DESIGN OF HEAT EXCHANGER NETWORK USING PINCH METHOD

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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.

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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

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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.

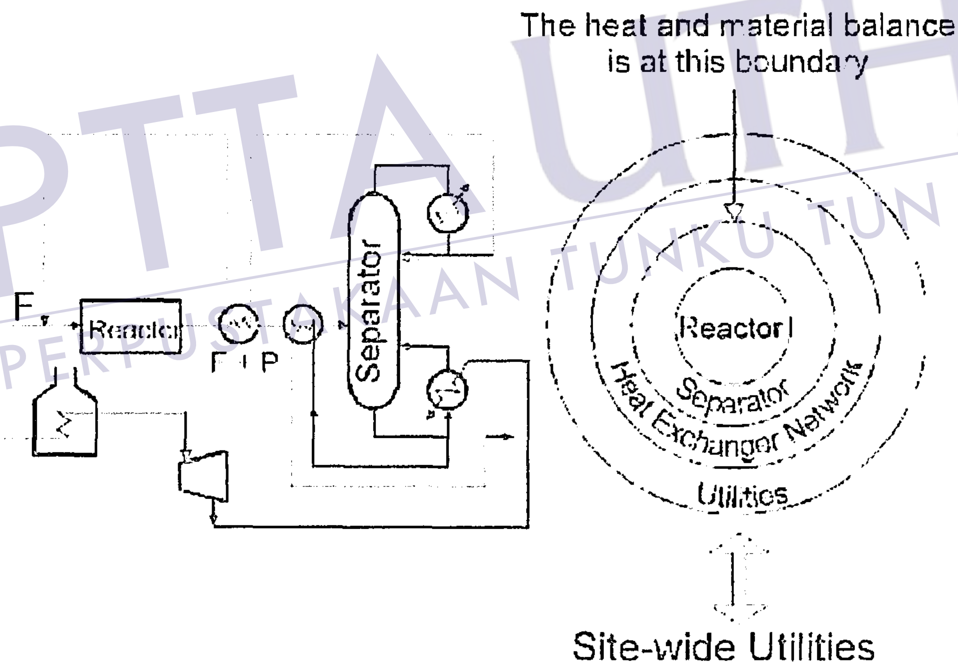

Figure 1.1: Onion Diagram of Hierarchy in Process Design

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 considering the fact that most processes involve a huge number of process and utility streams.

For this reason, one of the major worries of the designer has been the reduction of utilities consumption, as well as the reduction of fixed cost in the equipment. Thus, a lot of research work has been carried out to find the optimum configuration of a HEN both in terms of total cost and operability. The major challenge within HEN synthesis problem is to identify the best pair of process streams to be connected with the heat exchangers, so as to minimize the energy utilization.

The designing of HEN to be addressed in this thesis can be stated as follows: *A set of hot streams* to be cooled and cold streams to be heated are given which include multiperiod stream data with inlet and outlet stream temperatures, heat capacity flow rates and heat transfer coefficients. The objective then is, within the range of the operating conditions, to determine the HEN for energy recovery between the given set of hot and cold streams, so that the heat exchanger areas can be estimated. Hence, the annualized cost of the equipment plus the annual cost of utilities can be minimized. Lastly, a set of heat exchanger designs which may consist of process-to-process heat exchanger and utilities heat exchanger will be proposed.

1.2 Objectives

1) To design the HEN using Pinch Method.
2) To examine the effect of using three different values of minimum temperature approach (DTmin).
3) To demonstrate the practical implications of pinch analysis, DTmin and heat exchanger cost.
4) To propose the heat exchanger type and design.

1.3 Scope of Work

This project will be limited to these areas;

1) The design will be based on previous published data extracted from practical examples.
2) The data taken will be altered to make it more realistic and applicable to Malaysia's environment.
3) The project will synthesize HEN based on the pinch method analysis.
4) The designed HEN is only one of the numerous examples of the design which might be generated using the same method.
5) Many a priori assumptions have been made to accommodate the process of designing.

