DEVELOPMENT OF A COMPUTER SOFTWARE FOR OPTIMAL DESIGN AND RETROFIT OF HEAT EXCHANGER NETWORK IN A CHEMICAL PROCESS PLANT

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To my Beloved Dad, Mum and Sister

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ABSTRACT

Heat-MATRIX, a computer software for heat exchanger network design and retrofit based on the techniques of Pinch Technology and MATRIX (MAximising Total area Reuse In an eXisting process) has been proposed. *Heat-MATRIX* is a software to utilise the MATRIX technique which has been carefully tailored for use in an existing process plant. The software is a *Microsoft Windows*-based programme that has been developed to automate, and rapidly as well as efficiently assist the design and retrofit of heat exchanger network. Given a set of candidate process streams with potential for heat exchange, *Heat-MATRIX* would automatically generate the design targets – i.e. the heat recovery Pinch temperatures, the minimum hot and cold utility targets; both graphically and numerically. In addition, it can also automatically generate the optimal utility combination for a given process, and allow the automatic design of heat exchanger network to achieve the energy targets. Besides that, *Heat-MATRIX* provides a new tool named Exergy Block Diagram for analysis a retrofit of an existing plant's heat recovery network. At this stage, the software would automatically generate all probable heat exchange matches and eliminate the infeasible heat transfer matches. In network evolution, *Heat-MATRIX* also provides a more significant method in terms of cost savings through Path Optimisation. The software would plot a curve of total annual cost versus shifted heat load. From the curve, the software would search for the optimal heat load to be shifted along heat exchanger path.

ABSTRAK

Heat-MATRIX ialah satu perisian komputer untuk rekabentuk rangkaian pindahaba yang berdasarkan dua teknik iaitu *Pinch Technology* dan MATRIX (*MAximising Total area Reuse In an eXisting process*). *Heat-MATRIX* merupakan satu perisian yang menggunakan teknik MATRIX. Program yang berasaskan *Microsoft Windows* ini ditulis untuk membantu rekabentuk rangkaian pindahaba dengan pantas dan automatik. Diberi satu set aliran proses dengan pindahaba yang berpotensi, *Heat-MATRIX* akan menghasilkan sasaran rekabentuk secara automatik, termasuk suhu *Pinch*, sasaran minimum bagi utiliti panas dan sejuk melalui kaedah grafik dan berangka. Tambahan lagi, program ini dapat menghasilkan gabungan utiliti optimal bagi proses tertentu secara automatik dan membenarkan rekabentuk rangkaian pindahaba dilakukan secara automatik yang mencapai sasaran tenaga minimum. Di samping itu, *Heat-MATRIX* menyediakan satu alat panduan baru yang bernama *Exergy Block Diagram* untuk pembaikkan rangkaian pindahaba dengan menggunakan teknik MATRIX. Dalam peringkat ini, program ini akan menghasilkan semua kemungkinan pasangan alat pindahaba dan mengabaikan pasangan pindahaba yang tidak sesuai. Dalam rekabentuk rangkaian pindahaba, *Heat-MATRIX* juga menggunakan satu teknik *Path Optimisation* yang lebih berkesan dalam aspek penjimatan kos. Perisian ini akan menghasilkan lengkuk jumlah kos tahunan melawan haba yang dipindah. Daripada lengkuk ini, perisian ini berupaya menentukan haba pemindahan optima dalam rangkaian pindahaba.

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NOMENCLATURE

Symbols

θ	specific exergy, (kW/^{o}C)
ΔEx	exergy changes, (kW)
ΔH	enthalpy changes, (kJ)
$\Delta H_{uti(j)}$	energy load of j^{th} utility
ΔT_{int}	interval temperature difference, (^{o}C)
ΔT_{min}	minimum allowable temperature difference, (^{o}C)
FCp	flow rate (kg/s) × heat capacity (kJ/kg.^{o}C), or heat capacity flow rate, (kW/^{o}C)
Q	energy load of heat exchanger, (kW)
Q_{Cmin}	minimum cold utility requirement, (kJ)
Q_{Hmin}	minimum hot utility requirement, (kJ)
Q_i	heat flow at i^{th} interval
$T_{int(i)}$	temperature at i^{th} interval
T_{lm}	log mean temperature, (dimensionless)
T_o	reference temperature, (298.15 K)
T_S	supply temperature, (^{o}C)
T_T	target temperature, (^{o}C)
$T_{uti(j)}$	shifted inlet temperature of j^{th} utility

