Chapter III

THEORY

3.1 Introduction

It is generally accepted that an optimal network must feature a minimum number of units which reflects on a capital cost and minimum utility consumption which reflects on operating cost. A good engineering design must exhibit minimum capital and operating costs. For Heat Exchanger Network (HEN) synthesis, other features that are usually considered in design are operability, reliability, safety, etc. in recent years the attention in HEN synthesis has been focused on the operability features of a HEN, e.g. the ability of a HEN to tolerate unwanted changes in operating conditions. It has been learned that considering only a cost objective in synthesis may lead to a worse network, i.e. a minimum cost network may not be operable at some neighboring operating conditions (Grossmann and Morari, 1984). The design must not only feature minimum cost, but also be able cope with a fluctuation or changes in operating conditions. The ability of a HEN to tolerate unwanted changes is called *resiliency.* It should be note that the ability of a HEN to tolerate wanted changes is called *flexibility.*

However, in the HEN design literature, these two terms are used interchangeably. The resiliency property of a design becomes an important feature to be accounted for when the extent of integration of a design introduces significant interactions among process components. The energy integration of a HEN generates a quit complex interaction of process streams, despite the fact that the transfer of heat from hot to cold process streams is the only activity of the network. The goal of a network is to deliver the process streams to their target temperatures by using most of their heating and cooling availability and a minimum of heating and cooling utilities. The process streams are coupled through a net of heat exchangers. Changes in conditions of one stream in the network may affect the performances of many heat exchangers and the conditions of several process streams. Since resiliency is a property of a network structure, it cannot be added to a design by merely increasing the size or 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. Therefore, the important questions in Resilient Heat Exchanger Network (RHEN) design are *What kind of structure constitute HEN resiliency?* and *Can we identify configurations or patterns of matches that exhibit the property of resiliency?*

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 extreme conditions. Saboo et al. (1985) improve the combination method by testing the feasibility of a solution network at all corner pints. Floudas et al. (1986) use the feasibility combination method (multiperiod MILP transshipment model) to derive the superstructure multiperiod model and test its feasibility at the specified parameter points.

The design combination methods require repetitive effort in finding the resilient network solution. In their works, the generated networks must be tested for their fusibilities because the resiliency requirement is not accounted for in the optimization models. In general, it is difficult or impractical to include nonmonetary design objectives into the utility function. Recently Cerda et al. (1990) eliminated the trial and error nature of these methods by including the resilient into the optimization model. The energy recovery is set up in three levels with different priority. However the optimization techniques dose not use much of the knowledge of the resilient structure. Furthermore, the insight or understanding of the network behavior, which is important in network evolution, operation and control strategy development is somewhat lacking.

In this research the heuristic knowledge of HEN resiliency is used to generate resilient HEN structure for Hydrodealkylation Process (HDA Process). The match pattern heuristic, shift approach and the heat load propagation technique are describes in this chapter.

3.2. HEN Resiliency

The design for resiliency of a single unit is trivial, but for a system comprising interacting units, it is far more than simples empirical overdesign factor.

3.2.1. Definition of HEN Resiliency

In the literature, *resiliency* and *flexibility* have been used synonymously to describe the property of HEN to satisfactorily handle variations in operating conditions. It is our opinion that these two terms have difference in meaning.

The resiliency of a HEN is defined as the ability of a network to tolerate or remain feasible for disturbances in operating conditions (e.g. fluctuations of input temperatures, heat capacity flowrate, etc.) .As mentioned before, HEN flexibility is close in meaning to HEN resiliency, but HEN flexibility usually refers to the wanted (planed) changes of process conditions, e.g. different nominal operating conditions, different feed stocks, etc. That is, HEN flexibility refers to the preservation of satisfactory performance despite varying conditions, while flexibility is the capability to handle alternate (desirable) operating conditions.

A further distinction between resiliency and flexibility is suggested by Colberg *et al.* (1989). Flexibility deals with planed, desirable changes that often have a *discrete* set of values, resilience deal with unplanned, undesirable changes that naturally are continuous values. Thus a flexibility problem is a 'multiple period' type of problem. A resilience problem should be a problem with a continuous range of operating conditions in the neighborhood of nominal operating points. We can see that, from given distinction, resiliency and flexibility syntheses are not the same problem. The resiliency network may be flexible to operate at different operating conditions but the flexible network may fail to be operable at some intermediate points.

In this search the interest is focussed on the undesired changes of operating conditions, so the *resiliency* property of a network is the concern.

3.2.2. HEN Resiliency Measurements

A network A is more resilient than a network B means that a network A can tolerate more parameter variations than a network B. A scalar index that represents the size of feasible operating conditions space can be used to indicate resiliency.

Linnhoff and Flower (1978b) introduce a new property of a heat exchanger related to resiliency of a network called the freedom of heat exchanger to quantify a capability of a heat exchanger to handle an extra heat load. It is defined as:

$$F = W_L\,(\Delta T_s - \Delta T_{min})$$

Where W_L is the larger heat capacity flow rate of the two streams matched, ΔT_S is the smallest actual temperature difference.

This extra heat load may be considered as the available heat load of a heat exchanger. This term dose not represents a property of a whole network; however, it serves as an underlying concept that will be utilized further.

The design of a resilient HEN, in general, can be envisioned to two ways:

o Design HEN that is feasible to operate over specified ranges of operating conditions.

o Design HEN, for a given nominal operating condition, that has the maximum resiliency, i.e. has possible maximum range of operating conditions.

In the first case, a feasibility test is used to *justify* a design. In the second case, a measurement of resiliency is used to *evaluate* design.

For a single variation in process condition or disturbance, the resiliency test can be simply determined by using 'shift approach'. The disturbance (e.g. extra heat load) can be shifted from a source *down part* to heat exchangers provided that the resulting heat load availability of the down path heat exchangers are zero or positive. The network is resilient (feasible) when the extra heat load can be shifted and distributed to the down-path units. However, the 'shift approach' is inconvenient when several disturbances have to be considered together. For this case, a mathematical programming method can be used.

Most of the published resilient HEN synthesis methods do not incorporate the resilient structure in to the optimization models, so that the generated structure has to be tested for resiliency. The resiliency (flexibility) test can also be determined by the shifted approach or mathematically by solving a mix-integer optimization problem (Grossmann and Floudas, 1987). That is, a network problem formulated as mathematical equations described mass and energy balances and physical constraints. Geometrically, the test is to determine whether the 'range' of the given operation parameters is located inside the domain determined by design variables and uncertain parameters.

For the second approach, a procedure to determine a 'resilience index' for a heat exchanger network is needed. The index, in some sense, is the largest disturbance that the network can tolerate.

