Step by Step for Designing an Optimum Heat Exchanger Network

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Abstract

Features of energy crisis became more complicated due to shortage of non-renewable sources of energy. While energy requirements increase parallel to technology progress. Energy researchers always apply energy targeting methodology to reduce utilities consumption. Designing a Heat Exchangers Network [HEN] by application of pinch analysis is an effective technique for energy integration. I can say that this work is specific and simple course for designing a HEN through case study application. Where 8 alternatives Grass roots HEN designs with 66% of utilities saving are concluded. Minimization of units and cost, process control and operability are important factors for choosing the suitable HEN design. Revamping of the existing process to maximize energy recovery with least alterations and cost took place; where net annual saving reached to 1,400,000 $.

Graphical Abstract

What is the idea of Heat Exchanger Network??

Figure (1) the Idea of HEN
 Through two streams from any process
 Transferring Heat Load from Source (hot stream H) to Sink (cold stream C)
 Replacement both Cooler and Heater by a Heat Exchanger

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Index Terms: Heat recovery, Energy saving, Pinch Analysis, Minimum utilities

Heat Exchanger Network HEN, Cost estimation, Optimum HEN.

1-Introduction

As population increase and technology develop; demand for energy increase while in the same time we suffer from shortage of non-renewable sources, all these factors complete the energy crisis. Heat exchanger network (HEN) is an important technique for maximizing heat recovery in the industrial chemical process and reducing external heating and cooling utilities. Extensive research has been done to improve HENs design and synthesis over the past 40 years [1].

Pinch Analysis (PA); one of the most methods used to design (HEN) and integrate heat since it introduced by Linnhoff and Flower [2] & Linnhoff and Hinmarsh [3]. [Ahmad & Linnhoff and Ahmad] [4,5] introduced the “Supertargeting” procedure for the design of near-optimal heat exchanger network which systematically considers the energy capital trade off. This method involves searching for the optimum approach temperature that yields the lowest total annual cost for a HEN designing.

The effect of ΔTmin contribution on cost was modified by Sun et al [6] where economical balance and analysis between the capital and operating costs for a given ΔTmin took place. The effect of heat – exchangers specifications as material of construction, equipment type and rate of pressure on the HEN cost has modified by [Hall, Ahmad and Smith] [7].

A methodology for determination optimum loads of multiple utilities to trade-off the capital and energy cost of HEN was proposed by Shenoy et al. [8]. Akbarnia, Amidpour, and Shadaram [9] added piping costs to the heat exchanger capital cost which improves the accuracy of capital cost estimation and detects the optimum point for designing.

Kravanja and Glavič [10] proposed a simultaneous optimization for HEN cost targeting method based on process flow sheets using rigorous models and detailed cost for HEN functions. The nonlinear programming NLP model is a combination of pinch technology and mathematical programming and can be used to HEN synthesis with a large number of streams.

Mixed-integer-linear programming (MILP) transportation method; was formulated by Shethna, Jezowski, and Castillo [11] to optimize heat exchanging area, number of units and utilities load in order to achieve optimum cost target for HEN.

Reza, Reza, and Hassan [12] developed a mathematical model which affected by specifications shell and tube heat exchanger (materials of construction and heat transfer coefficients) in annual cost optimization of HEN.

The MILP-MINLP Methodology by Yee and Grossmann [13] was the base model for MO_MINLP simultaneous flexibility and operability technique for designing a flexible HEN. Where this HEN; can maximize energy recovery
although, there is deviation of the streams' conditions [14, 15, and 16].

2- Pinch Analysis Technique

We can consider the first “red” book by Linnhoff et al. [17]; is the first step for prevalence of heat integration topic in research sector. This User Guide: is still the massively cited in the literature and is considered as the beginning overview for energy integration. Where application of Pinch Analysis Technique (PAT); provides searchers with catalogue for solving the problem of process integration. The technique proved integration successfully through heat exchanger network synthesis, heat recovery targeting, and selecting multiple utilities [18]. In (PAT) utilities integration and energy recovery realized by transforming the process streams into the Composite Curves (CCs) [19]. From (CCs), we can estimate the minimum external requirements of hot and cold utilities which are the non-overlapping segments of the cold and hot composite curves. Maximum heat recovery represents in (CCs) by the overlap region between hot and cold composites curves. CCs play an important role in process design; for designing a Heat Exchanger Network (HEN) directly. The Grand Composite Curved (GCC) and the Problem Table Algorithm (PTA) are further development for heat integration techniques. Where minimum utilities and so on minimum emissions can be concluded [20].

