Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 2, No. 5, February : 2024

"HEAT EXCHANGER NETWORK DESIGN – A REVIEW"

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Abstract:
This review paper aims to provide an overview of the design of heat exchanger networks (HENs) using pinch analysis, a widely used technique in the process industries. The paper first introduces the concept of pinch analysis and explains its basic principles. It then discusses the various steps involved in the design of a HEN using pinch analysis, including the determination of the heat load targets, the identification of the pinch point, the selection of the appropriate heat exchangers, and the optimization of the network configuration. The review paper also highlights the key advantages of using pinch analysis for HEN design, such as its ability to identify the minimum energy requirement for a process, its flexibility in accommodating changes in process conditions, and its potential for reducing energy consumption and operating costs. The paper concludes by discussing of a case study in HEN design using pinch analysis, which includes integration of process intensification techniques and the use of multi-objective optimization algorithms. Overall, this review paper serves as a comprehensive guide for researchers and practitioners interested in the design of HENs using pinch analysis, providing a valuable resource for the process industries to improve energy efficiency and reduce environmental impact.
Keywords: Pinch analysis, Heat Exchanger Network (HEN), ΔTmin, minimum utility

I. Introduction
In today's industry, minimizing energy consumption is crucial due to the scarcity of traditional fuels and the instability in global markets. Heat Exchanger Networks (HENs) play a significant role in reducing heating and cooling utility consumption in industrial processes. However, problems like heat exchanger fouling, tube leakage, and changes in process stream conditions can degrade HEN performance. Pinch technology can identify appropriate changes in core process conditions to achieve energy savings. Design and optimization of HENs have been extensively studied, and the project objective is to apply detailed methodology to address an industrial case study. A good understanding of modelling and simulation of HENs in a simultaneous approach is necessary.

II. PINCH ANALYSIS
Pinch Technology is a systematic methodology for energy saving in processes and total sites based on thermodynamic principles. The process design hierarchy is represented by the "onion diagram" and starts with the core process (reactors), followed by separators, heat exchanger network, and utility system. Pinch Analysis begins with the heat and material balance for the process to identify appropriate changes in the core process conditions for energy savings. Targets for energy saving and utility loads can be set prior to the design of the heat exchanger network, ensuring these targets are achieved during network design. Pinch Technology extends to the site level, identifying appropriate loads on various steam mains to minimize site-wide energy consumption, providing a consistent methodology for energy saving from the basic heat and material balance to the total site utility system.

Industrial Engineering Journal
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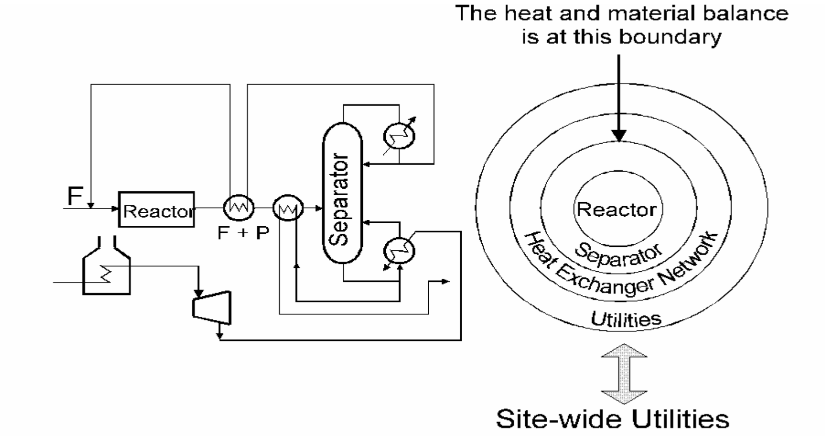

Figure 2.1:"Onion Diagram" of hierarchy in process design

2.1. PRINCIPLES OF PINCH ANALYSIS

Pinch Technology is a systematic approach for energy saving in processes and sites based on thermodynamic principles. The method utilizes the temperature-heat content diagram to visualize the heat exchange in the process. The T/H diagram can represent heat exchange, and a given stream can be plotted anywhere on the enthalpy axis if it has the same slope and runs between the same supply and target temperatures.

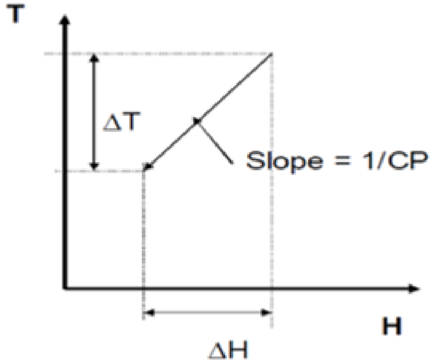

Figure 2.2: Presentation of hot stream on T-H Diagram

CP = mCp

where, m = mass flow rate, Cp = specific heat (physical property)

ΔH = mCp**Δ**T = CP**Δ**T

CP = **Δ**H/ **Δ**T

CP = Heat capacity flow rate, **Δ**H = Enthalpy Change

ΔT = Temperature Change

STEPS IN 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 ΔTmin value.
4) Estimation of minimum hot and cold utilities and defining of pinch point by:

- Construction of Hot and Cold Composite Curves
- Grand Composite Curve

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].