Abbreviation

BGCC	balanced grand composite curves
CW	cooling water
EBD	exergy block diagram
GCC	grand composite curves

HEN	heat exchanger network
HP	high pressure
LP	low pressure
MATRIX	MAximising Total area Reuse In an eXisting process
MER	maximum energy recovery
MP	medium pressure
Refri	refrigeration

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In view of the continuous increase in oil price for the past few years, energy conservation has become a prime concern for process industry. Atkinson reported in 1987, more than half of the investment for the chemical process industry in United Kingdom was directed towards retrofit of existing plants. This statistics show that process retrofit is important in chemical process industry. Douglas (1988) defined the process of retrofit or revamping as follows:

- Minor changes in the interconnections between process equipment
- Replacement of one or more pieces of equipment by some other equipment
- Change in the size of one or more pieces of equipment in an existing process.

In a typical refinery plant system, it is estimated that about 60% of the supply of energy leaves in the form of heated water and air. However, these losses can be reduced by several percent (Frantisek, 1992). The cost of the heating and cooling media is one third of the total operating cost of the plant (Samarjit and Pallab, 1999). This underlines the importance of optimal and efficient heat recovery for a plant. Cost savings on the facilities to accomplish the desired heat exchange between the hot and cold media became one of the main issues which was brought up by Samarjit and Pallab in 1999.

From Figure 1.1, we have noticed that the crude oil price increased from USD 15 to USD 40 per barrel from the year 1979 to 1980. Over the past few years (i.e. from 1999 to 2003), the crude oil price increased from USD 10 to a peak of USD 33 and returned to USD 28 per barrel. In Malaysia, the price of crude oil has increased further after the announcement of the increase in electricity tariff in the year 2001. A comparison between the tariffs before and after the increment is shown in Table 1.1.

Figure 1.1: Average monthly crude oil prices from January 1978 through September 2003 (Source: Plains Marketing, L.P.)

In view of the rising fuel price and utility costs for process plants, hence, it became critical to look for solutions to reduce a plant's operating costs and increase the profit margin for a company.

Table 1.1: Comparison between the old and new tariff rates (Source: Tenaga Nasional Berhad, Malaysia, 2003)

TARIFF CATEGORY		Unit	New Rates	Old Rates	% Increment
1	**Tariff B - Low Voltage Commercial Tariff**				
	For all units	sen/kWh	28.8	27	6.7%
2	**Tariff C1 - Medium Voltage General Commercial Tariff**				
	For all unit	sen/kWh	20.8	19	9.5%
3	**Tariff C2 - Medium Voltage Peak/Off-Peak Commercial Tariff**				
	For all unit during Peak Periods	sen/kWh	20.8	19	9.5%
	For all unit during Off-Peak Periods	sen/kWh	12.8	11	16.4%
4	**Tariff D - Low Voltage Industrial Tariff**				
	For all units	sen/kWh	23.8	22	8.2%
5	**Tariff E1 - Medium Voltage General Industrial Tariff**				
	For all units	sen/kWh	18.8	17	10.6%
6	**Tariff E2 - Medium Voltage Peak/Off-Peak Industrial Tariff**				
	For all unit during Peak Periods	sen/kWh	18.8	17	10.6%
	For all unit during Off-Peak Periods	sen/kWh	10.8	9	20.0%
7	**Tariff E3 - High Voltage Peak/Off- Peak Industrial Tariff**				
	For all unit during Peak Periods	sen/kWh	17.8	16	11.3%
	For all unit during Off-Peak Periods	sen/kWh	9.8	8	22.5%

Pinch Technology has been a very well-established tool for the design of heat exchanger network (HEN) in chemical process synthesis and has become much more than just an energy-saving tool (Linnhoff, 1993). The technique can be used to accurately predict the potential energy savings and the capital cost targets before design. Development of rigorous software programmes like PinchExpress, SuperTarget, Aspen Pinch has proved to be very useful in the analysis and improvement of complex industrial processes with speed and efficiency.