2-1 Principles of Pinch Analysis

Pinch Technology provides a systematic methodology for energy saving in processes and total sites. The methodology is based on thermodynamic principles, the basis equations are:

\[
\begin{align*}
CP &= m \cdot C_p \\
\Delta H &= m \cdot C_p \cdot \Delta T = CP \cdot \Delta T \\
CP &= \Delta H / \Delta T
\end{align*}
\]

Where:
- \(m\): mass flow rate
- \(C_p\): specific heat (physical property)
- \(CP\): Heat Capacity flow rate
- \(\Delta H\): Enthalpy Change
- \(\Delta T\): Temperature Change

![Figure (2) Presentation of hot stream on T-H diagram](image)

2-2 Steps of Pinch Analysis Technique

1) Identification of hot, cold, utility streams in the process.
2) Extraction of thermal data for process streams and utilities.
3) Selection of Initial \(\Delta T_{\text{min}}\) value.
4) Estimation of minimum hot and cold utilities and defining of pinch point by:
   - Construction of Composite Curves
• Problem Table Algorithm
5) Design of Heat Exchanger
Network [HEN].
6) Estimation of minimum energy
cost target.
7) Estimation of the capital cost
target.
8) Identification of the optimum
ΔTmin value.
9) Design of the optimum Heat
Exchanger Network [HEN].

2-3 Estimation of minimum utilities

Maximum energy recovery for any
process leads to minimization of the
required external heating and cooling
loads. Estimation of minimum hot and
cold utilities through pinch analysis by
two techniques (composite curve
& problem table) is done as a beginning
step for HEN designing.

2-3-1 construction of Composite
Curve

Transferring of all hot streams which
presented in T-H diagram into one
curve depending on summation the
streams loads of the same interval; this
curve named as hot composite curve.
By repeating this step with cold
streams; we get also cold composite
curve. The overlap region is the energy
recovery limits while the non overlap
are the required heating and cooling.
We can move composite curves
horizontally to change temperature
difference which affects on utilities
loads and heat transfer area. While
detecting ΔTmin value is realizing
maximum energy recovery and
minimum utilities [21].
See Figures (3 & 4)

T-H DIAGRAMS

• Composite Curve

Figure (3) Construction of Composite Curves
Figure (4) Definition of Pinch Point & control of $\Delta T_{\text{min}}$ by sliding cold composite curve

2-3-2 Problem Table

It is an analytical method for estimation of minimum utilities and its advantage no need for especial utensil as graph paper and scissors.

Steps of problem table method:

- Divide the process into intervals
- Limits of intervals are shifted temperatures (hot streams temperatures $-1/2 \Delta T_{\text{min}}$) & (cold streams temperatures $+1/2 \Delta T_{\text{min}}$)
- Schematic representation of the streams with a vertical temperature scale took place through interval boundaries (shifted temperatures $S_i$). See Figure (5)
- Enthalpy balances of every interval $i$, limited by shifted temperatures ($S_i$ & $S_{i+1}$) can easily be calculated as:
  $$\Delta H_i = (S_i - S_{i+1}) (\sum C_P_{\text{hot}} - \sum C_P_{\text{cold}})$$
- The positive magnitude of enthalpy balance equation named interval case as "surplus" while the negative named as "deficit" to produce a feasible network design based on the assumption that all "surplus" intervals rejected heat to cold utility, and all "deficit" intervals took heat from hot utility.
- Beginning of external heating of zero and accumulating of intervals loads ascending to define the highest deficit value which represent minimum hot utility ($Q_H$).
- Cascading the process interval with ($Q_H$) with accumulating of intervals loads will finally conclude minimum cold utility ($Q_C$) which is the load of last interval [22].
3- Design of Heat Exchanger Network

After classification the process into streams with its thermal and physical properties, estimation of minimum utilities and defining pinch point. Now we can begin the more interesting part which is HEN designing. The pinch separates the process into two subnetwork designs; above and below pinch.

