2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

Heat exchanger networks (HENs) are widely used in many process industries for the purpose of maximizing heat recovery and hence reducing utility consumption. Previously, HENs system has been well studies in terms of grassroots design. However, retrofit studies are still actively pursued to further improve energy recovery. It was reported that 70% of the projects conducted in the industry involved process retrofits. There are two main streams of the research regarding heat exchanger network (HENs) retrofit. One is based on thermodynamic analysis, namely Pinch Analysis, and another tackles the problem using Mathematical Programming.

2.1 Process Retrofit

Pinch Technology is applicable to both new design and retrofit situations. The number of retrofit applications is much higher than the number of new design application (Linnhoff M, 1998) [1]

Since the energy crisis of the early 1970s, much attention has been directed at better process design. One area success has been in process integration. In particular, pinch technology has demonstrated that good use of energy and capital. Applications of process integration fall into two categories are following below.

- Grassroots design
- Retrofit

Generally, process in methodology has been related to grassroots design. Applications in retrofit have had to be improvised. In the context of retrofitting, this implies the setting of targets for energy saving, capital cost, and payback.

The pioneer work in pinch technology addresses energy targets and recognized the existence of the pinch. Applications to industrial projects resulted in significant saving, even though energy was the primary consideration (Tjoe and Linnhoff, 1987).

2.1.1 Retrofit Targeting based on Capital-energy trade-off

Figure 2.1 provides an understanding of the capital – energy trade-off for a retrofit project using an energy plot.

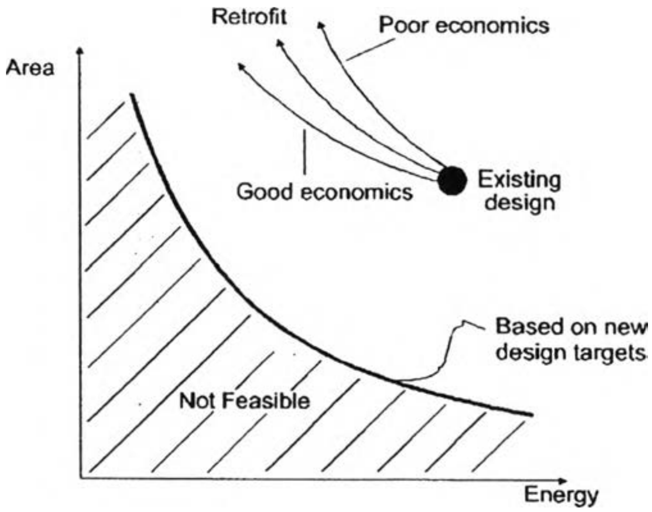

Figure 2.1 Capital energy trade off for retrofit applications (Linnhoff, 1998).

The curve (enclosing the shaded area) is based on new design targets for the process. The shaded area indicates performance better than the new design targets (which is infeasible for an existing plant). An existing plant will typically be located above the new design curve. The closer the existing plant is to the new design curve, the better the current performance. In a retrofit modification, for increased energy saving, the installation of additional heat exchanger surface area is expected. The curve for the additional surface area that is closest to the new design area-energy curve provides the most efficient route for investment (good economics). The following section explains how such a curve for a retrofit application can be developed ahead of design.

2.1.2 Maintaining Area Efficiency

Figure 2.2 depicts an approach for retrofit targeting based on the concept of "Area efficiency". An area efficiency factor α can be determined for an existing network according to the following equation;

$$\alpha = \frac{(A_{ideal})_0}{(A_{existing})} = \text{Area Efficiency}$$

$$\Delta\alpha = \frac{A_{ideal_1} - A_{ideal_0}}{A_{retrofit} - A_{existing}}$$

where; $A_{existing}$ = Existing surface area of the network

A_{ideal} = Target surface area for the new design at the existing energy consumption (Eex).