Resiliency Index. The resilience Index (RI) is presented by Saboo et al. (1985). RI is defined as *the largest disturbance load that a network is able to withstand without becoming infeasible.* Saboo et al., (1985) express this definition mathematically by the maximization problem:

$$RI = \max \Sigma |l_i|$$

$$\text{s.t. } \{Cz. \geq Dl + e, \forall l: \Sigma |l_i| \geq RI\}$$

where $l_i = w_i \Delta T_{i,}$, w_i is the heat capacity flow rate of stream i, ΔT_I is the variation in inlet temperature from nominal value. RI is, geometrically, the distance from the nominal operating condition to a vertex of the *polytope* inscribed in the region specified by the range of operating conditions. It directly represents the distance from the nominal operating condition to the extreme condition.

Flexibility Index. The Flexibility Index (FI) is given by Swaney *et al.* (1982). Geometrically, this index determines the size of the largest *rectangle* inscribed within the feasible region. Both methods measure ' the same thing ' but give different values because of the different of shape of the geometrical objects. FI measures the length of the sides of the rectangle whereas RI measures the 'diagonal' of the polytope. The mathematical method for determining FI is somewhat complicated and dose not has physical representation as the method of Saboo *et al.* (1985).

3.2.3. HEN Resiliency Targeting

By knowing a resiliency target, a design engineer can determine whether there is *room* for improving resiliency. However, knowing the target may not be as useful as we might expect. Unlike MER, a resilient target is not necessarily a bound. Resiliency can be improved even if it reaches the target by establishing trade-off between cost, energy and resiliency i.e., MER, ΔT_{min} can be relaxed and extra units can be added. On the other hand, if a design meets the resiliency requirements, improving resiliency may not offer much incentive. The procedure to calculate a resiliency target is proposed by Colberg *et al.* (1989).

3.2.4. Shift Approach

The variations of temperature and heat capacity flowrate can be viewed as a heat packet that can be is shifted *down path* through streams and heat exchangers to dissipate in heat sinks (coolers) or heat sources (heaters) of a network. There are two cases to be considered:

o Shifted to a utility exchanger within its subnetwork (heating or cooling subnetwork). To maintain maximum energy recovery (MER), the extra heat load must be shifted within the subnetwork of the disturbance origin to utility exchangers. The amount of shifted heat load, in principle is governed by the paths, i.e. *resiliency of a heat exchanger* or *freedom of the heat exchangers* on the paths.

o Shifted to a utility exchanger across a subnetwork. The amount of heat load that cannot be distributed within its subnetwork can be shifted to utility exchangers across the pinch temperature. This brings a MER violation and will be considered only when a resilient design cannot be achieved within a subnetwork. If the resiliency is a must, then the only consideration would be how to design a resilient HEN with the least penalty. A trade-off between cost and resiliency must be considered.

We focused on the first case where a synthesis procedure will be developed for a resilient HEN that features MER, minimum number of units. If such a solution does not exist, a trade-off can then be studied.

As stated, the shift approach can be envisioned as a disturbance load, treated as a heat packet, to be propagated from the sources (input stream positions) throughout the network to the sinks (heaters or coolers). This concept is best understood by considering the following example.

3.3. Problem Classification

Pinch relocation is an attempt by the network to reestablish a balance between heat surplus and deficiency of the new process conditions to achieve a new MER. It is caused by the changes of one or a combination of inlet temperatures, heat capacity flow rates and stream populations.

Saboo and Morari (1984) classify HENS problems into 2 classes based on whether the pinch-determining stream is fixed or changed when parameter variations occur. A class I problem is one in which the pinch determining stream is fixed throughout the variations. Further restriction of Class I problem is the pinch domain must be continuous. That is, Class I problems only account for temperature variations, but not all temperature variations problems are of Class I. It is generally believes that the pinch-determining stream is fixed only when the uncertainty ranges are small. If the disturbance is large so that the pinch-determining stream transitioned or jumped from one stream to another, it is a Class II problem.

For a Class I problem the design procedure is much more straightforward than a Class II problem. The complexity for a Class II problem arises from the transition of the pinch-determining streams in a network or discontinuity of a pinch domain. So ΔT_{min} must be considered at the new pinch and MER must be maintained throughout the network. Class I problem are considered in this chapter and Class II problem are discussed in the next Chapter.

3.4 The RHEN Design Method.

Usually, heat exchanger network synthesis is divided into 2 steps:

1. Network targeting.
2. Network invention.

In the targeting step, the following important properties are determined before the actual network is designed. They are used as the targets for a design. (1) The maximum energy (or the minimum utilities). The minimum utilities can be calculated by constructing the problem table (Linnhoff and Flower, 1978a). The values depend on the minimum approach temperature, ΔT_{min} (2) The minimum number of matches (or units). The minimum number of matches is calculated from

$$N_{match,min} = N_{HotStream} + N_{ColdStream} - 1$$

If a problem is separated by pinch, this equation must be applied separately to each separated problem.

In the network invention step, RHEN uses the design methods developed by Wongsri (1990). They are summarized as follows:

3.4.1 Heuristics

The heuristic approach is based on the use of rules of thumb to provide a plausible direction in the solution of problem. There are a number of design procedures using heuristics in structuring an optimal network featuring minimum number of matches and maximum energy recovery (Nishida et al., 1981, Linnhoff and Hindmarsh, 1963); however, there are to the best of our knowledge that use heuristics tostructure a resilient network. It should be noted that Marselle et al. (1982) Saboo and Morari (1984) and Floudas and Grossmann (1986) use heuristics but not at the structure generation level, to obtain HEN resiliency by combining design at selected design points. The heuristics method to generate a structure of resilient HEN developed in this research is original and is presenting.

Several HEN matching rules have been presented (Masso and Rudd, 1969, Ponton and Donalson, 1974 Rathore and Powers, 1975 Linnhoff and Hindmarsh, 1983, Jezowski and Huang, Metha and fan, 1988, etc.), They are, for example:

· <u>Heuristic C1.</u> To generate a network featuring the minimum number of heat exchanger units, let each match eliminate at least one of the two streams; a tick-off rule (Hohmann, 1971).

· Heuristic C2. Prefer the matches that will leave a residual stream at its cold end for a heating problem, or its hot end for a cooling problem. A match of this type will feature the maximum temperature difference.

· Heuristic C3. Prefer matching large heat load streams together. The significance of this rule is that the control problem (a capital cost) of a mach of this type (whether it is implemented by one or many heat exchangers) should be less than that of heating or cooling a large stream with many small streams.

· Heuristic E1. Divide the problem at the pinch into subproblems, one a heat sink (heating subproblem or hot end problem) and the other a heat source (cooling subproblem or cold end problem), and solve them separately (Linnhoff and Hindmarsh, 1983).

