CHAPTER 3

A REVIEW OF HEAT EXCHANGER NETWORK DESIGN

3.1 Problem Definition

The problem of heat exchanger network design can be described as follows:

A set of cold streams ($i = 1,n_c$) initially at supply temperature T_i^s and at heat capacity flowrate W_i is to be heated to target temperature T_i^t. Concurrently, a set of hot streams ($j = 1,n_h$) initially at supply temperature T_j^s and at heat capacity flowrate W_j is to cooled to target temperature T_j^t. Hot and cold utilities are available for use. The enthalpy vs temperature relationship is known for all streams. The appropriate physical properties for determining heat transfer characteristic are also given. The objective is to design the optimal network of heat exchangers, coolers and heaters to accomplish the desired temperature changes. Optimal usually means most economic for the capital and utility costs available.

3.2 Network Properties

Three major properties of a HEN may be:

1. The maximum energy recovery (MER) or minimum utility usage.
2. The minimum number of heat exchanger units (N_{min}).

3. The minimum approach temperature difference between hot process and cold process streams which is a bottleneck in a design.

3.3 Conventional Design Methods

The design procedure is normally partitioned into two steps:

1. Preanalysis or Targeting.
2. Network generation.

3.3.1 Preanalysis

This step determines targets for a network to be designed. The design target of a network are the maximum energy recovery (MER) and the minimum number of matches.

The Maximum Energy Recovery (MER). MER can be determined by using the temperature-enthalpy diagram (Hohmann, 1971) or by the problem table (Hohmann, 1971; Linnhoff et.al., 1982) or by mathematical programming techniques, i.e. the northwest corner algorithm, (Cerda and Westerberg, 1983a). The idea of the first two methods is to merge all hot streams into a single composite hot stream and all cold into a single composite cold stream. By shifting the position of the composite cold stream curve along the enthalpy axis to produce a separation between these two curves equal to the specified minimum approach temperature in the temperature-enthalpy diagram, the pinch temperature and the MER can be obtained.

The Pinch Temperature. The pinch temperature arises in networks which require both heating and cooling utilities. It is the point of closest approach, on the temperature scale, of the composite heating and cooling curves as dictated by the network ΔT_{min} or the minimum approach temperature between hot process streams and cold process streams.

The pinch temperature divides the network into two subnetworks with the requirement that no heat is allowed to transmit through that point in order to achieve MER. In each subnetwork, only one type of utility (heating or cooling) is required.

The Minimum Number of Matches. The probable minimum number of matches (heat exchanger, heaters and coolers) can be predicted by the following equation (Hohmann, 1971),

$$N_{min} = N_h + N_c + N_{hu} + N_{cu} - 1$$

Where N_h and N_{hu} are the numbers of hot process and utility streams; N_c and N_{cu} are the numbers of cold process and utility streams. For problems with a pinch this equation should be applied separately to the subnetworks above and below the pinch (Linnhoff et al., 1982).

3.3.2 Network Generation

Two fundamentally different approaches for HEN design are (i) optimization technique and (ii) heuristic method.

3.3.2.1 Optimization Techniques

The mathematical programming or algorithmic approach involves establishing optimization criteria for the network and subsequently solving its performance equations.

Transportation Problem. The finite linear programming methods in the field of operation research which are the techniques for maximizing the flows of some commodity between two specified node have been employed. The transportation problem formulation has been used by Cerda and Westerberg (1983b) to determine the optimum network for transporting a commodity (heat) from source (hot streams) directly to destinations (cold streams) through temperature intervals accounting for thermodynamics constraints in the transfer of heat. Papoulias and Grossmann (1983) use the transshipment model formulation which is a variation of the transportation problem to investigate the optimum network. The problem is formulated as a transportation problem, but instead of being sent directly to cold stream, the heat packets are sent from hot streams to intermediate nodes (i.e. temperature intervals) first and then to the cold streams. The models for the minimum utility cost target (linear programming or LP) and the minimum number of units target (mixed-integer linear programming or MILP) are developed. The solution of LP and MILP transshipment models, however do not automatically provide the final matches.