To achieve maximum energy recovery we must apply these next steps:

1. Do not transfer heat across the pinch point.
2. Do not use hot utility below the pinch point.
3. Do not use cold utility above the pinch point.
4. Begin with pinch match and move away.
5. Pinch matches obey this rule:
   - $C_{\text{hot}} \leq C_{\text{cold}}$ (above pinch)
   - $C_{\text{hot}} \geq C_{\text{cold}}$ (below pinch)

Algorithm of HEN designing is shown in Fig. 6
4- Economic Analysis of HEN Design

By applying pinch analysis technique, we can get many alternative designs for the same process. Economic balancing by cost estimation of every design helps us to reach to the optimum one. Cost Estimation Equations are:

\[
\text{Ann. Overall Cost of HEN} = \text{Ann. Capital Cost} + \text{Ann. Operating Cost}
\]

**Capital cost:**

\[
\text{Ann. Capital Cost} = \frac{\text{Capital cost of Units}}{\text{life time}}
\]

Capital cost of unit = \( f[A] \) \( \text{... (A } \Xi \text{ heat transfer area)} \)

\[
A = \frac{Q}{U} \times \Delta T_{lm}
\]

Where:

- \( Q \) = heat load of the unit
- \( 1/U = \frac{1}{h_i} + \frac{1}{h_j} \) \( \text{... (h } \Xi \text{ heat transfer coefficient)} \)
- \( \Delta T_{lm} = \frac{(T_{1} - t_2) - (T_2 - t_1)}{ln(T_{1} - t_2) / (T_2 - t_1)} \)
- Life time = 6 years
- Cost of piping = 8% Installed cost of Equipment

Effect of \( \Delta T_{min} \) on heat transfer area and capital cost is shown as next diagram:

![Diagram showing effect of \( \Delta T_{min} \) on heat transfer area and capital cost]

- Capital cost affected by number of units and minimum number of units for any HEN can be estimated by next equation:

\[
N_{min} = N_h + N_c + N_u - 1
\]

Where:

- \( N_{min} \) = Minimum Number of Units
- \( N_h \) = Number of hot streams
- \( N_c \) = Number of cold streams
- \( N_u \) = Number of utilities

**Operating Cost**

\[
\text{Total Operating Cost} = \sum_{u=1}^{N_u} Q_u \cdot C_u
\]

Where:

- \( Q_u \) = Duty of utility U, kW
Cu = Unit cost of utility U, $ / KW.yr

Nu = Total Number of utilities

5- Application of Pinch Analysis Technique on a case study

I applied Pinch technique on a case study with a plant flowsheet shown in Figure (7). Where:

- The feed is heated to the reaction temperature.
- The reactor effluent is further heated, and the products are separated in a distillation column.
- The reboiler and condenser use external utilities for control purposes.
- The overhead and bottoms products are cooled and sent for further processing.

Classification the process into streams with its thermal and physical properties is shown in table (1). As a beginning for HEN design I represent the streams in the form of grid diagram as shown in Figure (8) where the actual consumption of external utilities is:

- Heating load = 14000 Kw
- Cooling load = 13800 Kw
- Cost of hot utility = 140.2 $/ KW.yr
- Cost of cold utility = 7.1 $/ KW.yr

![Figure (7) A Typical Plant Flowsheet of the case study](image-url)
### Table (1): Streams data of the case study

<table>
<thead>
<tr>
<th>Stream No</th>
<th>Stream Name</th>
<th>Ts °C</th>
<th>Tt °C</th>
<th>CP (KW/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Reactor Feed</td>
<td>20</td>
<td>160</td>
<td>40</td>
</tr>
<tr>
<td>C2</td>
<td>Reactor Effluent</td>
<td>120</td>
<td>260</td>
<td>60</td>
</tr>
<tr>
<td>H1</td>
<td>Overhead Product</td>
<td>180</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>H2</td>
<td>Bottom Product</td>
<td>280</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

![Figure (8) Grid Diagram of the Flowsheet](image)

**Figure (8) Grid Diagram of the Flowsheet**

### 5-1 Estimation of Minimum Hot and Cold Utilities

- With $\Delta T_{\text{min}}$ of 30°C; minimum hot and cold utilities of the process estimated by graphical composite curve as shown in Figure (9).