1.4 The Importance of the Research

This work is about presenting the importance of application pinch analysis in process industry. Pinch analysis has evolved and its technique has been perfected. Significant examples of pinch analysis utilization is in designing HEN in process industry are those which may lead to energy saving, debottlenecking of the critical areas in a given process, minimization of raw material used, waste minimization, minimizing operating cost, minimizing capital investment and minimizing engineering cost and effort.

While pinch technology experience is important to the success of a project. There are several other factors that make the difference between saving money and having just another interesting study such as process understanding or knowledge of process improvement and familiarity to the oil and gas environment. Furthermore, this research has benefited the author in designing heat exchangers in the real process industry.

Table 1.1: PS Gantt Chart

No	ACTIVITIES	WEEK												
		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Brief study on HEN, Pinch Technology, review previous work													
2	Get used with method identified to synthesize HEN													
3	Gather data from industry/institution attached													
4	Data analysis and evaluation													
5	Improvement on result achieved													
6	Thesis final work													

Legend: ☐ Activities carried out

CHAPTER II

LITERATURE REVIEW

The needs for energy and materials savings, as well as economic incentives, have prompted the need to develop more efficient heat exchangers. A preferred approach to the problem of increasing heat exchanger efficiency, while maintaining minimum heat exchanger size and operational cost, is to increase heat exchange rate.

The heat exchanger is a device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid surface or the fluids are directly contacted. Figure 2.1 below shows the shell and tube heat exchanger (STHX), which one of the heat exchanger types that is commonly used in the process industry.

In the heat exchanger, hot and cold fluids separately enter the chambers or tubes of the surface type heat exchanger. The hot fluid transfers its heat to a conductive surface between it and the cold chamber, subsequently the partition transfers the heat to the cold fluid. This follows the second law of thermodynamics which states that the heat always flows from a higher to a lower temperature.

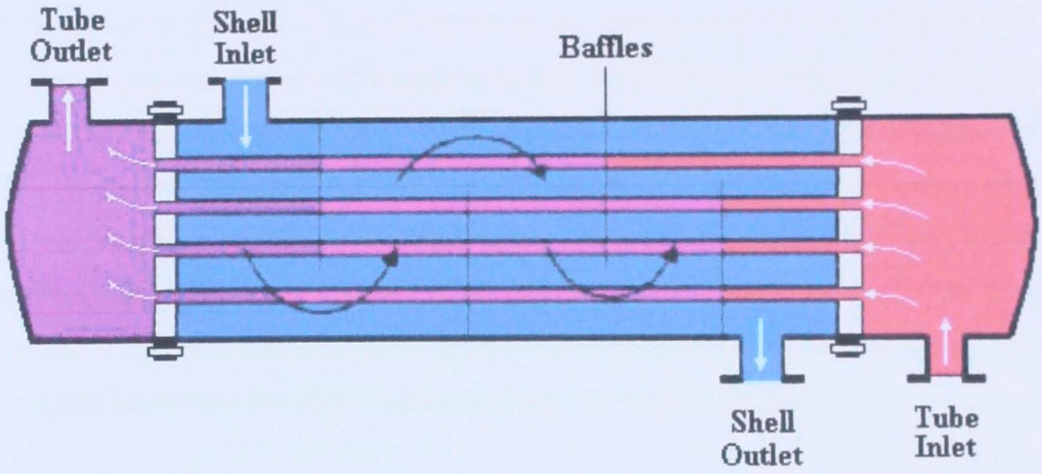

Figure 2.1: Shell-and-Tube Heat Exchanger

The STHX are widely used in process industrial applications. This type of heat exchangers are the most versatile and used in conventional and nuclear power stations as condensers, steam generators in pressurized water reactor power plants, and feed water heaters. They are also used in some air conditioning and refrigeration systems. STHX provides reasonably large ratios of heat transfer area to volume and weight and they can be easily cleaned. They offer great flexibility to meet almost any service requirement. Reliable design methods and fabrication facilities are available for their successful design and construction. The STHX can be designed for high pressures relative to the environment and high pressures differences between the fluid streams.

