product is similar to the competition, benefits like energy usage win customers. The benefit of reduced usage cost over time allows manufacturers to charge a higher premium while saving the customer money in the long run.

Excessive energy consumption by using hot and cold utilities influences the global cost of industrial processes. The supply and removal of heat in a modern oil refinery process plant represents an important problem in the process design of the plant. The cost of facilities to accomplish the desired heat exchange between the hot and cold media may cost up to one third of the total cost of the plant. To meet the goal of maximum energy recovery or minimum energy requirement (MER) an appropriate HEN is required. The design of such a network is not an easy task