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2.2.1. Identification of hot, cold, utility streams in the process

A hypothetical process model consisting of hot and cold streams is created and sorted. The hot and cold streams data are separated and plotted. During the initial plot the following rules are applied: one streams endpoint is the next streams initial point. After the cold stream, respective hot streams are plotted in separate TH-diagrams, the streams should not overlap and they should not have a gap on the H-axis in between them.

2.2.2. Extraction of thermal data for process streams and utilities

The given process flow-sheet (Figure 2.3. (a)) involves a two-stage reactor and a distillation column with heat recovery represented by two process-to-process heat exchangers. The process requires a hot utility demand of 1200 units and a cold utility demand of 360 units. Pinch Analysis principles will be applied to identify the energy-saving potential and subsequently design the heat exchanger network achieve that targeted saving

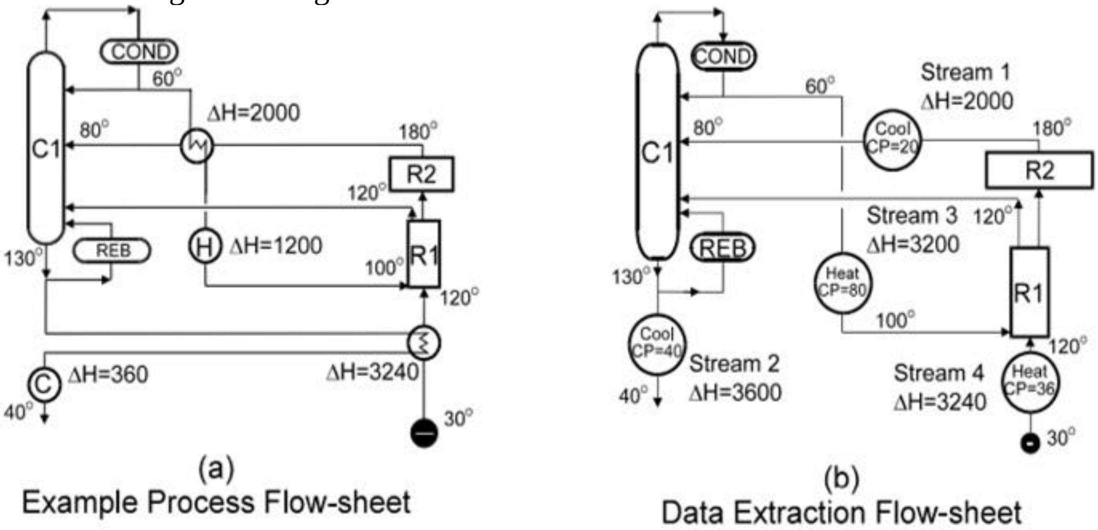

Figure 2.3: Data extraction for pinch analysis

Table 2.1: Thermal Data required for pinch analysis

Stream No	Stream Type	Start Temperature (Ts) (°C)	Target Temperature (Tt) (°C)	Heat Capacity Flowrate (CP) (kW/°C)
1	Hot	180	80	20
2	Hot	130	40	40
3	Cold	60	100	80
4	Cold	30	120	36

ΔTmin = 10°C

Utilities : Steam at 200 °C. CW at 25°C ⟹ 30°C

The thermal data required for pinch analysis is provided in a table 2.1, which includes the supply and target temperatures (Ts and Tt) and the heat capacity flow rate (CP) for hot and cold streams. The minimum temperature difference during the analysis is assumed to be 10ºC, which is the same as the existing process. The hot utility is steam available at 200ºC, and the cold utility is cooling water available between 25ºC to 30ºC.