2.1 Introduction to Heat Exchanger Network Analysis

Heat exchanger network (HEN) synthesis is an important field in petrochemical process because of its role in controlling the costs and environmental impacts of energy. HEN synthesis is one of the most broadly studied problems in petrochemical process synthesis. This is attributed to the importance of determining the energy costs for a process and improving the energy recovery in industrial sites. The first systematic method of energy recovery reported by Aaltola (2003) was the thermodynamic approach of the concept of pinch, introduced during the 1970s. This was followed by mathematical programming methods which have been used since the early 1980s to determine minimal utility costs and minimum number of units (Papoulias and Grossman, 1983). This method involves the formulation of a constrained optimization problem. Furman and Sahinidis (2002) reported that over 400 papers have been published on the subject over the last 40 years.

2.2 Pinch Design Method

The pinch design method (PDM) is the most widely practiced technique for the grassroots design of HEN. The success of the methodology lies in the visualization tools it provides, the understanding of the thermodynamic principles behind the pinch and the targets, and the development of evolutionary and automatic design methods based on the underlying concepts. Pinch technique, which has evolved as an energy-saving technique, presents simple and easy ways of optimization based on complex thermodynamics rules. Pinch technique divides the problem into a sequence of subproblems that can be more easily solved separately. The subproblems are solved successively with different targets in a heuristic order of decreasing significance. The technique gives the process engineer a clear picture of the optimum energy needed for any process: it can save effort and expenditure spent by engineers. Reports of industrial applications claim design improvements in energy saving, as well as reduced capital investment costs, due to optimizing the number of heat exchangers required for the same heat duty, after pinch technology was introduced (Ebrahim and Al-Kawari, 2000). Some of the recent pinch developments are: pressure drop optimization, fouling effects optimization, DTmin optimization and virtual heat exchangers.

Pressure drop is an important issue in the design of a HEN, which has yet to be addressed properly. To overcome pressure losses incurred when streams flow through heat exchangers, pumps/compressors must be installed. The total cost for a system of pumps and compressors consists of the purchase cost of equipment and the electricity cost to run these equipment. This cost could occupy a significant part of the overall cost for a HEN design. Therefore, the pressure drop aspect should be considered together with the costs for heat exchanger area and utility consumption. Zhu and Nie (2002) proposed a new approach to consider the pressure drop aspect in the overall context of a HEN design. . This method consists of three stages, the targeting stage, the initialization stage and the final optimization stage. In the targeting stage, the authors firstly determined the optimal DTmin through three-way trade-offs between heat exchanger area, utility requirement and pressure drop at the targeting stage. As a result of targeting, targets for area, utility and pressure drops can be established ahead of the network design. In this procedure, the pressure drop is considered at both the targeting stage and the design stage in a systematic manner. In order to calculate the pressure drops vis-à-vis heat transfer, four thermophysical properties are needed. These are specific heat capacity (Cp), density (ρ), viscosity (η), and thermal conductivity (k).

After the optimal DTmin is determined by the targeting procedure, the initialization stage determines an initial network structure. The initialization starts with the block decomposition, which is determined using the two criteria based on the thermodynamic feasibility and area performance. With these two criteria, the subjectivity for determining blocks using heuristic rules (Zhu et al., 1995) is avoided. Once the block decomposition is determined, an initial network structure can then be obtained by optimizing the block based superstructure.

At this stage, the block boundary temperatures are fixed, so the logarithmic mean temperature difference (LMTD) for every candidate match becomes constant. This simplification reduces the problem dimension dramatically, which makes it possible to handle the pressure drop aspects and large industrial problems.

Optimization of the block based superstructure removes a large number of significantly uneconomic matches. The result is an initial structure or a reduced superstructure, which still includes many possibilities for matches and hence many degrees of freedom for further optimization. In the final stage of optimization, block boundary temperatures are defined as variables and local superstructures are implemented for split configurations present in the initial network, which provides additional degrees of freedom for further optimization. Optimization of the overall structure then gives the optimal final design.

