Chapter I

Introduction

1.1 Background

The rapid escalation of oil costs in mid-1970's has served as a driving force to develop new strategies for retrofitting chemical plants and designing new processes. Heat exchanger networks (HENs) have been one of the central subjects in the field as they offer a large potential for energy savings. Many HENs synthesis techniques have been proposed (see section 1.4) since the problem was first formally defined back in 1969. In particular, pinch technology has proved to be effective in developing the best integrated process designs for both new plants and retrofits [1: 56, 2: 33, 3: 1, 4: 54]. This has been demonstrated in hundreds of successful projects, carried out mainly in the USA, the UK and several other European countries. These projects have covered a wide range of industries using both continuous and batch operations.

Table 1.1 summarizes the results of applying the pinch technology in Union Carbide in 1982. The studies covered a wide variety of processes and facilities, ranging from large petrochemical or organic bulk chemical units to small specialty chemical units. The available energy savings were identified. The investment required in plant modification projects typically range from 1 to 18 months in payback time.

The application of pinch technology is mainly on HENs design. However, it has been extended to combined heat and power systems [5: 72, 6: 742, 7: 748, 8: 898], integrated distillation columns [9: 423, 10: 1175] and general process design [2: 33].

Table 1.1 First results of appplying the pinch technology in Union Carbide. [2: 33]

Process	Project type	Energy cost reduction ($/yr)	Installed capital cost ($)	Payback (Months)
Petrochemical	Mod.*	1,050,000	500,000	6
Specialty Chemical	Mod.	139,000	57,000	5
Specialty Chemical	Mod.	82,000	6,000	1
Licensing Package	New**	1,300,000	Saving	-
Petrochemical	Mod.	630,000	Unclear	?
Organic Bulk Chemical	Mod.	1,000,000	600,000	7
Organic Bulk Chemical	Mod.	1,243,000	1,835,000	18
Specialty Chemical	Mod.	570,000	200,000	4
Organic Bulk Chemical	Mod.	2,000,000	800,000	5

* Plant modification.

** New plant design.

1.2 Objectives

The objectives of the present research are as follows:

a. Develop computer software to aid in the synthesis of heat exchanger networks.

b. Design heat exchanger networks by using the developed software.

c. Analyse the designed networks economically, i.e., evaluate utility costs, investment costs, annual costs and payback periods.

1.3 Scope of Work

In this research the computer program is first developed mainly for unrestricted matching of heat transfer streams. Thereafter it is modified to cover simple restricted stream/stream matches.

1.3.1 Capability of the developed computer software

The developed software has the following capability:

a. Evaluate energy targets, minimum requirements of hot and cold utilities.

b. Evaluate pinch temperature (pinch point).

c. Synthesize heat exchanger networks for both restricted and unrestricted conditions by using pinch technology coupled with heuristic rules.

d. Automatically search and break primary loops up to the second-level. Higher-level loops must be searched and handled by the user.

e. Carry out economic analyses for the designed networks.

1.3.2 Assumptions

The software program is applicable under the following assumptions:

a. The operating conditions, such as inlet and outlet temperatures, flowrates and heat capacities, are given and remain fixed.

b. No phase change occurs in any working fluid stream.

c. Heat loss to the environment is negligible.

1.4 Literature Survey

A large number of synthesis methods for heat exchanger networks have been proposed in the last two decades. However, only a relatively modest number can be implemented as computer tools for the full automatic generation of network configurations. The suggested procedures for automatic synthesis can be classified into the following three categories [11: 276]:

(1) Acyclic networks without stream splitting.
(2) Cyclic networks without stream splitting.
(3) Networks with stream splitting.

A selected review of previous methods for automatic generation of the above types of networks is given below.

In the first category, Lee et al. [12: 48] proposed a branch and bound procedure for the generation of acyclic heat exchanger networks, which successively match the hot and the cold streams, starting with their inlet temperatures. Since the streams exchange as much heat as possible, each pair of streams can only be matched once. Pho and Lapodus [13: 1182] presented an alternative method based on a decision tree, in which the nodes contain a compact matrix representation for acyclic networks. Enumeration of the entire tree is performed using a depth-first search procedure. When a complete enumeration is not possible, a heuristic partial enumeration method may be used.

In the second category, Ponton and Donaldson [14: 2375] proposed a fast heuristic method for synthesis of cyclic heat exchanger networks, obtained by counter-current matches of hot and cold process streams. This method is based on the heuristic of matching sucessively the hottest inlet of all remaining hot streams with the hottest outlet of all remaining cold streams. In this method the network configurations may involve several matches for the same pair of streams. Grossmann and Sargent [15: 1] devided the optimum design of cyclic heat exchanger networks in two stages. In the first stage they used the implicit enumeration algorithm coupled with heuristic estimates to determine the optimum sequence of counter-current matches for process streams. In the second stage, the structure found in the first stage is optimized using nonlinear programming.