$A_{retrofit}$ = Retrofit surface area of the network

$\Delta\alpha \approx \alpha$ if $\alpha > 0.9$ or $\Delta\alpha \approx 1$ if $\alpha < 0.9$

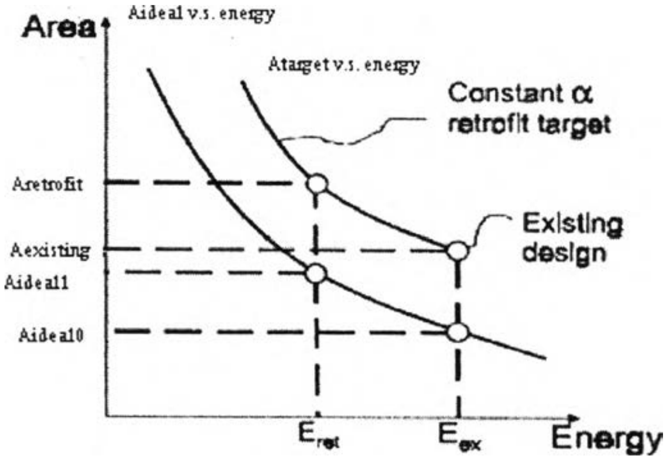

Figure 2.2 Area efficiency concepts (Linnhoff, 1998).

Area efficiency determines how close the existing network is to the new design area target. In order to set a retrofit target, one approach is to assume that the area efficiency of the new installed area is the same as the existing network as shown in Figure 2.2. Moreover the maximum retrofit area can be found by below equation.

$$A_{retrofit} = \frac{\left(A_{ideal_1} - A_{ideal_0}\right)}{\Delta\alpha} + A_{existing}$$

2.1.3 Retrofit targeting based on ΔT_{min} – Energy curves

Finally the project time constraints may limit the use of the capital cost targets for retrofit targeting. In this section a simpler approach to retrofit targeting based on the analysis of energy target variation with ΔT_{min} is described.

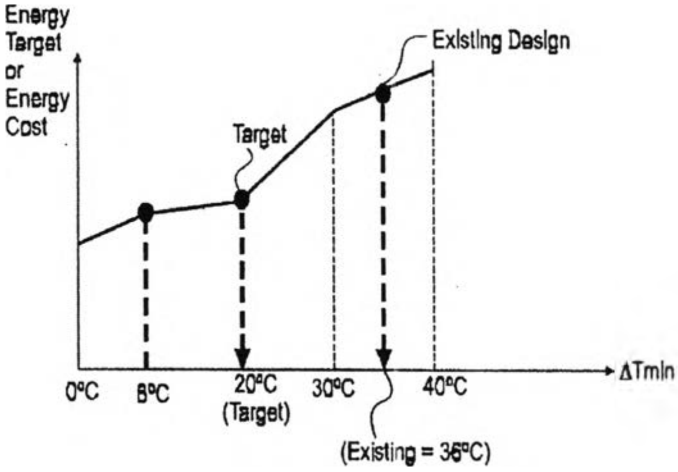

Figure 2.3 Targeting for retrofit application (Linnhoff, 1998).

Figure 2.3 shows an example of a ΔT_{min} – Energy plot for a process. The plot can be directly obtained from the process composite curve. The vertical axis can represent energy target or energy cost. Existing design corresponds to the ΔT_{min} of 36 °C between the composite curves. The plot shows that the variation of energy target (or energy cost) is quite sensitive to ΔT_{min} in the temperature range from 30 °C to 20°C. However between 20 °C and 8 °C the energy target is not sensitive to ΔT_{min} On the other hand the capital cost may rise substantially in this region. It therefore implies that 20 °C is an appropriate target for the retrofit. Although the ΔT_{min} – Energy plot does not directly account for the capital cost dimension, it is expected that dominant changes in the energy dimension will have an impact on the capital energy trade-off. The above approach, coupled with previous application experience on similar processes provides practical targets in many situations.

2.2 Mathematical Software

Ma et al. [9] proposed an MILP model that can solve the HEN retrofit in one single step. The model adopted the stage-wise superstructure from Yee and Grossmann, which takes into account the energy consumption; network structural modifications as well as new exchanger areas were considered implicitly by setting a minimum approach temperature in order to remove the non-linearity of exchanger area calculation. With this simple model, good design alternatives are quickly determined. The drawback of this approach was that exchanger areas were not considered explicitly inside the model; therefore, further optimization was required for the selected network. The details of the formation are presented as follows:

2.2.1 Overall heat balance for each stream

$$(Tout_j - Tin_j)F_j = \sum_{k\in ST}\sum_{i\in HP} q_{ijk} + qhu_j \quad j\in \mathrm{CP}$$

$$(Tin_i - Tout_i)F_i = \sum_{k\in ST}\sum_{j\in CP} q_{ijk} + qcu_i \quad i\in \mathrm{HP}$$