From the observation made in the case study, when the pressure drop aspect is considered, the value of optimal DTmin will be larger than that determined from two-way trade-off. The shifting of DTmin may lead to significantly different network structures and costs. The case study shows that the delay in considering pressure drop causes a large penalty in total cost.

Brodowicz and Markowski (2003) presented a method for designing of HEN, which reduces the effects of thermal fouling resistance. In the petrochemical industry, the significant heat effects occur, which are caused by fouling from liquid hydrocarbons, flowing through heat exchangers of a heat recovery system. A processing plant needs to work continuously for one, two or more years before further routine repairs, such as the cleaning of heat exchangers, are carried out. A continuous increase of fouling causes an increase of thermal resistance during the exploitation period. On the other hand, the heat recovery system must be subordinated to the processing plant to keep constant temperatures in order to follow an increase in driving exergy resulting in an increase of thermal fouling resistance.

The authors have presented a new design of a heat recovery system, which takes into account the need for compensation of heat fouling effects. Such installations have been designed by the authors and have been working efficiently for some years (Markowski, 1995). The method is based on pinch technology, extended by two transformations. These are based on the criterion of minimum sensitivity to the fouling effects by a single heat exchanger and the HEN. The proposed method has been applied in the petrochemical industry where the two heat recovery systems, designed by this method have been working successfully for some years.

The proposed method aims to get a design network starting from a basic network, which is next transformed to a virtual network. The basic network contains the following information: a description of all connections between heat exchangers, a matrix of the temperatures and characteristics of all heat exchangers. Virtual network is developed from the basic network and contains some extra information concerned with a description of the fouling effects. Design network, which originates from virtual network, takes into account some practical limitations concerned with the lack of available space for new heat exchangers or extra piping etc. The numerical algorithms of successive transformations, particularly for obtaining virtual network, were developed and implemented. A basic network is based on pinch technology method by creating the composite curves and defining the minimum temperature difference at the pinch point.

Ravagnani et al. (2003) proposed a new methodology by including the effect of pressure drops and fouling effects in grassroots as in retrofit designs. Heat exchangers are detailed designed during the heat exchanger network synthesis. Pinch analysis is used to obtain the heat exchangers network with the maximum energy recovery, and a new systematic procedure is proposed to the identification and loop breaking. Bell–Delaware method for the shell side is used to design the heat exchangers. An example of the literature was studied and the results show differences between heat exchangers, with and without the detailed design, relative to heat transfer area, fouling and pressure drop. The great contribution of this work is that individual and global heat transfer coefficients are always calculated, in despite of the current literature, where these values are assumed in the design step. Moreover, the methodology proposed to the heat exchangers design assures the minor heat exchanger according to TEMA standards (1988), contributing to the minimization of the heat exchanger network global annual cost. The new heat exchanger network considering pressure drops and fouling effects presents values more realistic then those one neglecting the equipment detailed design.

Pinch analysis, because of its simplicity of application and great interactivity was used for HEN synthesis, combined with the Bell–Delaware method for the shell side for the heat exchangers design. The heat exchanger network is synthesized using a technique for loop breaking. The algorithm proposed to the identification and loop breaking based on the incidence matrix, as presented in Pethe et al. (1989) and in the concept of loop level, as discussed in Ravagnani (1994). The first step is the construction of the incidence matrix, using the HEN that needs evolution. In this matrix, lines represent streams, including utilities, and columns represent heat exchangers, including heaters and coolers. By using this procedure, one can obtain the minimum number of heat transfer units, without increasing the utilities demand.

In the heat exchangers design in the network, a new systematic procedure was proposed, as presented in Ravagnani (1994), by using the Bell–Delaware method for shell-side. In this procedure, the global and individual heat transfer coefficients are always calculated, contrary as usually presented in the previous literature. Also, pressure drops and fouling are calculated and the heat exchangers are rated, based on values fixed previously. The design follows the TEMA standards. Comparing the actual and the expected area, without the design, one can see that there are great differences. In some cases, the actual area is greater than the expected one, and in other cases it is not, for both methods. This results show the importance of the design in the synthesis of heat exchangers networks. It is because important features like pressure drops and fouling are always neglected in heat exchanger network synthesis. The results showed the differences between the short-cut design and the detailed design. In the point of view of industrial applications, it is very important to have more realistic values, and the details of the heat exchangers.