The procedures mentioned above cannot guarantee minimum utility consumptions for the generated networks since that may require splitting of streams [16: 633]. A method for unsplit networks that does satisfy the minimum utility targets is the "Thermodynamic Combinatorial" method [17: 1]. The method uses thermodynamic and topological arguments to enumerate minimum utility consumption networks. However, only unsplit networks can be handled with this enumeration method.

In the third category, Kobayashi S. and coworkers [18: 1367] proposed a systematic way of synthesizing an optimal heat exchanger network. The method consists of formulating the problem as an optimal assignment problem in linear programming and carrying out the solution by the Complex method. However, this method is valid only under the prestated assumptions. Umeda T. and coworkers [19: 795] proposed an integrated approach to the synthesis of optimal processing system. In this method all the alternative systems are combined into an integrated system and split ratios are introduced at the source point, where each stream is split into more than two streams. The resulting system is solved by the Box Complex method. This method will not be effective when a synthesis problem with no larger number of alternative systems is to be solved. Nishida et al. [20: 77] proposed evolutionary rules for the derivation of network configurations that involve stream splitting. This method, however, does not guarantee minimim utility comsumption nor the fewest number of exchanger units. Su and Motard [21: 67] proposed an algorithmic evolutionary approach based on searching and breaking loops in an initial network structure derived from Temperature-Interval method [16: 633]. This procedure, in most cases, yields networks that feature a minimum number of units.

Papaolias and Grossmann [22: 695, 23: 707, 24: 723] proposed a mixed-integer programming method for systhesis of utility systems, heat recovery networks and total processing systems. The procedure involves the derivation of a general configuration or superstructure that embeds all the alternative flowsheets that are to be considered, and from which the optimal solution will be selected. The superstucture is commonly derived by making use of engineering judgement, heuristics and/or thermodynamic considerations. Linnhoff et al. [25: 7, 26: 745] proposed the pinch design method. This method utilizes the fact that the pinch is the most temperature-constrained region. It divides the process streams into two parts, those above and those below the pinch, which are to be synthesized independently. The design always starts at the pinch and moves away. Rew E. and Fonyo Z. [27: 601] combined the pinch design method with a modification of the Fast Algorithm [14: 2375] for synthesis of heat exchanger networks. Floudas et al. [11:

276] proposed linear and mixed-integer linear programming transhipment model for generating heat exchanger network structures which achieve the minimum utility targets and minimum number of units. This procedure is based on a superstructure which includes alternatives for splitting, mixing and bypassing of process streams. A final structure is derived by optimizing the superstructure through nonlinear programming.

On the other hand, from an industrial environment point of view all the above mentioned procedures handle only fixed operating conditions, such as constant inlet and outlet temperatures, flowrates and heat capacities. The procedures are no longer valid if the industrial environment is subject to uncertainties. To overcome this shortcoming a number of procedures have been proposed. Saboo and Morari [23: 579, 29: 1553, 30: 577, 31: 591] introduced the Resilience Index to quantify the ability of a heat exchanger network to cope with inlet and outlet temperature changes. The index characterizes in some sense the largest disturbance that the network can tolerate without becoming infeasible. Cerda and Westerburg [32: 1723] modified their linear transportation model to synthesize restricted stream/stream matches. Floudas and Grossmann [33: 153] proposed a multiperiod version of mixed-integer-linear programming (MILP) transshipment model for the synthesis of flexible heat exchanger networks, in which flowrates, inlet and outlet temperatues can be changed in a finite set of periods of operation. This approach consists of designing a network for each condition separately and then combining the network configurations manually. To overcome the manual synthesis task, they proposed a procedure for synthesizing the final network configuration [34: 123] by extending the nonlinear programming approach proposed by Floudas et al. [11: 276]. In this procedure additional by-pass streams around each heat exchanger and overall by-pass streams from the inlet to the outlet of each stream are added and the independent stream superstructures developed in each period of operation is combined into one overall superstructure.

In this research work, the network design procedure is based mainly on the pinch design method [25: 7] and heuristic rules. The developed software is capable of designing network structures for all the above catagories at constant industrial environment condition. The generated initial network structure is further evolved based on the algorithmic evolutionary approach [21: 67] in order to minimize the number of exchanger units. The developed software also includes a program for carrying out quick economic analysis of the generated network structure.