1.2 Traditional Design Approach versus Pinch Technology Approach

The traditional design approach is depicted in Figure 1.2 (Ahmad *et al*., 2000). The core of the process is designed with fixed flow rates and temperatures, yielding the heat and mass balances for the process. Then, the design of a heat recovery system is completed. Next, the remaining duties are satisfied by the use of the utility system. In the traditional approach, each of these tasks is performed independently of the others.

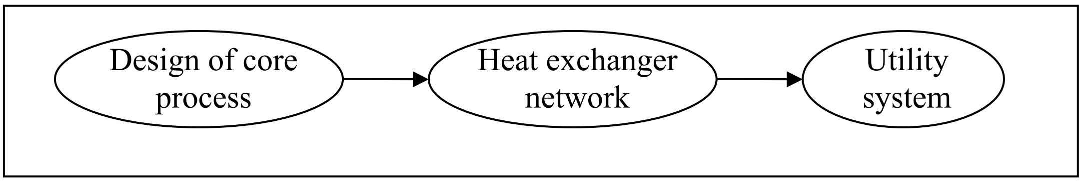

Figure 1.2: Traditional design approach

Process integration using pinch technology offers a novel approach to generate targets for minimum energy consumption before the heat recovery network design. Heat recovery and utility system requirements and constraints are taken into consideration during the design of the core process. Interactions between the heat recovery and utility systems are also considered (see Figure 1.3). The pinch design can reveal opportunities to modify the core process to improve heat recovery. The pinch approach is unique because it treats all processes with multiple streams as a single, integrated system. This method helps to optimise the heat transfer equipment during the design of the equipment.

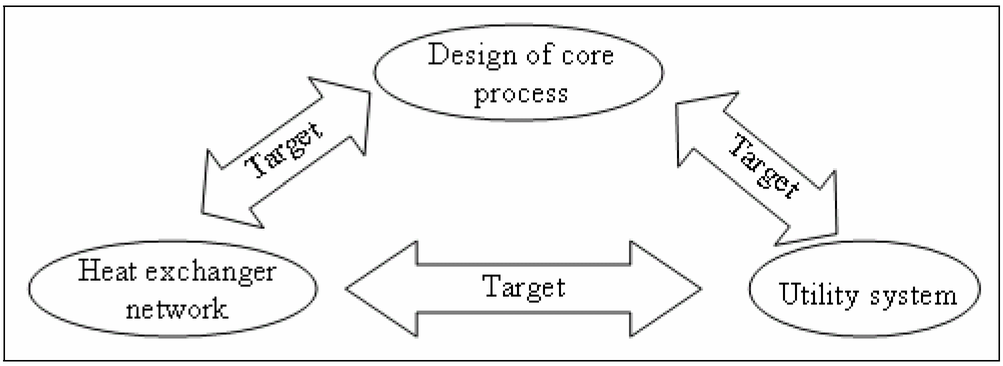

Figure 1.3: Pinch Technology Approach

1.3 The Significance of a Pinch Software

The development of pinch software has begun in the early 90's. A person applying the techniques of pinch technology for process design will need to perform plenty and rigorous calculations and generate many graphical illustrations. All the onerous works will become easy with the advent of a computer software. This is because, a computer is capable of making logical decisions at speeds of millions, and even billions, of times faster than human being. Therefore, an engineer can consider many different heat integration alternatives faster, towards the aim of finding out the best design.

1.4 Problem Statement

Even though the procedure for the optimal design of heat recovery network has been very well-established, the available techniques and the software for improving an existing heat recovery network in process plants have many key limitations.

Many popular approaches including Pinch Analysis technique are too dependent on ΔT_{min} as the decision variable for retrofit, giving rise to rigid retrofit solutions that are either too complex to implement or not flexible enough to address the existing process constraints.