Finally, the proposed methodology in this work guarantees that the calculated heat exchangers are the smallest, and it shows its advantages to obtain more realistic values in the heat exchangers network including important features like pressure drop and fouling in the design of heat exchangers networks, maintaining the targets fixed in the beginning with respect to the maximum energy recovery. The systematic procedure of identification and loop breaking has a great contribution in the HEN optimization. Being interactive, the designer can chose between break or not the loops, to maintain or increasing the minimum demand of utilities.

In pinch analysis, selecting a minimum temperature approach is important. This represents the smallest temperature difference that two streams leaving or entering a heat exchanger. Typical values are 5°C and 20°C. The range of 5°C to 20°

is typical but not cast in concrete (Turton et al., 2003). Indeed, any value greater than zero will yield a viable heat exchanger network. However, the economic trade-offs are straightforward. As the minimum approach temperature increases, the heat transfer area for the process heat exchanger decreases, but the loads on the hot and cold utilities increase. Therefore, capital investment decreases but the operating costs increase.

Ravagnani et al. (2002) proposed a method in finding an optimum value of DTmin. The proposed methodology uses pinch analysis, together with heuristic method called Genetic Algorithm. To find the optimal DTmin the function global cost is obtained by summing the annual cost of energy and the capital cost. In this stage, the heat exchangers network is not yet synthesized. In this way, the heat transfer area to be used in the cost function is the minimum possible heat transfer area, to the network to be synthesized.

The value of optimum DTmin is obtained by finding the minimum cost of the heat exchangers network. This is, therefore, the objective function to be minimized in the first stage in this work. A genetic algorithm is used to the minimization of this non-linear function. By using the optimum DTmin, found in the previous stage, the problem is divided in two different regions, below and above the pinch. Above the pinch, just hot utilities are allowed and below, only cold utilities.

The authors obtained an optimal heat exchanger network using pinch analysis, by following three steps. The first one consists of finding the minimum energy demand, the minimum number of heat exchangers and the minimum global annual cost. The second step consists of the heat exchangers network synthesis, or the definition of the streams that must exchange heat, as well as the best sequence of the equipments, to achieve the objectives defined in the first stage. In the third step, the network is evolved by identifying and breaking loops.

Ruyck et al. (2002) proposed a technique to enlarge the capabilities of pinch analysis. Conventional pinch analysis is limited to heat exchange between streams of unchanging composition, whereas in reality, much heat exchange occurs in components such as chemical reactors, mixers etc. This can be overcome by introducing virtual heat exchangers that convert the considered components into equivalent heaters and coolers where the stream compositions remain unchanged. In this way, they are automatically taken into consideration in the current pinch analysis packages, which may lead to different and better optimization.

The idea consisted in replacing the reactor by a virtual heat exchanger where the reaction heat enters or leaves the reactor as if it is an internal utility. The present paper illustrates the new concept of virtual heat exchangers in pinch analysis. The application of virtual heat exchangers is applied to chemical reactors in the case of methanol synthesis and showed better optimization.

The concept of virtual heat exchangers has been implemented in a client–server interface program working through Aspen Plus as Process simulator with Aspen Properties and SupercTarget as pinch analyzer. The program converts all reactors into equivalent virtual heat exchangers and computes the required heats of reaction and virtual temperatures.

2.2.1 Pinch Application

There were myriad of works on pinch application reported in the literature. In a wide variety of chemical processes, CANMET Energy Technology Centre-Varennes (2003) stated that pinch techniques have been able to achieve a savings in energy consumption by 10% to 35%, savings in water consumption by 25% to 40% and savings in hydrogen consumption up to 20% by adopting this technique.

Matijaševiæ and Otmaèæ (2001) show the application of pinch technology in nitric acid plant. The author outlined and illustrated the fundamental principles of the pinch for energy integration on the example of nitric acid production in the plant Petrochemical Industry in Croatia and the results shows the possibility to reduce the demand for cooling water and medium pressure steam. With the problem table algorithm, data were quickly extracted from the flowsheet and were analyzed for energy saving.