2.2.3. Selection of Initial ΔTmin value

The energy goal (ΔT min) is defined after taking into consideration several aspects such as available technology, the process needs, technological data and financial factors. It shows how close the hot and cold composite curves can be before disobeying the second law of thermodynamics. If a process has a

Industrial Engineering Journal
ISSN: 0970-2555
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higher ΔTmin in their processes today and desire to lower it they should be aware that big restructurings very likely will be needed and therefore obtaining a lower ΔTmin is an investment. A ΔTmin close to zero gives in theory heat exchangers with areas reaching infinity. The best way is to weigh the financial investment with available technology and choose a suitable ΔTmin after this consideration. A normal range for the pinch point is anywhere between **10 ≤ ΔT min ≤ 40.**

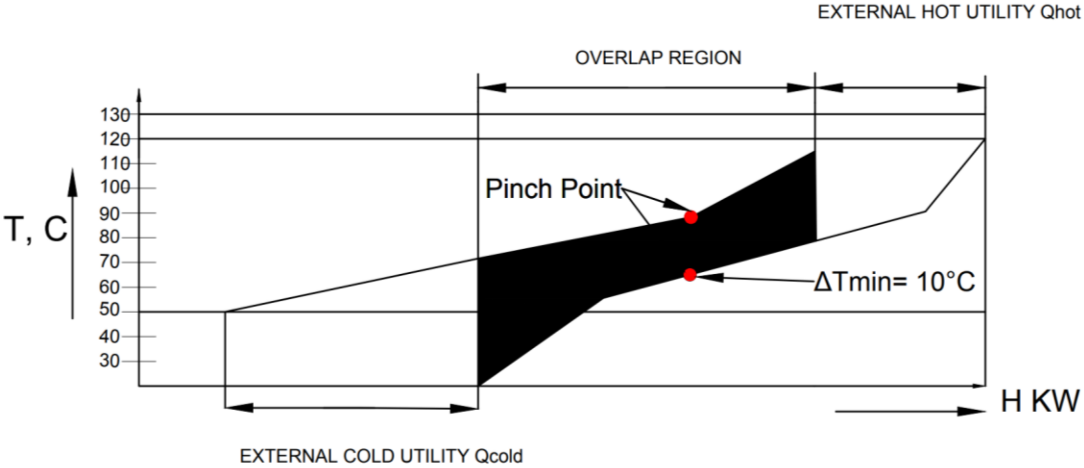

Figure 2.4: Overlap and Non-Overlap Regions

2.2.4. Estimation of minimum hot and cold utilities and defining of pinch point

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.

- **Construction of Composite Curves**

Transferring of all hot streams which presented in T-H diagram into one curve depending on summation of the streams loads of the same interval; this curve named as hot composite curve. By repeating this step with cold streams; we also get cold composite curve. The overlap region is the energy recovery limits while the non-overlaps are the required heating and cooling. We can move composite curves horizontally to change temperature difference which affects the utilities' loads and heat transfer area. While detecting ΔTmin value is realizing maximum energy recovery and minimum utilities. See Figures (2.5 &2.6)

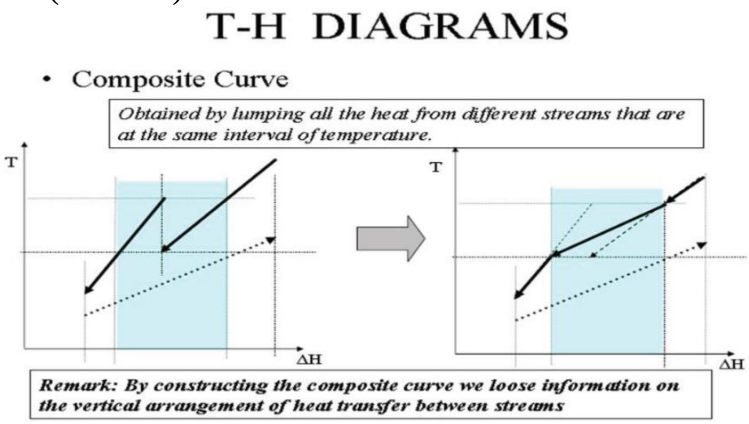

Figure 2.5: Construction of Composite Curves

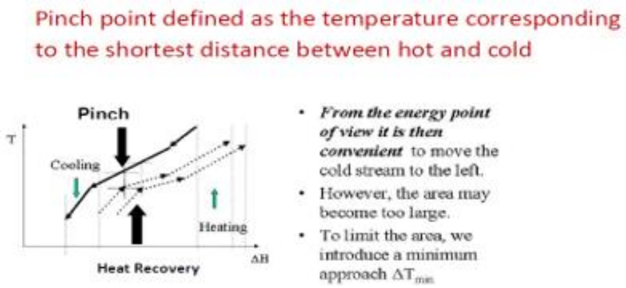

Figure 2.6: Definition of Pinch Point & control of ΔTmin by sliding cold composite curve

Grand Composite Curve

- The Grand Composite Curve (GCC) is a graphical representation of the heat cascade. Grand Composite Curve are based on the same process stream data as Composite Curves. Grand Composite Curves highlight the process interface.
- It gives clear visualization of hot and cold utility and provides an easy approach to use multiple utilities in the process.
- GCC is a plot of the net heat flow against the shifted (interval) temperature.
- It is also called residual heat curve.
- It highlights process/utility interface.
- It indicates the difference between the heat available from the process hot streams and the heat required by the process cold streams, relative to the pinch, at a given shifted temperature.
- GCC not only tells about how much net heating and cooling is required, but also provides an opportunity to find at what temperature level it is needed.