2.2.2 Heat balance of each stream at each stage

$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i\in HP} q_{ijk} \quad j\in \mathrm{CP},\ k\in \mathrm{ST}$$

$$(t_{i,k} - t_{i,k+1})Fi = \sum_{j\in CP} q_{ijk} \quad i\in \mathrm{HP},\ k\in \mathrm{ST}$$

2.2.3 Assignment of superstructure inlet temperature

$$Tin_j = t_{j,N+1} \quad j\in \mathrm{CP}$$

$$Tin_i = t_{i,1} \quad i\in \mathrm{HP}$$

2.2.4 Feasibility of temperature

$t_{j,k} \geq t_{j,k+1}$ j∈CP k∈ST

$Tout_j \geq t_{j,1}$ j∈CP

$t_{i,k} \geq t_{i,k+1}$ i∈HP k∈ST

$Tout_i \leq t_{i,N+1}$ i∈HP

2.2.5 Hot and cold utility load

$(Tout_j - t_{j,1})F_j = qhu_j$ j∈CP

$(t_{i,N} - Tout_i)F_i = qcu_i$ i∈HP

2.2.6 Logical constraints

$q_{ijk} - \Omega_p Y_{ijk} \leq 0$ i∈HP j∈CP k∈ST

$qhu_j - \Omega_p Y_{hj} \leq 0$ j∈CP

$qcu_i - \Omega_c Y_{ic} \leq 0$ i∈HP

Y_{ijk}, Y_{hj}, Y_{ic} are binary variables.

2.2.7 Feasible driving force

$dt_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma_{ij}(1 - Y_{ijk})$ i∈HP, j∈CP, k∈ST

$dt_{ijk} \leq t_{i,k+1} - t_{j,k+1} + \Gamma_{ij}(1 - Y_{ijk})$ i∈HP, j∈CP, k∈ST

$dthu_j \leq Tout_{HU} - t_{j,1} + \Gamma_{h_j}(1 - Y_{hj})$ j∈CP

$dtcu_i \leq t_{i,N+1} - Tout_{CU} + \Gamma_{ic}(1 - Y_{ic})$ i∈HP

dt_{ijk+1}, $dthu_j$ and $dtcu_i \geq EMAT$ i∈HP, j∈CP, k∈ST

The above constraints are used to model the heat flows of stage-wise superstructure and restricted all heat exchange approach temperatures of the required matches to be larger or equal to the Exchanger Minimum Approach Temperature (EMAT).

2.2.8 Objective function

Finally, the objective function can be defined as the annual cost for the network. The annual cost involves the combination of the utility cost, the fixed charges for the exchangers,

The objective function is defined as follows:

Minimize

$$\sum CCU \cdot qcu_i + \sum CHU \cdot qhu_j + \sum\sum\sum CF_{ij} z_{ijk} + \sum CF_{i,CU} \cdot zcu_{ijk} + \sum CF_{j.HU} \cdot zhu_i$$

i∈HP, j∈CP, k∈ST

Nomenclature

Indices

i	hot process stream in retrofit network
j	cold process stream in retrofit network
k	stage in retrofit network 1,...,N and temperature location 1,...,N+1
h	hot utility
c	cold utility

Sets

HP	i|i is a hot process stream
HU	hot utility. s
CP	j|j is a hot process stream
CU	cold utility, s
ST	k|k is the stage in superstructure, k=1,…,N

Parameters

Tin	inlet temperature of stream
Tout	outlet temperature of stream
F	heat capacity flow rate
N	total number of stages
Ω	upper bound for heat exchanged
Γij	upper bound for temperature difference between stream i and j
Γhj	upper bound for temperature difference between hot utility h and stream j
Γic	upper bound for temperature difference between stream i and cold utility c

Binary variables

Y_{ijk}	required process match (i,j,k) in retrofit network
Y_{hj}	required hot utility match (h,j) in retrofit network
Y_{ic}	required cold utility match (i,c) in retrofit network

Variables

dt_{ijk}	temperature approach for match (i,j) at temperature location k
$dthu_j$	temperature approach for the match of hot utility and cold stream j
$dtcu_i$	temperature approach for the match of hot stream i and cold utility
q_{ijk}	heat exchanged for match (i,j) in stage k
qhu_j	heat exchanged for hot utility match (h,j)
qcu_i	heat exchanged for cold utility match (i,c)
$t_{i.k}$	temperature of hot stream i at temperature location k
$t_{j,k}$	temperature of cold stream j at temperature location k

