CHAPTER II

LITERATURE REVIEWS

Research in process systems synthesis has progressed toward talking structural properties of process systems such as operability and controllability into account. This make sense because *the structural properties* should be designed in *the structure generating phase* rather than be augmented or modified in the final design phase. Recently synthesis design, resiliency of a network has been discussed and several resilient HEN design methods have been reported (Floudas and Grossmann, 1986, Saboo et al. 1984, Colberg 1989, and Cerda et al. 1990). These methods need repetitive effort to find the solutions except the method by Cerda et al. (1990) where the resiliency requirement is included in the optimization model.

2.1. Problem Definition

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

A set of a 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 T_i^t. Concurrently, a set of cold streams ($j = 1, n_h$) initially at supply temperature T_i^s and at heat capacity flow rate W_j is to be heated to target temperature T_j^t. Variations in these temperatures and heat capacity flow rates may arise due to real world situations. Hot and cold utilities are available for use. The enthalpy versus temperature relationship is known for all streams. The appropriate physical properties for determining heat transfer characteristics 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.

For resilient HEN synthesis, the design objective is to design a cost optimal HEN that is feasible under a variation of operating conditions. By feasible we mean that a network must perform satisfactorily by meeting design target temperatures and maximum energy recovery.

Three major properties of a HEN may be:

1. The maximum energy recovery (MER) or minimum utility usage.
2. The 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.

In consideration of the ability of a HEN to tolerate a fluctuation of operating condition, we might add:

4. The resiliency of a network.

2.2. Conventional Design Methods

Here the word conventional means a case where a network is designed at nominal (fixed) operating conditions to achieve N_{min} and MER. The extensive rewiews on the conventional design can be found elsewhere (Nishida et al. 1981, Hohmann 1984, Gundersen and Naess 1988, and Liu 1987).

The design procedure is normally partitioned into two steps:

1. Preanalysis or Targeting.
2. Network generation.

2.2.1. Preanalysis

This step determines targets for a network to be designed. The design targets of a network are the maximum energy (MER) and the minimum number of matches. Other targets proposed in replacing the minimum number of units are (1) heat transfer area, (2) capital cost, and (3) number of shells, see Gundersen and Naess (1988) for the literature review.

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 merges 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 the obtained.

The Pinch Temperature. The pinch temperature arises in heat exchanger network 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 subnetworks with the requirement that no heat is allowed to transmit through that point in order to achieve MER. In each subnetwork, only one utility (heating or cooling) is required.

The Minimum Number of Matches. The probable minimum number of matches (heat exchangers, 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_{hu} are the numbers of 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).

2.2.2. Network Generation

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

2.2.2.1. 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 are the techniques for maximizing the flows of some commodity between two specified nodes 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 sources (hot streams) directly to destinations (cold stream) through temperature intervals accouting 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 streams, the heat packets are sent from hot streams to intermediates 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.

2.2.2.2. Heuristic Methods

The design methods that fall into this classification use heuristics. Since there is no complete theory of how a network is derived, any methods that make use of process knowledge, thermodynamic laws, matching heuristics, 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 flowrate (Nishida et al. 1971, Pehler and Liu, 1983), the heat enthalpy diagram, temperature versus enthalpy (Whistler, 1948). The design strategy is trying to match the heat load (e.g. area of the plot) of hot streams against those of cold streams by intuitive judgement 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. Design obtained by using the TI method or other methods resulting in having more units than minimum or not achieving MER. The designs can be improved 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 1978a). 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 flow rate 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 dept first and heuristics 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 etal. 1970, Rathore and Power 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 uses 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, an early version of the OPS5 rule-based language.

2.3. Resilient Heat Exchanger Network

Design research aimed at the analysis and synthesis of resilient or flexible process systems in order to achieve a better systematic design have been reported. (Resiliency and flexibility are used interchangeably in the literature, even their meaning are somehow different). Much of the attention has been placed on the energy recovery systems since it determines, to a large extent, the energy efficiency of the process. The following review will focus on research in this particular area.

2.3.1. Problem Classes

Saboo and Morari (1983) classified flexible HENs into two classes according to the kind and magnitude of disturbances that effect the pinch location. For the temperature variation, they show that if the MER can be expressed explicitly as a function of the stream supply and target conditions the problem belongs to Class I, i.e. the case where small variations in inlet temperatures do not affect the pinch temperature location. If an explicit function for the minimum utility requirement valid over the whole disturbance range dose not exist, the problem is of Class II, i.e. the case where large changes in inlet temperatures or flow rate variations cause the discrete changes in pinch temperature locations.