Houa et al. (2005) presents a method of performance optimization of solar humidification–dehumidification desalination (HDD) process using Pinch technology. Pinch Technology is used in the humidification process to determine the maximum possible saturated air temperature and the temperature of water rejected from the unit, and then in dehumidification process to determine the temperature of water leaving from heat exchanger. From pinch chart, all the thermal energy rejected, supplied and recovered are determined easily. Both the optimum mass flow rate ratio of water to dry air and maximum thermal energy recovery rate is obtained by adjusting mass flow rate ratio of water to dry air. The curve of optimum mass flow rate ratio of water to dry air at a different spraying water temperature is acquired by changing spraying water temperature follow the above steps. The analysis method using Pinch technology in HDD process proves very simple, visual and efficient.

Herrera et al. (2002) discussed the pinch technology application in a hospital. The two most important results of this application are: a thermal power savings potential of 38% and the identification of the optimum heat exchanger network design. To achieve this energy saving potential the pinch point technology the authors suggested to place four heat exchangers in the hospital complex. The analysis of the grand composite curve strongly suggests that the use of more compatible technologies such as solar collectors and heat pumps could be a source of major energy and economics reductions of the present high level diesel consumption in the complex. The energy savings potential is 38% which means a yearly energy savings of 246 thousand diesel liters and a yearly economic savings close to US$100,000 in 1999.

2.3 Mathematical Programming Approach

2.3.1 Sequential Approach

Mathematical optimization methods for HEN synthesis can be classified as sequential and simultaneous approaches (Floudas, 1995). The sequential strategy involves partitioning the problem into temperature intervals and, if possible, into subnetworks according to the pinch. Next, the problem is decomposed into three sub-problems, which are then solved according to the heuristic of finding the minimum cost network subject to the minimum number of units, which is subject to the minimum utilities costs. The heat recovery approach temperature is the only fixed parameter in the three sequential stages and can subsequently be updated by performing some search algorithm. This HEN synthesis strategy is recommended to be applied for all global solutions of a minimum number of units.

Pettersson (2004) outlined a sequential approach which generates networks for industrial sized heat exchanger network synthesis (HEN) problems. The proposed sequential approach solves four different subproblems in order to result in a close to optimal design. The first three subproblems reduce the problem into manageable sized design tasks, without loosing too many promising stream matches. In the first step, a solution to the defined HEN synthesis problem is obtained when only heat exchanger area costs and utility costs are included in the model. Thus, when the fixed unit costs are omitted, the model is a linear programming (LP) problem and the solution obtained presents a lower bound on the total costs. In second step, the number of matches included in the set of interesting matches is reduced by introducing unit costs in the objective function. The LP model from step 1 is modified to roughly consider the unit costs by introducing one binary variable for each match. As a result of the third step a number of groups with streams are given as well as the matches belonging to each group. In the final step, the design tasks are solved separately and can be implemented with any HEN synthesis model. In this paper, the author presented a design method based on a MILP formulation. It is a further development of the LP transportation formulation used in steps one and two.

The advantage of this formulation is that it is simple and reasonably fast and allows splitting and non-isothermal mixing, also can be simplified if only one exchanger unit is allowed for each match to keep the problem size small.

The decomposition-based approaches have proved in many case studies to be powerful HEN synthesis tools (Aaltola, 2003). The main shortcoming of the sequential approaches is the fact that the three-way trade-off between energy, units and area are not considered rigorously. Furthermore, the decision to decompose the original problem into sub-problems relying on pinch analysis may result in sub-optimal networks. Therefore, the HEN synthesis problem should be treated as a single-task problem.

2.3.2 Simultaneous Approach

On the other hand, the simultaneous approach captures this trade-off properly (Shivakumar and Narasimhan, 2002). In the simultaneous approach, the structure of the HEN, the exchanger loads and areas as well as the utility requirements are simultaneously determined. Simultaneous heat exchanger network synthesis methods aim to find the optimal network without or with some decomposition of the problem. This method is primarily mixed integer nonlinear program (MINLP) formulations of the HEN synthesis problem and formulated by making use of a HEN superstructure. The basic idea of a superstructure is to embed all possible network configurations and process stream matches. To facilitate the solution of these complex models, various simplifying assumptions are used.