· Heuristic E2. Do not transfer heat across the pinch.

· Heuristic E3. Do not cool above the pinch.

· Heuristic E4. Do not heat below the pinch.

· Heuristic T1. In a heating problem, if a supply temperature of a cold stream is less than a target temperature of a hot stream by ΔT_{min} or more and the heat capacity flowrate of a hot stream is less than or equal to the heat capacity flowrate of a cold stream, the match between these two streams is feasible. Immediately above the pinch tem perature, the heat capacity flowrate of a cold stream must be greater than or equal to that of a hot stream.

· Heuristic T2. In a cooling problem, if a supply temperature of a hot stream is greater than a target temperature of a cold stream by ΔT_{min} or more and the heat capacity flowrate of a hot stream is greater than equal to the heat capacity flowrate of a cold stream, the mach between these two streams is feasible. Immediately below the pinch temperature, the heat capacity flowrate of a hot stream must be greater than or equal to that of a cold stream.

3.4.2 Position of a Match

One heuristic prefers a match at the cold end and another prefers a match at the hot end. Pinch heuristics prefers a match at the cold end in a heating subproblem and a match at the hot end in a cooling subproblem. However, there are other possibilities.

· By using the tick-off heuristic, there are four ways that two streams can match. This leads to the basic four match patterns. (Wongsri, 1990)

3.4.3 Heat Load (between hot and cold streams)

The heuristic that concerns heat load state that one must match large heat load hot and cold streams first. This leads to two additional heuristic:

· Heuristic N1. For a heating subproblem , a match where the heat load of a cold stream is greater than that of a hot stream should be given higher priority than the other .The reason is that the net heat load heating subproblem is in deficit. The sum of heat loads of cold streams is greater than of hot streams. The purposed match will likely be part of a solution, (Wongsri, 1990).

· Heuristic N2. Conversely, we prefer a mach where the heat load of a hot stream is greater than that of a cold in a cooling subproblem, (Wongsri,1990).

3.4.4 Residual Heat Load.

No heuristics for this quantity have thus far appeared in the literature. Two new heuristics are introduced. For a match in a heating subproblem that satisfies the heat load preference;

· Heuristic N3. We prefer a match where the residual heat load is less than or equal to the minimum heating requirement (Wongsri, 1990).

For a match in a cooling subproblem that satisfies the heat load preference or heuristics N.2:

· Heuristic N4. We prefer a match where the residual heat load is less than or equal to the minimum cooling requirement, (Wongsri, 1990).

The reasoning behind the above two heuristics N3 and N4 is that the residual may be matched to a utility stream. One has the possibility of eliminating two streams at once.

3.5. Physical Approach

In this section a physical or heuristic approach to synthesize a resilient heat exchanger network (RHEN) is described. By a physical approach we mean the use of the principle knowledge of HEN and the synthesis heuristics. We believe that this approach will give not only an understanding of the design, but also an insight to the problem of control and operation as well. The match pattern and the heat load propagation concepts will be explained. The match pattern representation and the heat load propagation method will be used extensively in the RHEN design.

The following definitions are for clarity and identifying the scope of terms that will be used in this research.

Definition 3.1 Positive Disturbance, D^+. A positive disturbance load is a disturbance that will increase the heat load of a stream. For example, when the inlet temperature of a disturbed hot stream increases. The disturbance heat load must be dissipated as much as possible by transferring or shifting it to the streams that are serviced by utility exchangers. The positive disturbance load of a hot stream will increase heat duties of coolers and decrease heat duties of heaters. The positive disturbance load of a cold stream will increase heat duties of heaters and decrease heat duties of coolers.

Definition 3.2 Negative Disturbance, D^-. A negative disturbance load is the disturbance that will make the heat load of a stream decrease. For example, when the input temperature of a disturbed hot stream decrease or of the disturbed cold stream increases. The deficient heat load must be provided by utility exchangers so that the design objective is to construct a network that has thermal links between disturbance sources and utility exchangers. The negative disturbance load of a hot stream will increase the heat duties of heater or decrease the heat duties of coolers. The negative disturbance of a cold stream will decrease heat duties of heaters or increase the heat duties of coolers. It will be convenient in the synthesis procedure if only one kind of disturbance is considered so that the dimensionality of things to be considered will be reduced at least by half. The design conditions will be described later.

Definition 3.3 Resilient network: A resilient network is a network that provides a down path for variable process streams so that their specified input heat load disturbances can be shifted to the heaters or coolers in their own subnetwork without violation in the specified target temperatures and MER

Definition 3.4 Heat Exchanger Load (L_{Ei}): Heat exchanger load is a load of heat exchanger, E_i at the design condition.

Definition 3.5 Process Stream Load (L_{Si}): Process stream load is a load of process stream, S_i at the design condition.

Definition 3.6 Heat Exchanger Resilience Parameter (E): Heat exchanger resilience parameter is the measure of how far ΔT_s is far from ΔT_{min}

$$E_{i,j} = W_j(\Delta T_s - \Delta T_{min})$$

where (i,j) is a pair of matched streams. $L_i > L_j$. When $\Delta T_s = \Delta T_{min}$, $E_i = 0$

Definition 3.7 Heat Exchanger Resiliency ($R_{i,j}$): Heat exchanger resilience of a stream i (which matched to a larger stream j) is the value of the extra heat load that can be shift from a stream i to a stream j via such a heat exchanger. The value depends on the particular match pattern of the heat exchanger. In general, $R_{i,j}$ can be the value of $E_{i,j}$ canor R_j whichever is less, where R_i is the resiliency of a residual stream j to a stream i.

Definition 3.8 Propagated Disturbance (D^{prop}): A propagated disturbance is a disturbance received from other streams. More description is given in the section of the disturbance load propagation method.

Definition 3.9 Original Disturbance (D_i): The original disturbance of a stream is the disturbance entered at the supply temperature, i.e. the disturbance originated outside the heat exchanger network. It is usually an experimental estimation.

$$D_i = (T_{i,\max}^{\sup ply} - T_{i,\min}^{\sup ply}) \times W_i$$

Definition 3.10 Utility Exchanger Resiliency (R_U): Utility resilience is the capability of a utility exchanger to handle extra load. The value depends on the kind of disturbances: propagated disturbance or own disturbance.

For a positive disturbance, the maximum utility exchanger resiliency is the value of utility exchanger duty at the specified design condition. For an own disturbance or a negative propagated disturbance, utility exchanger resiliency can be unlimited. This is possible if there is a bypass line to direct the unwanted flow rate to the utility exchanger. Of course, there is a limit for practical realization.