2.3.2. Meaning of Resiliency

Several terms have been used in the literature to describe the additional attributes of HENs which have a capability to tolerate change in input or operational parameters while achieving the targets. Operability has been used to describe the ability of the system to perform satisfactorily under normal and abnormal conditions different design condition. Normal refers to the steady state operation while abnormal refers to the transient operation during failure, start up or shut down periods. Flexibility has been used to describe the ability of process systems to readily adjust to meet the requirement of changes, i.e. different feed stocks, product specifications or process conditions. *Resiliency* refers to the ability of HEN to tolerate and recover from undesirable parameter variations, and the term *static resiliency* or simply resiliency has been used in the same sense as flexibility. *Dynamic resiliency* refers to the ability to handle the unsteady-state operation.

Colberg (1989) suggest that flexibility should deal with planed, desirable changed which often have a *discrete* set of values. Whereas resilience deals with unplanned, undesirable changes which are naturally continuous values. Thus a flexibility problem is a 'multiple period' type of problem. A resilience problem should be a problem with a *continuous* rage of operating conditions in the neighborhood of nominal operating points.

2.3.3. Resiliency Analysis

In the absence of a method to derive a resilient HEN right from a structure generation stage, a network must be tasted for its resiliency. Two procedures to measure resiliency of a design are proposed (Saboo and Morari 1985, Swaney and Grossmann 1985).

Saboo and Morari (1985) proposed the resiliency index (RI) which measures the resilience of the largest arbitrary disturbance load that can be shifted through every exchanger in the network without making any exchanger load or resilience parameter negative. The disturbance load is defined as:

$$L_i = W_i \, \Delta T_i^s$$

where W_i = heat capacity flow rate, ΔT_i^s = variation on inlet temperature from nominal value.

RI for the network structure is estimated as:

$$RI = min\ \{L_{i,max}\}$$

And

$$L_{i,max} = min\ \{L_0, R_0\}$$

where L_0 and R_0 are the load and resilience parameter at the nominal operating point. RI is, geometrically, the distance from the nominal operating conditions to a vertex of the *polytope* inscribed in the region specified by the range of operating conditions. It directory represents the distance from the nominal operating condition to the extreme condition.

Swaney and Grossmann (1985) proposed a quantitative index called the flexibility index (FI) which measures the size of the region of feasible steady state operation. Qualitatively, the largest size of a parameter that can be inscribed in the feasibility region.

Calandranis and Stephanopoulos (1986) present an operability analysis for a HEN by exploring nonconvexity of a network. Several cases of HENs are investigated, e.g. pinch jump, temperature variation, etc. Their method is written in ZETALISP and the program is operated in interactively.

Saboo and Morari (1987) use a mathematical programming approach to analyze resiliency of a HEN. A general semi-infinite nonlinear program is simplified to a linear program for a sample case, or mixed-integer programming for a case with piece wise constant heat capacity flowrates, for example. Both temperature and flowrate variations, i.e. Class I and Class II problems are investigate.

2.4. Resilient Network Design

There has been no direct method resilient network synthesis until recently. The strategy has been one of generating designs at a base case and some extreme conditions and to combine those designs and reduce the number of units. Recently, Cerda et al. (1990) present a direct design procedure by using a multioptimization technique to generate a resilient network structure. Otherwise, there is no heuristic design method reported.

2.4.1. Combination of Designs

Generating designs at a base case and some extreme conditions and combining those designs to a base design requires that the designs should be similar. However, the networks designed at extreme conditions can be very different from each other. This poses difficulties in the combination. These methods involve repetitive effort in funding a resilient structure because the resiliency objective has not been included in their models. Also, the problem of selecting extreme conditions is far from trivial. Grossmann and Morari (1984) show that the extreme conditions that seem logical can load to a poor design. Most of us would select the maximum and minimum operating conditions as design conditions. However, in their example the extreme condition is located at the intermediate value. Extra units in a combined design are then eliminated by either inspection or using optimization methods to obtain a minimum unit solution. A minimum unit solution is tested for resiliency using mathematical programming or inspection techniques. If a network is not feasible, the network is modified in an hoc fashion.

Worse cases design. Marselle et al. (1982) addressed the problem of synthesizing heat recovery networks, where the inlet temperatures vary within given ranges and presented the design procedure for a flexible HEN by finding the optimal network structures for four selected extreme operating conditions separately. The specified worst case of operating conditions are the maximum heating, the maximum cooling, the maximum total exchange and the minimum total exchange. The network configurations of each worst condition are generated and combined by a designer to obtain the final design. The strategy is to derive similar designs (matches) in order to have as many common units as possible in order to minimize number of units.