Shivakumar and Narasimhan (2002) in their paper proposed a new formulation of this approach by representing the HEN superstructure as a process graph. The authors borrowed ideas from Mehta, Devalkar, & Narasimhan (2001) who proposed an optimization-based approach for evolutionary synthesis of HENs using graph theoretic principles, in which a graph representation of a HEN is used.

They have shown that a HEN can be evolved by circulating heat loads around a set of independent cycles of the graph. The authors employed this key idea in developing a NLP formulation for grass-root design of a HEN.

In their formulation, the use of binary variables for existence of heat exchangers is avoided by using the heat loads of exchangers themselves. In order to develop a robust NLP formulation, the smooth approximation of Duran and Grossmann (1986) is used in combination with the concept of maximum possible heat load of exchangers to derive the thermodynamic feasibility constraints. The smooth approximation technique is also used to handle fixed charges of exchangers and negative approach temperatures that can occur during the course of optimization. No additional simplifying assumption is required to either reduce the problem size or to make it robust. This formulation can also take into account design constraints such as forbidden, required and restricted matches, target temperatures being variables etc.

Even for small problems, these formulations are able to achieve considerable reduction in the number of optimization variables and a modest decrease in the number of constraints. Several examples have been demonstrated, the robustness of proposed formulation to converge from arbitrary initial starting solutions, and also give optimal or near-optimal solutions in all cases.

Chen and Hung (2004) extended the work from the previous research of Konukman et al. (2002) by simultaneously considering minimization of the total utility consumption, maximization of operational flexibility to source-stream temperatures, and even minimum number of matches as multiple design objectives. The authors used the fuzzy multi-criteria optimization approach to synthesize the HEN where some conflict design objectives such as the total utility consumption, the flexibilities to source-stream temperature variations, and even the total number of heat exchange units can be considered simultaneously. This approach was adopted from the work of Chen et al. (2003).

Such a flexible HEN synthesis problem can be formulated as a multi-objective mixed-integer linear programming (MO-MILP). The attractive features of the proposed MO-MILP model are that it not only considers the trade-off among the utility consumption, the source-stream temperature flexibility, and even the number of matches, but also avoids the determination of structural boundaries, as discussed in previous work of Konukman et al. (2002). Two numerical examples with various studied cases demonstrating that the proposed strategy can provide a feasible compensatory solution for the multi-criteria HEN synthesis problem.

However, even if much effort has been put on research within this area, many of the mathematical models consider only grassroots design, whereas most practical cases today seem to be retrofit situations. In addition, these models are likely to be either rigorous but not solvable for bigger (large-scale, real life examples) or deficient and solvable for large-scale problems. Bjork and Nordman (2004) took an attempt to address these problems simultaneously and to develop a rigorous optimization framework based on both a genetic algorithm and a deterministic MINLP-approach and to present an extended model for large-scale retrofit heat exchanger network design problems.

The new model is based on the Synheat (model A1) which formulated by Bjork and Westerlund (2002), but is altered to be able to tackle retrofit situations. Since many retrofit heat exchanger network optimization problems are large-scale, a hybrid method was used in the optimization phase.

A Synheat model by Yee and Grossman (1990) did not contained simplifying assumptions (such as linear area-cost functions, no stream splitting or similar assumptions), to the global optimum. The Synheat model solves a heat exchanger network design problem through minimizing both annual investment costs as well as operational costs, assuming a stage-wise superstructure where splitting and isothermal mixing is allowed. Considering that both previous works only regarded grassroots heat exchanger network design, the authors find other models that do so.