Definition 3.11 Stream Resiliency (R_S): Under the assumption that a bypassed line is a standard feature of every units. The stream resiliency is the sum of the resiliency of the down path units on that stream.

$$R_{S.i} = \sum_{j \in E_{S_i}} R_{X.j} + R_{U.i}$$

where E_{Si} is a set of heat exchanger on a stream i and U_i is an utility exchanger if there is any.

Definition 3.12 Network Resiliency (R_N): Network resiliency is the minimum value of stream resiliency.

$$R_N = min\{R_{Si}\}$$

Where $S_i \in H \cap C$. H and C are sets of the hot and cold streams, respectively, in the specified problem.

3.5.1 Design Conditions

There are several design conditions for resilient HEN synthesis. Usually, these are specified at extreme operating conditions. The following conditions are:

1. *Nominal Operating Condition.* This is an operating condition that is obtained from a steady state heat and mass balance of a process. In a good design, a network must be operated at this condition most of the time. In general, a fluctuation in operating condition is plus and minus from this point.
2. *Maximum Heat Load Condition.* This is a condition where all process streams are at their maximum heat loads. For example input temperatures of hot streams are the highest and of cold streams are the lowest. This is also known as the largest maximum energy recovery condition.
3. *Maximum Cooling Condition.* This is a condition where hot process streams are at their maximum heat loads whereas cold process streams are at their minimum heat loads. For example input temperatures of hot and cold streams are the highest.
4. *Minimum Heating Condition.* This is a condition where hot process streams are at their minimum heat loads whereas cold process streams are at their maximum heat loads. For example input temperatures of hot streams are the lowest and those of cold streams are the highest.
5. *Minimum Heat Load Condition.* This is a condition where all process streams are at their minimum heat loads. For example input temperatures of hot streams are the lowest and of cold streams are the highest. This is also known as the lowest maximum energy recovery condition.

It would be convenient in the synthesis process if only one kind of disturbances (positive or negative disturbance) is considered, e.g. recorded used in match feasibility and resiliency tests. The maximum heat load and the minimum heat load conditions are very interesting because they deal exclusively with only one kind of disturbances. Since at these two conditions the differences of conditions between hot and cold streams are extreme (maximum or minimum) whereas the other are not.

3.5.2 Match Patterns

HEN synthesis is usually considered as a combinatorial matching problem. For a HEN in which a design property is regarded as a network property, or an structural property (e.g. resiliency), we need to look beyond the match level to a higher level where such a property exists, e.g. to a match structure or match pattern. Match patterns are the descriptions of the match configuration of two, and possibly more, process streams and their properties that are thermally connected with heat exchangers. Not only the match description, e.g. heat duty of an exchanger and inlet and outlet temperatures is required but also the position of a match, e.g. upstream or downstream, the magnitude of the residual heat load and the heat capacity flow rates between a pair of matched streams. So, we regard the resilient HEN synthesis problem as a match pattern combinatorial problem where more higher-level design qualities are required.

By using the 'tick off rule' there are four match patterns for a pair of hot and cold streams according to the match position and the length (heat load) of streams. The four patterns are considered to the basic match pattern classes. The members of these classes are the patterns where other configurations and properties are specified. The four match pattern classes are simply called A, B, C and D and are shown in Figure 3.1, 3.2, 3.3 and 3.4 respectively. Any eligible match must belong to one of the four match pattern classes.

Definition 3.13 Class A Match Pattern: The heat load of a cold stream is greater than the heat load of a hot stream in a pattern, i.e. the hot stream is totally serviced. The match is positioned at the cold end of the cold stream. The residual heat load is on the hot portion of the cold stream. (See Figure 3.1.)

A match of this class is a first type match at cold end position and the heat load of the cold stream is greater than that of the hot stream. This is a upstream match. For a heating subproblem, a Class A match is favored, because it leaves a cold process stream (N1) at the pinch heuristics. (See Table 3.1.)

Definition 3.14 Class B Match Pattern: The heat load of a hot stream is greater than the heat load of a cold stream in a pattern, i.e. the cold stream is totally serviced. The match is positioned at the hot end of the hot stream. The residual heat load is on the cold portion of the hot stream. (See Figure 3.2.)

A match of this class is a second type match; a hot end match and the heat load of the hot stream is greater than that of the cold stream. This is an upstream match. For a cooling subproblem, a Class B match is favored, because it leaves a hot process stream at the cold end and also follows the pinch heuristics. (See Table 3.1.)

Definition 3.15 Class C Match Pattern: The heat load of a hot stream is greater than the heat load of a cold stream in a pattern, i.e. the cold stream is totally serviced. The match is positioned at the cold end of the hot stream. The residual heat load is on the hot portion of the hot stream. (See Figure 3.3.)

A match of this class is a first type match; a cold end match and the heat load of the hot stream is greater than that of the cold stream. This is a downstream match. (See Table 3.2.)

Definition 3.16 Class D Match Pattern: The heat load of a cold stream is greater than the heat load of a hot stream in a pattern, i.e. the hot stream is totally serviced. The match is positioned at the hot end of the cold stream. The residual heat load is on the cold portion of the cold stream. (See Figure 3.4.)

A match of this class is a second type match; a hot end match and the heat load of the cold stream is greater than that of the hot stream. This is a downstream match. (See Table 3.2.)

When the residual heat load in a match pattern is matched to a utility stream, it is closed or completed pattern. Otherwise, it is an open or incomplete pattern. It can be seen that if the heat load of the residual stream is less than the minimum heating or cooling requirement then the chances that the match pattern will be matched to a utility stream is high. So we give a match pattern which its residual less than the minimum heating or cooling requirement a high priority in match pattern.