  Where \( Q_{\text{H min}} = 4750 \text{ KW}, Q_{\text{C min}} = 4550 \text{ KW}, T_{\text{hp}} = 150 \text{ °C} \text{ and } T_{\text{cp}} = 120 \text{ °C} \)

- The Analytical problem table method got the same results of minimum utilities and pinch point as shown in Figures (10, 11) and Table (2)
Figure (9) Estimation of Minimum Utilities by Composite Curve

\[ TB = Si = Th - \frac{1}{2} \Delta T_{\text{min}} \]
\[ TB = Si = Tc + \frac{1}{2} \Delta T_{\text{min}} \]

**Figure (10) Representation of Streams on Boundary Intervals**
Table: (2) Definition and Calculation of Enthalpy Change for Every Interval

<table>
<thead>
<tr>
<th>Temperature T °C</th>
<th>Interval NO</th>
<th>Ti - Ti+1</th>
<th>( \sum CP_{cold} - \sum CP_{hot} )</th>
<th>( \Delta H_i )</th>
<th>Surplus or Deficit</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>1</td>
<td>10</td>
<td>60</td>
<td>600</td>
<td>Deficit</td>
</tr>
<tr>
<td>265</td>
<td>2</td>
<td>90</td>
<td>30</td>
<td>2700</td>
<td>Deficit</td>
</tr>
<tr>
<td>175</td>
<td>3</td>
<td>10</td>
<td>70</td>
<td>700</td>
<td>Deficit</td>
</tr>
<tr>
<td>165</td>
<td>4</td>
<td>30</td>
<td>25</td>
<td>75</td>
<td>Deficit</td>
</tr>
<tr>
<td>135</td>
<td>5</td>
<td>90</td>
<td>-35</td>
<td>-3150</td>
<td>Surplus</td>
</tr>
<tr>
<td>45</td>
<td>6</td>
<td>10</td>
<td>-5</td>
<td>-50</td>
<td>Surplus</td>
</tr>
<tr>
<td>35</td>
<td>7</td>
<td>30</td>
<td>-45</td>
<td>-1350</td>
<td>Surplus</td>
</tr>
</tbody>
</table>

Figure (11) Estimation of minimum Utilities by Problem Table Algorithm through heat Cascade Principle

5-2 Designing of Subnetworks for the Case Study

By applying pinch technique sequences for HEN designing as mentioned before in text 3, four subnetworks alternatives are concluded. Two above Pinch. See Figures (12-a) & (12-b) and the other two subnetworks were designed below pinch point. See Figures (12-c) & (12-d).
5-3 Synthesis of HEN Designs by Subnetworks Combination

By combination between every two subnetworks (above –below); I got four alternatives HEN designs for the case study, Figures (13-a, 14-a, 15-a, and 16-a). All the designs achieved minimizing of utilities but differed in matching and number of units. As a result of combination; loops appear due to match repeating between the same streams as represented in Figures by purple dashed line. In this case; modification of design by breaking the loop is required by replacement the 2 H.E with 1 to minimize the units’ number and so on reduce capital cost as shown in Figures (13-b, 14-b, 15-b and 16-b). The summary of the economic analysis of the modified designs is shown in table (3); where HEN of Fig.15-b has the least cost.