Corner point theorem. Saboo and Morari (1984) proposed the corner point theorem which state that for temperature variation only, if a network allows MER without violating ΔT_{min} at M corner points ($M = 2N_h + 2N_c$), then the network is structurally resilient or flexible. This is the case where the constraint is convex (temperature variation is convex), so examining the vertices of the polyhedron is sufficient. This procedure again can only apply to restricted classes of HEN problem. Their design procedure is similar to Marselle et al. (1982), but using two extreme cases to develop the network structure. The strategy for both procedures is finding similar optional network structures for the extreme cases and the base case design in order that they may be easily merged and not have too many units. Two extreme cases are:

o When all streams enter at their maximum inlet temperatures and the heat capacity flow rates of hot streams are maximal and those of cold streams minimal. This is the case of maximum cooling

o When all streams enter at their minimal temperatures and the heat capacity flow rates of hot streams are minimal and those of cold streams maximal. This is an opposite case the above one and in this case maximum heating is required.

The 'base' design is then generated by using an optimization technique (or any technique) and the final design is obtained by combining these designs. A test for resiliency (calculating RI) is required. If the design is not feasible a modification is done by attempting to reduce ΔT_{min} and if not successful, a new heat exchanger will added or some heat exchangers are relocated. If the modified network is still not resilient, synthesize network structures at all corner points where the current design is not feasible. The new structures should be as similar to the current design as possible. The new design is obtained by superimposing the current structure and the new structures. The unneeded heat exchangers are inspected and removed.

Multiperiod Operation Design. This is the problem of synthesizing a flexible heat exchanger network when flowrate, inlet and outlet temperature for several operating conditions are given. It uses the design combination method. Floudas and Grossmann (1986) presented a method to solve the multiperiod operation problem by extending the MILP transshipment model. The idea behind this method is to construct networks for each operating condition and select a combination that has the lease number of units, i.e. an option that has the most common units in that combination.

Superstructure Design. Floudas and Grossmann (1987) presented a synthesis procedure for resilient HENs. Their multiperiod operation transshipment (optimiziation) model (Floudas and Grossmann, 1986) is used to find a match structure for selected design points. The design obtained for feasibility at the match level. If it is not feasible, the critical point is added as an additional operating point and the problem is reformulate and solved. If the match network is feasible then the multiperiod superstructure is derived and formulated as an NLP problem to find a minimum unit solution. The network solution of the NLP problem will be further tested for flexibility index (Swaney the grossmann, 1985). If the network structure is not resilient, either maintain the same structure and change the size of the heat exchangers or add new critical design conditions to the transshipment model and resolve the problem.

Computer Design Package. The interactive software package called RESHEX has been developed for resilient HEN synthesis and analysis (Saboo and Morari 1986a, 1986b). The resilience of a network can be tested for a specified disturbance range of a network is based on a modification of the MILP model of Papolias and Grossmann (1983).

Downpath Technique. Linnhoff and Kotjabasakis (1984) developed a design procedure for operable HENs by inspection and using the concept of downstream paths, i.e. the paths that connect the disturbed variables downstream to the controlled variables. They generate HEN design alternatives by the pinch method for the nominal (the base case designs) operating condition. Then, the alternative designs are inspected for the effects of disturbances on the controlled variables and they are removed by breaking the troublesome downstream paths. Path breaking can be done by relocating and / or removing exchangers. If this procedure is not feasible, control action is inserted into the structure.

Sensitivity Table. Kotjabasakis and Linnhoff (1986) developed a sensitivity table to examine the changes of the controlled variable based on the variations in the disturbed variables. The base case design is developed and the other cases are derived and added as a contingency to the base case design. Then, the sensitivity table are constructed to give the correlation between changes in inlet variables temperatures.

Their procedure is aimed at establishing the trade-off between energy, capital and flexibility. The designer will decide which contingency is cheapest by inspection.

2.2.2. Drawbacks of Design Combination Methods

As it might be apparent, the drawbacks of these are the same because they use the same design combination strategy. They are:

1.How to identify the worst cases; the network may be operable at the selected design conditions but fails elsewhere. In general, the worst operating conditions are not readily known and may not occur at the extreme points.

2.The combination is done in an ad hoc fashion so, trial and error effort may be required.

3.Since in general these configurations are not necessarily similar to each other, there is no guarantee that the final network will feature the minimum number of units.

4.The effect of pinch relocation is not considered. It may effect MER and in the worst scenario, a network derived may not be feasible.

2.4.3. Direct Resilient Network Design

Resilience of a network is designed directly at a structure generation level so, a network solution will have the required resiliency.