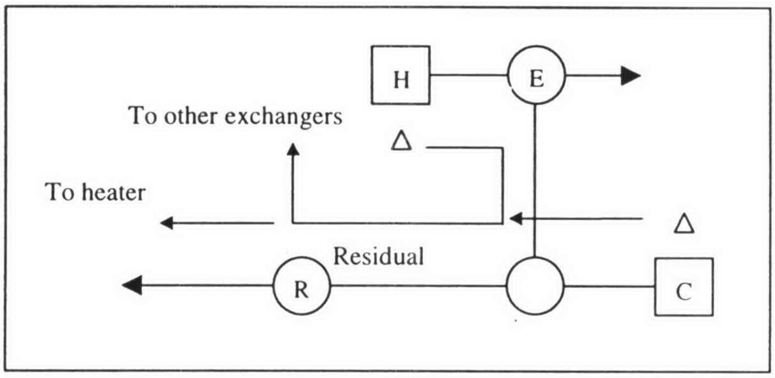


Figure 3.1 Class A Match Pattern

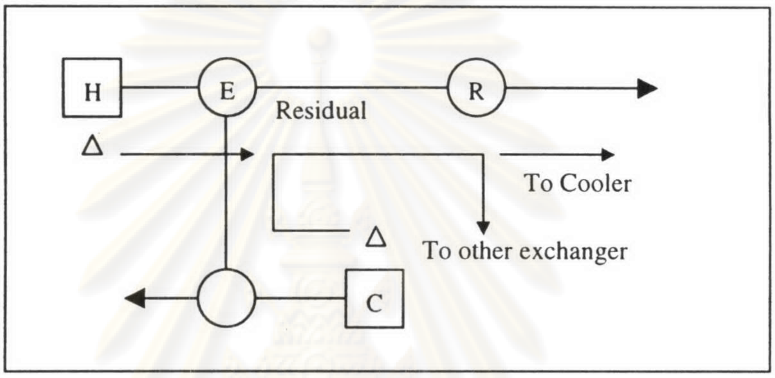


Figure 3.2 Class B Match Pattern

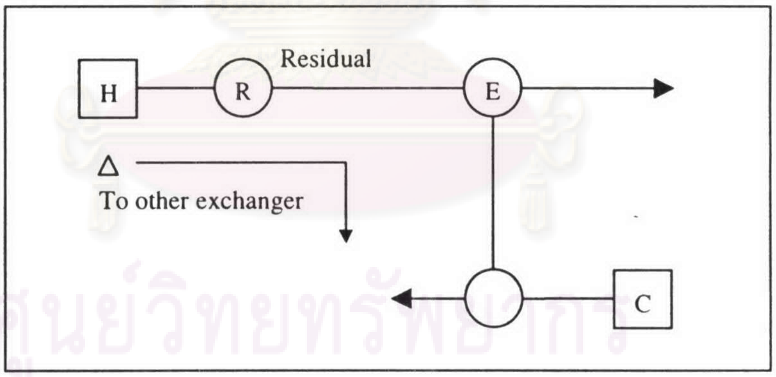


Figure 3.3 Class C Match Pattern

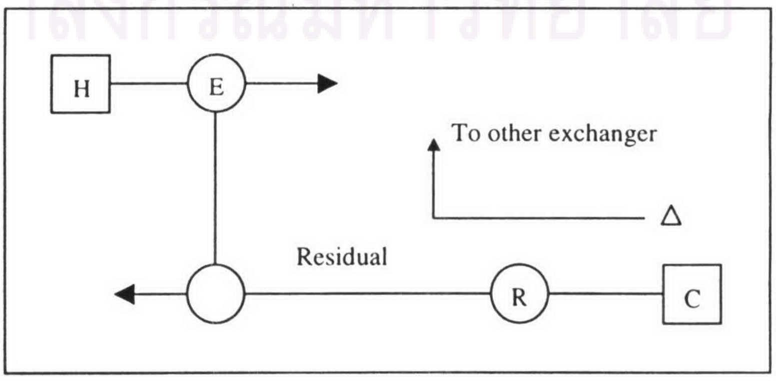
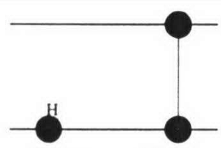
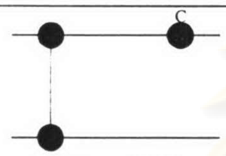
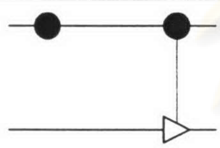
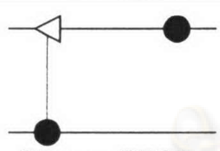
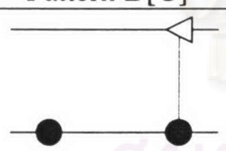
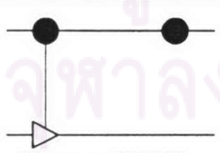


Figure 3.4 Class D Match Pattern

A match of Class A or Class C will leave a residual at the hot end, while a match of ClassB or D will leave a residual at the cold end. Heuristics N.3 and N.4 will be use heuristics to further subclassify matches of Class A and B into matches of high priority.

Table 3.1 Match Pattern Operators of Class A and B

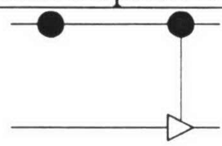
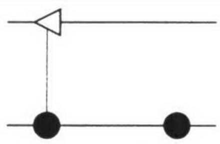
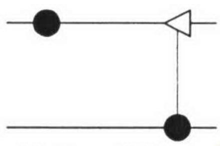
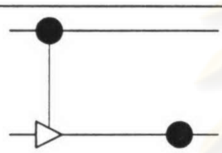
Match Operators	Conditions	Actions
 Pattern AH	$T_H^s * \geq T_C^t$ ** $L_H \leq L_C$ $T_H^s \geq T_C^s + L_H W_C^{-1}$ $L_C - L_H \leq Q_{\min}^{heating}$	Match H and C Status of H $\Leftarrow$ Matched*** $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern BK	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $T_C^s \leq T_H^s - L_C W_H^{-1}$ $L_H - L_C \leq Q_{\min}^{cooling}$	Match H and C Status of C $\Leftarrow$ Matched $T_H^s \Leftarrow T_H^s - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern A[H]	$T_H^t \geq T_C^s$ $L_H \leq L_C$ $W_C \geq W_H$	Match H and C Status of H $\Leftarrow$ Matched $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern B[C]	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_C \leq W_H$	Match H and C Status of C $\Leftarrow$ Matched $T_H^s \Leftarrow T_H^s - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern A[C]	$T_H^t \geq T_C^s$ $L_H \leq L_C$ $W_C < W_H$ $T_H^s \geq T_C^s + L_H W_C^{-1}$	Match H and C Status of H $\Leftarrow$ Matched $T_C^s \Leftarrow T_C^s + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern B[H]	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_H < W_C$ $T_C^s \leq T_H^s - L_C W_H^{-1}$	Match H and C Status of C $\Leftarrow$ Matched $T_H^s \Leftarrow T_H^s - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$

* T^t=target temp, T^s=supply temp, W=heat capacity flowrate, L, Q=heat load.

** Cold stream temperatures are shifted up by ΔT_{min}.

*** There are two status of process streams, 'active' and 'matched'. This will exclude this stream from a set of process streams to be selected next.