An important improvement in the new model was the superstructure used. The superstructure should in general hold the most common and promising structures and, as for the example of a superstructure according to the Synheat model, it could preferably be constructed in a number of stages. The mathematical optimization procedure is able to identify the best structure among the available structures, such that it omits non-profitable heat exchangers and identifies profitable ones. Due to this feature, the optimization problem includes binary variables (to describe whether a certain heat exchanger is used or not). As a result of the non-convex functions describing the areas and the binary variables used to describe the existence of a certain heat exchanger, the network synthesis problems is a non-convex MINLP problem.

The authors aim to present a method for the solution of retrofit heat exchanger design problems, where the superstructure is rigorous and the solution time is not exponentially sensitive to the problem size (having the possibility to solve problems with more than 50 streams). It will be achieved through a hybrid optimization framework, where a genetic algorithm will decompose the original (big) problem into several subproblems, after which a deterministic optimization method optimizes the design and operational conditions within the subproblem.

Since many retrofit heat exchanger network optimization problems are large-scale, a hybrid method was used in the optimization phase. The hybrid method is not very sensitive to the problem dimension, which is the problem with normal MINLP-solver for this problem formulation. It relies on a genetic algorithm that assigns each stream to a set of subsystems, where the subsystems do not interact with each other. Finding the optimal structure for each subsystem is part of evaluating the fitness of the chromosomes. This was accomplished by solving each subsystem with model presented in this article. The optimization framework successfully solved a medium-sized problem, but the methodology can also handle very large-scale problems.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Introduction

In this chapter a framework for designing heat exchanger network (HEN) over a specified range of variations in the flow rates and temperatures of the streams is presented, so that the exchanger areas and selection of matches are minimized. First, a short description of pinch method is given and then a step-by-step description of the HEN synthesis framework is presented to give an overview of the proposed method. After that, a complete explanation of those steps is outlined to provide more information on the method used. Upon the completion of the pinch analysis, the process of heat exchanger selection and design will be presented.

3.1.1 Overview of Pinch Design Method

The Pinch Design Method (PDM), proposed by Linnhoff & Hindmarsh in 1983 (Liporace et. al., 1999) became the most popular method of (HEN) synthesis because it is fast, easy and capable of interactivity. Pinch analysis is a rigorous, structured approach that maybe used to tackle a wide range of improvements related to process and site utility. This includes opportunities such as reducing operating costs, improving efficiency and planning capital investment. Major reasons for the success of pinch analysis are the simplicity of the concepts behind the approach and the impressive results that have been obtained worldwide.

3.1.2 What is Pinch Technology?

Pinch technology presents a simple methodology for systematically analyzing chemical processes and the surrounding utility systems with the help of the first and second law of thermodynamics. The first law provides the energy equation for calculating the enthalpy changes in the streams passing through a heat exchanger. The second law determines the direction of heat flow. That is, heat flow may only flow in the direction of hot to cold. This prohibits temperature crossovers of the hot and cold stream profiles through the exchanger unit. In a heat exchanger unit neither a hot stream can be cooled below cold stream supply temperature nor can a cold stream be heated to a temperature more than the supply temperature of hot stream. The hot stream can only be cooled to a temperature defined by the temperature approach of the heat exchanger. The temperature approach is the minimum allowable temperature difference (DTmin) in the stream temperature profiles, for the heat exchanger unit. The temperature level at which DTmin is observed in the process is referred to as pinch point.

The pinch analysis starts with the heat and material balance 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. After the heat and material balance is established, targets for energy saving can be set prior to the design of the heat exchanger network. This method ensures that these targets are achieved during the network design. Targets can also be set for the utility loads at various levels (e.g. steam and refrigeration levels). The utility levels supplied to the process may be a part of a centralised site-wide utility system (e.g. site steam system). Pinch technology extends to the site level, wherein appropriate loads on the various steam mains can be identified in order to minimise the site wide energy consumption. Pinch technology therefore provides a consistent methodology for energy saving, from the basic heat and material balance to the total site utility system.

3.1.3 Objectives of Pinch Analysis

Pinch analysis is used to identify energy cost and HEN capital cost targets for a process and recognizing the pinch point. The prime objective of pinch analysis is to achieve financial savings by better process heat integration, which are maximizing process-to-process heat recovery and reducing the external utility loads.

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