MILP model Floudas et al. (1986) proposed a procedure for automatic generation of a network featuring minimum utility and minimum number of units. The LP and MILP transshipment models are used to provide information for deriving the stream superstructure, i.e. the structure including alternatives on stream matches, splits, by-passes, etc. The superstructure is then optimized by using nonlinear programming (NLP) formulation for final network configuration with minimum investment cost.

NLP model Colberg and Morari (1990) use the transshipment model formulation to calculate the area and capital cost targets for heat exchanger network synthesis with unequal heat transfer coefficients and different capital cost law (for different materials of construction, pressure rating, etc.) when there are constraints on the number of matches (exchanger) forbidden matches and required matches with specified areas. With these NLPs, the trade-off between area and number of units can be evaluated before synthesis.

3.3.2.2 Heuristic Methods

The design methods that fall into this classification use heuristics. Since there is no complete theory of how a network is derived, and methods that make use of process knowledge, thermodynamic laws, matching heuristic, graphics, except optimization, in reducing the number of possible combinatorial matches to be considered, or making matching suggestions are under this category.

Graphs or diagrams Graphs or diagrams have been used as tools to understand the problem and to devise the solution networks. The graphs or diagrams which have been used are the heat-content diagram, a plot of temperature versus heat capacity flow rate (Nishida el. al. 1971, Pehler and Liu, 1983), the heat-enthalpy diagram, temperature versus enthalpy (Whistler, 1984). The design strategy is to try to match the heat load (e.g. area of the plot) of hot streams against those of cold streams by intuitive judgment of designers and heuristic rules (e.g. match the hottest hot stream against the hottest cold stream first) in order to achieve minimum number of units while maintaining MER or vice versa.

Temperature interval (TI) method Linnhoff and Flower (1978a) divides the network into several subnetworks (temperature intervals) according to supply and target temperatures. The matches in each subintervals are easy to find. The final combined network however, is not simple especially for large problems. The temperature interval method must be combined with some evolutionary design methods.

Evolutionary design methods Designs obtained by using the TI method or other methods resulting in having more units than minimum or not achieving MER. The designs can be proved by minimizing the number of units and utility consumption. Several evolutionary design rules are reported (e.g. Linnhoff and Flower 1978b, Pehler and Liu 1983, and Su and Motard 1984).

Pinch method The pinch method (Linnhoff and Hindmarsh 1983) utilizes design heuristics and insights derived from the previous work (Linnhoff and Flower 1987a). The problem first must be identified as to whether it is (1) a heating problem or, (2) a cooling problem or, (3) both, which divides the network at the pinch. If it is pinched, the heat must not be allowed to transfer across the pinch. The suggested matching heuristics are: start matching from the pinch, do not transfer heat across the pinch, observe the heat capacity flowrate constraints, etc.

Enumeration methods This approach employs a variety of search techniques and heuristics for selecting the optimal matches through the search space. It needs a reduction of the search space in order to be competent. The search methods that have been reported are depth-first and heuristic search (e.g. evaluating a cost function of the next 2 steps) by a computer program written in FORTRAN IV (Pho and Lapidus 1973), branch and bound method (Lee et al. 1970, Rothore and Powers 1975), thermodynamic-combinatorial method (Flower and Linnhoff 1980), depth-first search with branch and bounds (Jezowski and Hahne 1986).

Ruled-Based methods Mehta and Fan (1987) used knowledge-based programming to solve the synthesis problem. In their work, two rules for a hot end and cold end matches are used to find matches. Grimes et. al. (1982) use two match types, Type E and Type M, along with other heuristics to synthesize a HEN. A type E match is a match with the largest average ΔT_{min} and a type M match is a match with the smallest average ΔT_{min}, among the current choices. Their method and heuristics are implemented on OPS3RX, and early version of the OPS5 rule-based language. Chen et.al. (1989) present a knowledge-based system for aiding in the construction of practical heat exchanger network called SPHEN. The created network configurations feature low utility cost, low capital investment, rather stable heat recovery during operation.