Given a set of process streams that requires cooling (hot streams) and another set of streams that requires heating (cold streams) with their respective supply temperatures (T_S), target temperatures (T_T) and heat capacity flowrates (F x C_p), it is desired to rapidly and efficiently design a new heat recovery network, as well as analyse and retrofit an existing network to maximise energy efficiency at the minimum total cost.

As the tasks of the design, analysis and retrofit of heat recovery network involve graphical techniques as well as rigorous and repetitive computations; a rapid, efficient, and in some cases automated approach is truly vital. A computer software is proposed to achieve the outlined goals.

1.5 Objectives of This Research

This research aims to develop a user-friendly computer software for the rapid and efficient

1. generation of an optimal heat exchanger network to achieve maximum energy recovery.
2. analysis and retrofit of an existing heat recovery network using the new MATRIX (MAximising Total area Reuse In an eXisting process) technique.

1.6 Research Scopes

The scopes of the research include

1. The development of algorithms to automatically generate and calculate the

   - pinch temperatures,
   - minimum hot and cold utility consumption,
   - minimum number of heat exchanger units,

2. Design of heat recovery network

This involves automatic and semi automatic synthesis of the heat recovery network to achieve the minimum utility targets predicted.

3. Optimal utility placement

Once the heat exchanger network is designed, it is necessary to search for the most economical combination of hot and cold utilities. The software is designed to generate the optimal utility combination for a given process; i.e. the one that yields the cheapest utility mix in terms of the amount (load) and quality (level).

4. Retrofit of heat recovery network

Given an existing process heat exchanger network, the software would systematically analyse it for inefficiencies and propose ways to improve the existing structure. A visualisation tool based on the new technique named MATRIX assist designers to improve the current network.

5. Path Optimisation

Path optimisation involves final evolution of the retrofitted heat recovery network. The software would plot a curve of the total annual cost versus heat load shifted along heat exchanger path. Then, it automatically finds the optimal shifted heat load and hence, the final retrofitted network based on minimum total annual cost for a retrofit design.

1.7 Research Contributions

The contributions of this research can be summarised as follows:

1. This is the first software that uses two techniques; pinch technology and MATRIX as the basic concept to solve the problem of heat exchanger network. Pinch technology can be used to accurately calculate the potential energy saving in grassroots design. The MATRIX technique which has been developed in UTM would provide another option of HEN retrofit as a simple and practical alternative to the well-established pinch approach.

2. The development of a new algorithm to find the optimum shifted heat load for the generation of final heat recovery network with the minimum total annual cost.

3. As far as our search in the open literature has revealed, this is the first locally developed user-friendly computer software for heat exchanger network (HEN) design. The basic concept of HEN design is based on pinch technology and the new MATRIX technique.

1.8 Summary of Thesis

This thesis contains five chapters.

Chapter 1 provides the introduction and background of the research, problem statement, overall objective of the research, and the scopes of research.

Chapter 2 reviews the relevant theory and critically analyses the previous work related to the research. The concepts of pinch technology and the new MATRIX approach are explained here. The subsequent section covers the development of software for heat integration.

Chapter 3 describes the algorithm involved in the development of the pinch software. This begins with the construction of the composite curves and the algorithm for problem table to get the minimum energy requirements and the pinch temperatures. Then, the multiple utilities design is performed. This is followed by an explanation of the algorithm for heat exchanger network design. The next section describes the algorithm for Exergy Block Diagram for exergy analysis. The last section presents the methodology for path optimisation in retrofit design.

Chapter 4 discusses the results of the research through a demonstration of the capability of the software on five selected cases study. The first case study compares the single utility with the multiple utilities design. The second case study discusses the "threshold problem" design. The third case study demonstrates the automatic heat exchanger network design. The fourth case study uses the new MATRIX technique for the retrofit of a palm oil refinery. Finally, the fifth case study uses MATRIX to solve the Tjoe's retrofit project.

Chapter 5 concludes the research with some highlights of the unique features of the software developed for HEN design. Finally, the future works to be completed is discussed.

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