Table 3.2 Match Pattern Operators of Class C and D

Match Operators	Conditions	Actions
 Pattern C[H]	$T_H^l \ge T_C^s$ $L_H > L_C$ $W_H \le W_C$	Match H and C Status of C $\Leftarrow$ Matched $T_H^l \Leftarrow T_H^l - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern D[C]	$T_H^s \ge T_C^l$ $L_H < L_C$ $W_H \ge W_C$	Match H and C Status of H $\Leftarrow$ Matched $T_C^l \Leftarrow T_C^l + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$
 Pattern C[C]	$T_H^l \ge T_C^s$ $L_H > L_C$ $W_C < W_H$ $T_C^l \le T_H^l + L_C W_H^{-1}$	Match H and C Status of C $\Leftarrow$ Matched $T_H^l \Leftarrow T_H^l - L_C W_H^{-1}$ $L_H \Leftarrow L_H - L_C$
 Pattern D[H]	$T_H^s \ge T_C^l$ $L_H \le L_C$ $W_H < W_C$ $T_H^l \ge T_C^l - L_H W_C^{-1}$	Match H and C Status of H $\Leftarrow$ Matched $T_C^l \Leftarrow T_C^l + L_H W_C^{-1}$ $L_C \Leftarrow L_C - L_H$

3.5.3. Derivative Match Patterns

Subclass AH. A match of this subclass is a member of Class A, a heating subproblem where the residual is less than or equal to the minimum heating requirement. See Table 3.1.

Subclass BK. A match of this subclass is a member of Class B, a cooling subproblem where the residual is less than or equal to the minimum cooling requirement. See Table 3.1.

A match of subclasses AH in a heating subproblem have the highest priorities. We further discriminate match patterns according to heat capacity flowrate. By following pinch heuristics, in a heating subproblem, we prefer a match where the heat capacity flowrate of a cold stream is greater than or equal to that of a hot stream. For example, A[H] is a match in which the heat capacity flowrate of the cold stream and the residual of the cold stream is matched to the heating utility. Similarly in a cooling subproblem, we prefer a match where the heat capacity flowrate of the hot stream is greater or equal to that of the cold stream. For example, B[C] is a match in which the heat capacity flowrate of the hot stream is greater than of the cold stream and the residual of the hot stream is matching to the cooling utility.

For example, the rankings of the match patterns in a heating subproblem are AH, A[H], B[C], A[C], B[H], C[H],D[C], C[C] and D[H]; for a cooling subproblem BK, B[C],A[H], B[H], A[C], D[C], C[H], D[H] and C[C]. There are more derivative match patterns, see Wongsri (1990).

3.5.4. Resilient Match Patterns

We are now in a position to discuss the resiliency of the four match pattern classes. Resiliency of a match pattern can be archived if the disturbances in input conditions of the hot and cold streams can be transferred to the active stream (a residual portion). In effect, the transferred disturbances are the responsibility of and will be managed by the resiliency of the active stream whose resiliency is yet to be determined. So, the degree of resiliency depends on how much the disturbances can be passed to the residual. In general, resiliency of any individual match pattern depends on (1) the resiliency of the active residual stream, (2) the heat exchanger.

For Class A and Class B match patterns, the disturbance of a member stream can be transfer to the residual. So they are considered to be potential resilient match patterns. For the Class C and Class D match pattern, we can see that only the disturbances of a hot stream in Class C and of a cold stream in Class D can be managed but neither a cold stream in Class C nor a hot stream in Class D. Since these two classes cannot handle disturbance of one of their streams, they are considered nonresilient match patterns.

3.5.5 Disturbance Propagation Design Method

In order for a stream to be resilient with a specified disturbance load, the disturbance load must be transferred to heat sinks or heat sources within the network. With the use of the heuristic: To generate a heat exchanger network featuring the minimum number of heat transfer units, let each match eliminate at lease one of the two streams.

We can see that in a match of two heat load variable streams, the variation in heat load of the smaller stream S1 will cause a variation to the residual of the larger stream S2 by the same degree: in effect the disturbance load of S1 is shifted to the residual of S2. If the residual stream S2 is matched to S3 which has larger heat load, the same situation will happen. The combined disturbance load of S1 and S2 will cause the variation in the heat load to the residual S3. Hence, it is easy to see that the disturbance load in residual S3 is the combination of its own disturbance load and those obtained from S1 and S2. Or, if S2 is matched to a smaller heat load stream S4, the new disturbance load of residual S2 will be the sum of the disturbance loads of S1 and S4. Form this observation, in order to be resilient, a smaller process stream with specified disturbance load must be matched to a larger stream that can tolerate its disturbance. In other words, the propagated disturbance will not overshoot the target temperature of the larger process stream.

However, the amount of disturbance load that can be shifted from one stream to another depends upon the type of match patterns and the residual heat load. Hence, in design we must choose a pattern that yields the maximum resiliency, e.g. a maximum value of E or R_S. We can state that the resiliency requirement for a match pattern selection is that the entire disturbance load from a smaller heat load stream must be tolerated by a residual stream. Otherwise, the target temperature of the smaller stream will fluctuate by the unshifted disturbance. Of course, the propagated disturbance will be finally handled by utility exchangers. In short, the minimum heat load value of a larger stream must be less than a maximum heat load value of a smaller stream.

By choosing the minimum heat load condition for the design, the new input temperature of a residual stream to its design condition according to the propagated disturbance. The propagated disturbance will proportionally cause more temperature variation in the residual stream and the range of temperature variation of the residual stream will be larger than its original range.

A Definition of propagated disturbance is appropriate:

Definition 3.17 Propagated Disturbance. The propagated disturbance of a stream is the disturbance caused by a variation in heat load of 'up-path' streams to which such a stream is matched. Only a residual stream will have a propagated disturbance. The new disturbance load of a residual stream will be the sum of its own disturbance, if any, and the propagated disturbance. See Figure 3.5 and 3.6.