Figure (13- a) First alternative HEN design, combination between (12-a) and (12-d)

<table>
<thead>
<tr>
<th>Pinch match</th>
<th>CPhot ≤ CPcold</th>
</tr>
</thead>
<tbody>
<tr>
<td>QH min = 4750 KW</td>
<td></td>
</tr>
<tr>
<td>Qc min = 4550 KW</td>
<td></td>
</tr>
</tbody>
</table>

Figure (12-a) & (12-b) Subnetworks above pinch

Figure (12-c) & (12-d) Subnetworks below pinch
Figure (13-b) First alternative HEN design after loop breaking

Figure (14-a) Second alternative HEN design, combination between (12-b) and (12-c)

Figure (14-b) Second alternative HEN design after loop breaking
Figure (15-a) Third alternative HEN design, combination between (12-b) and (12-d)

Figure (15-b) Third alternative HEN design after loop breaking

Figure (16-a) Fourth alternative HEN design, combination between (12-a) and (12-c)
5-4 Revamping of the Case Study through Heat Recovery Technique

As a new design (grass-root) for the case study; all the last alternatives HEN designs can be used according to availability and operability conditions. While the revamping technique depends on choosing the least alterations HEN design compared to the existing. That’s guarantees minimizing added capital cost. So The HEN design of Figure (14-b) is our pivot for existing process revamping. The modification is only adding two heat exchangers represented by yellow circles as shown in Figure (17).

Maximum energy recovery realized where external heating reduced from 13800 to 4750 KW and external cooling reduced from 14000 to 4550 KW. The summary of economic analysis due to revamping is shown in Table (4); where the net saving is around 1,400,000 $/y
Figure (17) The flowsheet of the case study after revamping

Table (4) Economic Analysis for Revamping the Case study

<table>
<thead>
<tr>
<th></th>
<th>Existing HEN</th>
<th>Revamped HEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Utility KW</td>
<td>13800</td>
<td>4750</td>
</tr>
<tr>
<td>Cold Utility KW</td>
<td>14000</td>
<td>4550</td>
</tr>
<tr>
<td>Cost of hot utility $/y</td>
<td>1,934,760</td>
<td>665,950</td>
</tr>
<tr>
<td>Cost of cold utility $/y</td>
<td>229,366</td>
<td>32,305</td>
</tr>
<tr>
<td>Operating Cost $/y</td>
<td>2,163,826</td>
<td>698,255</td>
</tr>
<tr>
<td>Saving of Operating Cost $/y</td>
<td></td>
<td>1,465,571</td>
</tr>
<tr>
<td>Added Capital Cost $/y</td>
<td></td>
<td>82,678</td>
</tr>
<tr>
<td>Net Saving $/y</td>
<td></td>
<td>1,382,893</td>
</tr>
</tbody>
</table>
Conclusion

This study is a summary of pinch analysis to design Heat Exchanger Network HEN step by step. Designing of HEN is an effective technique for maximizing energy recovery and so on minimizing external utilities. It's proved its validity through application on a case study where percentage of utilities' saving reached to (65% & 68%) for hot utility and cold utility respectively. The process revamping got excellent results where maximization of saving realized by least alterations represented in adding two heat exchangers and the net annual saving reached to 1,382,893 $ which is great.

Recommendation

This technique is recommended for any chemical process where energy saving is an international target for all countries (rich or poor). We need to reduce energy consumption to save money and protect environment.

Acknowledgment

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Nomenclature

- $Q_{h\text{min}}$: Minimum hot utility (kW)
- $Q_{c\text{min}}$: Minimum cold utility (kW)
- $\Delta T_{\text{ln}}$ : Minimum temperature difference log mean
- $T_{hp}$: hot pinch point (°C)
- $T_{cp}$: cold pinch point (°C)
- $T_B$: Boundary temperature (°C)
- $T_s$: Supply temperature (°C)
- $T_t$: Target temperature
- $A$: heat exchanger area (m²)
- $h_i$: heat transfer coefficient of hot stream (kW/m²°C)
- $h_j$: heat transfer coefficient of cold stream (kW/m²°C)
- $U$: Overall heat transfer coefficient (kW/m²°C)
- $N_{\text{min}}$: Minimum Number of Units
- $N_h$: Number of hot streams
- $N_c$: Number of cold streams
- $N_u$: Number of utilities
- $H$: enthalpy (kW)
- $C_P$: heat capacity flow rate (kW/°C)
- $T_1$: Inlet temperature of hot stream (°C)
- $T_2$: outlet temperature of hot stream (°C)
- $t_1$: inlet temperature of cold stream (°C)
- $t_2$: outlet temperature of cold stream (°C)
- $\Delta T_{\text{min}}$: minimum temperature difference approach

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