2.3. Literature Survey

There are two main cases of research for heat exchanger network (HEN) retrofit. One is based on thermodynamic analysis including Pinch Analysis. Another is using Mathematical Programming. Tjoe and Linnhoff **[1]** first proposed the application of the pinch concept in retrofit HEN. They suggested a two–step procedure namely Targeting and Design. The target method leads to a desired heat transfer approach temperature (ΔTm) by information such as the process stream data, costs and economical information, current network conditions (energy consumption and exchanger surface areas). This ΔTm fixes the amount of energy recovery and predicts the additional amount of heat exchanger area. The drawback of this method is that the targets do not tell exactly where the additional areas are added and how many networks restructure modifications such as re–piping, re–routing are required. On the other hand, mathematical programming for HEN retrofit does not require too much expertise; this approach can handle different kinds of constraints simultaneously. HEN retrofit problem is basically a Mixed Integer Non-Linear Programming (MINLP) problem. Good solution for solving one single MINLP model has still not yet succeeded because of non-linearity of the area equations and the complexity of the reassignment constraints. So the problem is normally simplified as a Mixed Integer Linear Programming (MILP) model by imposing some assumptions. By transshipment model from Papoulias and Grossmann [2], Yee and Grossmann [3] formulated an MILP model, namely assignment–transshipment model. It can minimize the cost of structural modifications. The model assumed a fixed level of energy recovery and did not take into account the exchanger cost explicitly. Yee and Grossmann [4] developed a two–step approach. First they used their assignment–transshipment model to look retrofit network structure at difference energy recovery levels. In the second, they optimized by using MINLP. Even though the network structure is simplified, solving the MINLP model was still time consuming task and solution are still very often trapped at local optimum. Ciric and Floudas [5] also proposed a two-step approach. They made an MILP model for considering all decision regarding matching, reassignment and purchasing new areas or units. The transshipment constraints were incorporated with predetermined temperature intervals that linearized equations of heat exchanger area calculation. Solution at this step determines the stream matching and the reassignment of existing matches in the first step. In the second step, a non-linear programming (NLP) formulation is used to optimize the heat transfer area as well as energy consumption based on the network structure obtained at the previous step. Ciric and Floudas [6] combined two–steps into a single step by using a MINP formulation to simultaneously optimize heat exchanger area, energy reassignment and other aspects of a HEN. Asante and Zhu [7] proposed a step by step interactive approach for heat exchanger network retrofit by combining the features of Pinch and mathematical programming. They introduced a concept of network pinch that identifies the bottleneck of the network and the most effective change. An MILP model was formulated for this purpose. Once a topology change is accepted either the addition of a new exchanger or a new split, a relocation of an existing heat exchanger, the new topology will then be optimized as an NLP. The procedure is repeated until the designer could not find any more economical change. The procedure identifies a single topology change at a time in a sequential manner that may in theory yield a sub-optimal solution. Also, sensible user interaction is required for meaningful result. Briones and Kokossis [8] used only MILP models in a two–step approach, namely screening and optimization. At the screening step, an MILP model was used for network modifications as well as the additional heat exchanger area. Range area targets were calculated and translated into an investment–saving plot. The objective of this step is to identify the right level of energy recovery and selected the existing matches that are at high efficiency. The selected matches are retained in the retrofit network and the remaining matches will be considered for reassignment. After fixing the energy recover level, an MILP model was then used in the second step to determine the remaining part of the network by utilizing the unused and new exchanger.

It can be concluded that most of the works uses mathematical programming which require two steps (screening and optimization) because of solving the HEN retrofit problem at one step with consideration of energy, heat transfer area and reallocation of heat exchanger explicitly is very time consuming or the quality of solution cannot be guaranteed. The screening step is very important since it determines or restricts the final topology of network. A good screening step also simplifies the network structure so that solution time at the second step could be minimized. Most of the models used for the screening step had fixed energy consumption; therefore, approach–temperature at each enthalpy interval could be fixed. This assumption linearized the problem so that it could be solved as an MILP. The disadvantage of this kind of model is that the pre-selected energy consumption (or the network's minimum approach temperature) affects the quality of solution. Another serious problem in fixing enthalpy intervals is that it generates a huge number of integer variables so often for assigning heat exchanger matches among those intervals. This significantly increases the solution time.