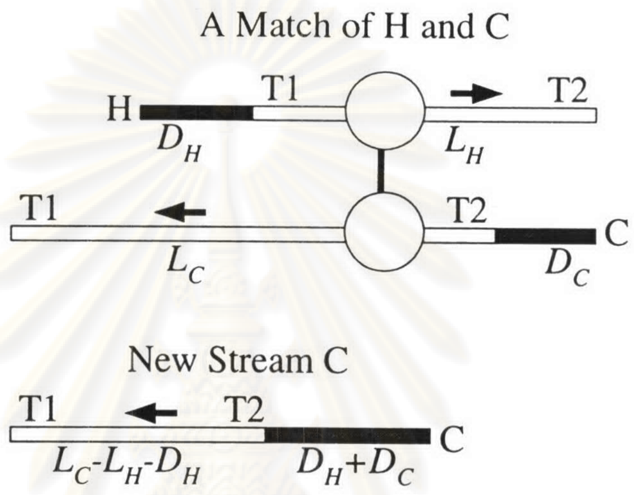


Figure 3.5 A Concept of Propagated Disturbance

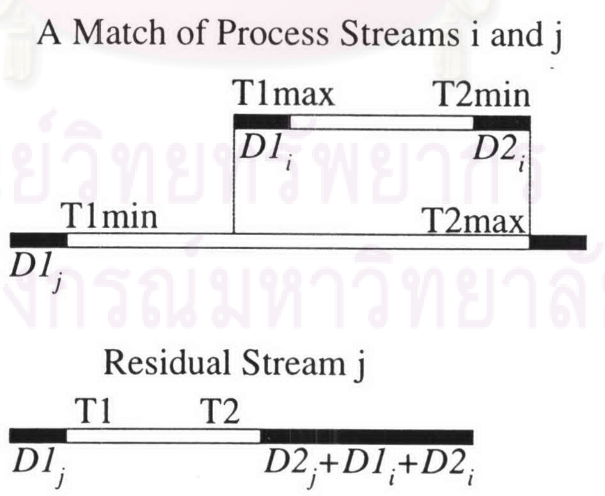


Figure 3.6 A General Concept of Propagated Disturbance

Hence, a stream with no original variation in heat load will be subjected to variation in heat load if it is matched to a stream with disturbance. Another design consideration is that the disturbance load travel path should be as short as possible, i.e. the lease number of streams involved. Otherwise, the accumulated disturbance will be at high level. From the control point of view, it is difficult to achieve good control if the order of the process and the transportation lag are high. From the design viewpoint, are may not find heat sinks or sources that can handle the large amount of propagated disturbance.

3.5.6. Stream Partitioning Procedure

For a pinch problem, the process streams are partitioned into heating and cooling subproblems. The pinch temperature for the resilient HENS problem is no longer a fixed point but is defined by a region determined by one or more pinch determining streams. The pinch range can be a single continuous range or two or more disjointed pinch continuous ranges.

A new procedure for stream partitioned must be developed for the disturbance propagation technique. *Maintaining MER means that the balance of the heat load of portions of process streams above the pinch point must be transferred to heaters and the balance of parts of process streams below the pinch point must b transferred to coolers.*

The provision for pinch variation is made in our synthesis procedure:

o The inlet and outlet temperatures of the partitioned process streams, by our convention, are subject to modification within the range of the pinch region. The partition point for a hot end is the lowest pinch temperature in the pinch region and that of a cold end the highest pinch temperature.

o The minimum cold end temperature and the minimum hot end temperature, T1 for process streams in a cooling subproblem is the lowest pinch temperature.

o The pseudo or pinch-induced disturbances are created to account for the pinch temperature variation.

3.5.7. Flowrate Variations

The following are the definitions of the new parameters that will be used in our design procedure and discussion.

Definition 3.18 Heat Capacity Flowrate W_i: The heat capacity flowrate of stream i for design is the minimum value in its range.

Definition 3.19 Stream Resiliency Parameter S**:** The stream resiliency parameter is a measure of the difference in heat load of a stream I from its current value to when its heat capacity flowrate equals the heat capacity flowrate of stream j, W_j

$$S_i = (W_j - W_i) (T_i^{\,1} - T_i^2)$$

Where (i, j) is a pair of hot and cold streams, $L_j \geq L_i$, T^1 is a hot end temperature and T^2 is a cold end temperature of a process stream. If $W_i > W_j$, S_i will have a negative value.

Definition 3.20 Flowrate Disturbance D^w**:** The flowrate disturbance is the increased heat load due to an increase of heat capacity flowrate from its minimum (design) value to its maximum value over the maximum temperature range of such a stream. See Figure 3.7.

$$D_i^w = (W_{i,max} - W_{i,min}) (T^1_{\;i,max} - T^2_{\;i,min})$$

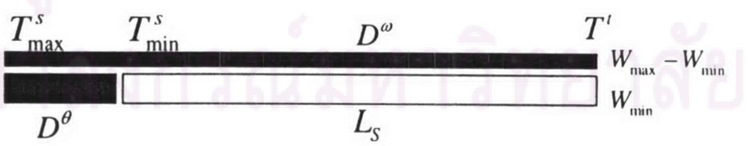


Figure 3.7 Description of Disturbances

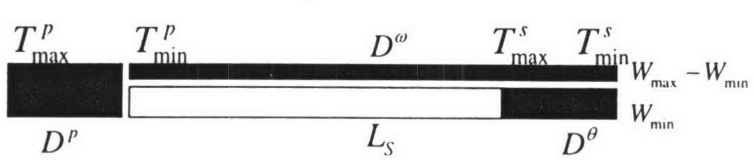


Figure 3.8 Description of Pinch Disturbance for a Cold Stream

Definition 3.21 Original Disturbance D: Now the original disturbance included the heat capacity flowrate disturbance. See figure 3.8.

$$D_i = D_i^{\theta} + D^{w}{}_i$$

Where D_i^{θ} is a disturbance caused by temperature variation.

$$D_i^{\theta} = W_{i,min} \left(T^{s}{}_{i,max} - T^{s}{}_{i,min} \right)$$

Where T^s is the supply temperature.

Definition 3.22 Pinch Induced Disturbance D^p : The pinch-induced disturbance is a disturbance caused by pinch variation. The pinch-induced disturbances are not independent from each other so, they are not additive as ordinary disturbance but deductive. The pinch-induced disturbance is:

$$D^{p}{}_i + W_i \left(T^{p}{}_{I,mar} - T^{p}{}_{I,min} \right)$$

where T^p is pinch temperature.

Definition 3.23 Minimum Heat Load Condition. The minimum heat load condition where all process streams are at their minimum heat loads. For example input temperatures of hot streams are the lowest and those of cold streams are the highest. The heat capacity flowrate of hot and cold streams are at their lowest.

Definition 3.24 Temperature Disturbance Induced by Flowrate Variation. When a process stream with heat capacity flowrate variation is matched to another stream, the heat capacity flowrate variation will induce temperature variations in the matched stream. The design procedure cannot consider the heat capacity flowrate variations alone. Both types of variations must be treated together.

3.6. Network Resiliency

The new synthesis method generates a resilient HEN structure directly from the match level. This new method is different from the other methods that generate cost optimal HENs at various selected design conditions and merge those designs together.

We have learned that HENs cannot be made resilient by increasing heat transfer areas of heat exchangers or adding extra heat exchangers to a network regardless of the fact this the overdesign strategy works very well for a single unit. We assert that network resiliency is more a property of the structure than of the structure than of the unit. In match selection test e.g., the information about a residual stream, The position of a match, etc.

Match Structure. The four basic match patterns are classified according to match positions and the 'tick-off' heuristics. Two of them namely, Class A and Class B, are the potential resilient match structures are shown in Figure 3.1 and 3.2.