Multiple Objective Optimization. Two possible routes for using optimization techniques to synthesize a resilient network are: (1) infinite nonlinear programming, where the flow of heat from *source* to *sinks* is varied, and (2) multioptimization methods, where resiliency can be measured and set up as another sub-objective function along with costs. The first route seems to be a formidable task and the second case requires a new idea for setting up an appropriate global objective function.

The problem of synthesizing a HEN which features MER, minimum number of matches and resiliency can be formulated as a multi-objective optimization (MOO) problem. In fact the capital cost (reflected by the number of matches), the operating cost (utility) and the resiliency are in general non-commensurable. So, they should be dealt with separately i.e., with different functions in the objective representation in the multi-optimization problem:

$$Max\ [f_1(x),\ f_2(x)\ ,f_3(x)\ ]\ \text{ subject to: } g_I(x) \leq 0,\ I = 1,\ldots,m$$

Resiliency Cerda et al., (1990) devised a technique to incorporate resiliency into the optimization model. The process streams are partitioned into two sets: (1) the permanent streams – a set of streams at their lowest inlet temperatures, i.e. the variable portions are not cut off, and (2) the transient streams – the process streams whose entire temperature ranges are subjected to changes, i.e. the variable parts. They reformulated the problem into 3 levels of objectives to be achieved:

1. Maximize the heat transfer among the permanent streams.
2. Maximize the heat transferred from the transient hot streams to the residual permanent cold streams and the allocation of permanent heat surplus to the transient streams.
3. Maximize the heat transfer among the transient streams.

The resiliency of a network is interpreted as secondary and tertiary energy targets that must be achieved after the primary target. The optimization objectives are the combination of these three objectives which are weighted differently. The higher priority is given to the first objective and the last priority is the third objective.

In order to develop a resilience target, we need a definition of Resilience for HEN. Consider an Uncertainty range of uncertain parameters (supply temperatures and flowrates) over which a HEN is expected to operate. A HEN structure is resilient in the giving uncertainty range if for every combination of supply temperatures and flowrates in the uncertainty range is: (1) achieves the specified target temperatures of each streams; (2) satisfied the specified minimum approach temperature (ΔT_{min}) in each exchanger; (3) satisfying a specified utility consumption constraint (minimum utilty combination, or some relaxation factor times minimum utility combination).

Note that we are interested in the effects in the effects of HEN structure (topology) upon resilience before sizing individual exchangers, we define HEN resilience with respect to ΔT_{min} rather than area. Since resiliency is a property of a network structure, it can not be added to a design by merely in creasing the size of number of components of a structure, but only by generating a proper structure. Resiliency must be considered at the beginning of a structure generating phase.

The resilient HEN synthesis methods presented by Marselle et al.(1982), Saboo et al.(1985) , Floudas et al.(1986) and Cerda et al.(1990) . Marselle et al.(1982) identify heuristically the extreme conditions to design a HEN and the network solution is obtained by combining the networks designed at the specified conditions. Saboo et al. (1985) improve the combination method by testing the feasibility of a solution network at all corner points. Floudas et al. (1986) use the combination method (multiperiod model and test its feasibility at the specified parameter points. Cerda et al. (1990) eliminated the trial and error nature of these methods by including the resilient requirement into the optimization model. The energy recovery is set up in tree levels with different priority.

While the studies by Marselle et al (1982) and Saboo and Morari (1983) have as their objective the synthesis of resilient HENs for a specified range of operating conditions, Often the analysis or the assessment of the resilience is important. An analysis technique can be useful both at the design state and for existing networks: Conventional synthesis procedures often yield alternative HEN designs having similar economic characteristics but widely different "resilience". "Resilience" could then be used as a criterion for the selection of the appropriate design.

On the other hand resilience analysis could be used to detect and remove bottlenecks from networks in operation. It could help to locate the exchanger which limit the network resilience as well as the stream which causes the problems, that is, on which the smallest disturbance is allowed. The engineer could then make a decision either to modify the network structure, increase the areas of some exchangers or impose stricter temperature controls on the stream giving rise to difficulties.

Wongsri (1990) developed the heuristics and procedures for resilient heat exchanger network synthesis. The heuristics are used to developed basic and derived match patterns which were classified according to their (1) resiliency (2) chances that they are in solution and (3) the matching rules like the pinch method, and the thermodynamics law, etc. The mach patterns are also ranked to these properties. Furthermore the same author developed for synthesize heat exchanger network called the Disturbance Propagation Method to be used together with the match pattern. The match pattern concept is used with the developed disturbance load propagation technique to facilitate the bookkeeping of resiliency and the propagated disturbance loads. This method will find a resiliency network structure directly from the resiliency requirement and also feature minimum number of units (MNU) and maximum energy recovery (MER).