The match structures, Class A and Class B, need to be analyzed further for the resiliency requirement i.e., whether they can handle a specified amount of disturbance.

3.6.1 Resiliency Requirement Test

The test of a resilient match for the flowrate variation case must also test for the resiliency according to temperature and heat capacity flowrate variations.

3.6.1.1 Temperature Disturbance.

For the temperature variation case, a match of streams (i,j) ,where $L_i \leq L_j$, is resilient if the following requirement is satisfied:

$$D^{\theta}{}_{i} \leq min\ \{E_{j,i}\ ,R_{j,i}\ \}$$

where $E_{j,i}$ is the exchanger resiliency parameter and $R_{j,i}$ is the resiliency of the residual stream j. If the match pattern is A[H] or B[C] then,

$$D^{\theta}{}_{i} \leq R_{j,i}$$

3.6.1.2 Flowrate Disturbance

Two test are required for a specified resiliency for a match with flowrate variation, the first one is the disturbance load as in the temperature disturbance case and the other one is for the heat capacity flowrate constraint.

o Disturbance load constraint. This test is to check whether the given disturbance can pass through a heat exchanger to the residual stream and whether a residual stream can handle the given disturbance.

$$D_i^w \leq min\ \{E_{i,j}\ ,\ R_{j,i}\ \}$$

For match patterns A[H] and B[C] ,

$$D_i^w \leq R_{j,i}$$

o Heat capacity flowrate constraint. This test is to verify whether a match is able to deliver a small heat load process stream to its target temperature.

$$D_i^w \leq E_{i,j} + S_{i,j}$$

In general, for a match with both type of disturbances, the resiliency requirement are:

$$D^\theta + D^w{}_i \leq min\ E_{i,j}\ \ ,\ R_{i,j}$$

$$D_i^w \leq E_{i,j} = S_{i,j}$$

In shot for the heat capacity flowrate variation case, one more test is required in addition to a temperature variation case:

o Temperature variation case: The propagated disturbance load.

o Heat capacity flowrate variation case: The heat capacity flowrate constrain. Using an equivalent argument, to be resilient a process stream with a lower heat load much match its maximum heat load against the minimum heat load of a larger process stream.

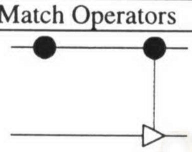
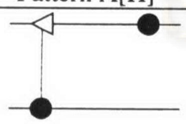
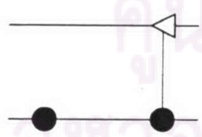
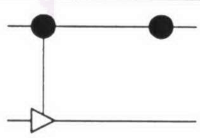
Class C and Class D Match Patterns. Class C and Class D match patterns where streams are matched at downstream positions can be resilient by a feed forward control technique i.e., the fluctuation of a smaller stream is sent to a controller to manipulate either (1) a larger stream at its upstream position or (2) a stream to which the residual is matching. The manipulate resiliency for Class C and Class D match structures is called a secondary resiliency. However, in our design procedure, Class C and Class D match are less preferable than Class A Class B matches since they require by-pass lines and control equipment which maybe not be required with Class A or Class B patterns.

The disturbance propagation design technique can be used for these two classes in as much as provisions are made for the propagated disturbance at the downstream or upstream positions of the residual stream. Let us consider the following examples:

3.6.2 Match Operators

The match test and resiliency test equations of Class A and Class B match patterns are shown in Table 3.3. Those of Class C and Class D are shown in Table 3.4. In the tables, the temperatures of the cold streams are scales up by ΔT_{min}.

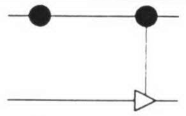
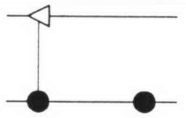
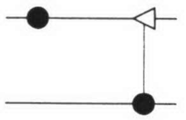
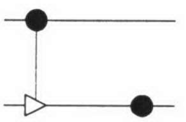
Table 3.3 Match Operators I

Match Operators	Match Test Equations	Resiliency Test Equations
 Pattern A[H]	$T_H^t \geq T_C^s$ * $L_H \leq L_C$ $W_C \geq W_H$	$D^\theta + D^\omega \leq R_{C.H}$ $D^\omega \leq E_{C.H} + S_{C.H}$
 Pattern B[C]**	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_C \leq W_H$	$D^\theta + D^\omega \leq R_{H.C}$ $D^\omega \leq E_{H.C} + S_{H.C}$
 Pattern A[C]	$T_H^t \geq T_C^s$ $L_H \leq L_C$ $W_C < W_H$ $-S_{C.H} \leq E_{C.H}$	$D^\theta + D^\omega \leq \min\{R_{C.H}, E_{C.H}\}$ $D^\omega \leq E_{C.H} + S_{C.H}$
 Pattern B[H]**	$T_H^s \geq T_C^t$ $L_C \leq L_H$ $W_H < W_C$ $-S_{H.C} \leq E_{H.C}$	$D^\theta + D^\omega \leq \min\{R_{H.C}, E_{H.C}\}$ $D^\omega \leq E_{H.C} + S_{H.C}$

* A scale of T_C is shifted up by ΔT_{min}

** The test equations for Class B match patterns can be obtained from those of Class A by substituting H by C and vice versa, e.g. A[H] ↔ B[C], L[H] ↔ L[C], etc.

Table 3.4 Match Operators II

Match Operators	Match Test Equations	Resiliency* Test Equations
 Pattern C[H]	$T_H^l \geq T_C^s$ $L_H > L_C$ $W_H \leq W_C$	$D^\theta + D^\omega \leq R_{H.C}$ $D^\omega \leq E_{H.C} + S_{H.C}$
 Pattern D[C]**	$T_H^s \geq T_C^l$ $L_H < L_C$ $W_H \geq W_C$	$D^\theta + D^\omega \leq R_{C.H}$ $D^\omega \leq E_{C.H} + S_{C.H}$
 Pattern C[C]	$T_H^l \geq T_C^s$ $L_H > L_C$ $W_C < W_H$ $S_{H.C} \leq E_{H.C}$	$D^\theta + D^\omega \leq \min\{ R_{H.C}, E_{H.C} \}$ $D^\omega \leq E_{H.C} + S_{H.C}$
 Pattern D[H]**	$T_H^s \geq T_C^l$ $L_H \leq L_C$ $W_H < W_C$ $S_{C.H} \leq E_{C.H}$	$D^\theta + D^\omega \leq \min\{ R_{C.H}, E_{C.H} \}$ $D^\omega \leq E_{C.H} + S_{C.H}$

* Secondary resiliency

** The test equations for Class D match patterns can be obtained from those of Class C by substituting H by C and vice versa, e.g. C[H] ↔ D[C], W[H] ↔ W[C], etc.