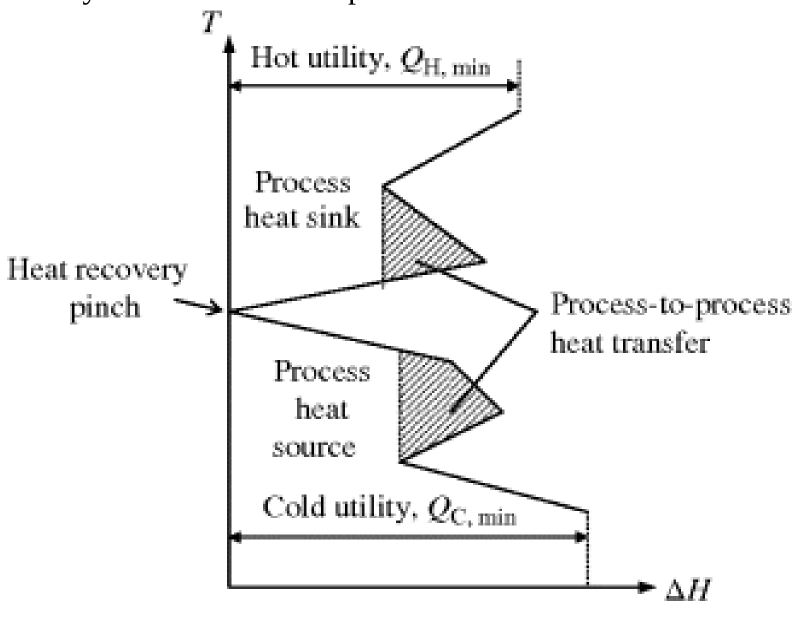

Figure 2.7: Grand Composite Curve.

2.2.5. Design of Heat Exchanger Network [HEN]

Using the pinch method incorporates two important features: a) it recognizes that the most constrained part of the problem is the pinch region and b) designers are allowed to choose between the match options. The designer examines which hot streams can be matched to the cold stream by heat recovery. Every match brings one stream to its target temperature and the pinch separates the heat exchanger systems into two thermally independent regions, heat exchange networks above and below pinch temperature. When the heat recovery is maximized, the remaining thermal needs are supplied by external heat utility.

However, it is important to remember some rules when designing the HEN:

- The network above and below the pinch shall be designed separately (independently)
- Start with placing a heat exchanger close to the pinch point and continue outwards
- Allow the heat exchangers transfer heat as much as possible
- The need of heat load for hot streams shall be satisfied above the pinch point.

For designing a heat exchanger network, the most helpful representation is the "grid diagram". The streams are drawn as horizontal lines, with high temperatures on the left and hot streams at the top; heat exchange matches are represented by two circles joined by a vertical line. The grid is much easier to draw than a flowsheet, especially as heat exchangers can be placed in any order without redrawing the stream system.

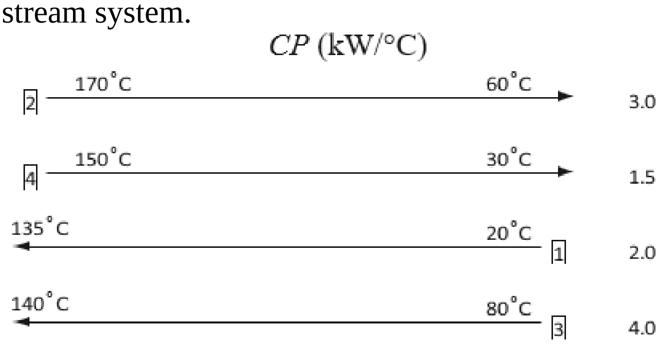

Figure 2.8: Initial grid diagram for four-stream problem

We will now produce a simple heat exchanger network for the four-stream problem and represent it on the grid diagram. Figure 2.8 shows the initial situation. We want to exchange heat between the hot and cold streams, and logically we should start at one end of the temperature range. Matching the hottest hot stream 2 against the hottest cold stream 3 should give the best temperature driving forces and ensure feasibility. If we match the whole of the heat load on stream 4 (240kW), we can calculate that stream 2 has been brought down to 90°C, which is just acceptable for the given ΔT_{min} of 10°C. Then we match stream 4 against stream 1, and find that we can use the whole of the 90kW in stream 4 while again achieving the ΔT_{min} 10°C criterion at the bottom end. This raises stream 1 to 65°C, so it needs an

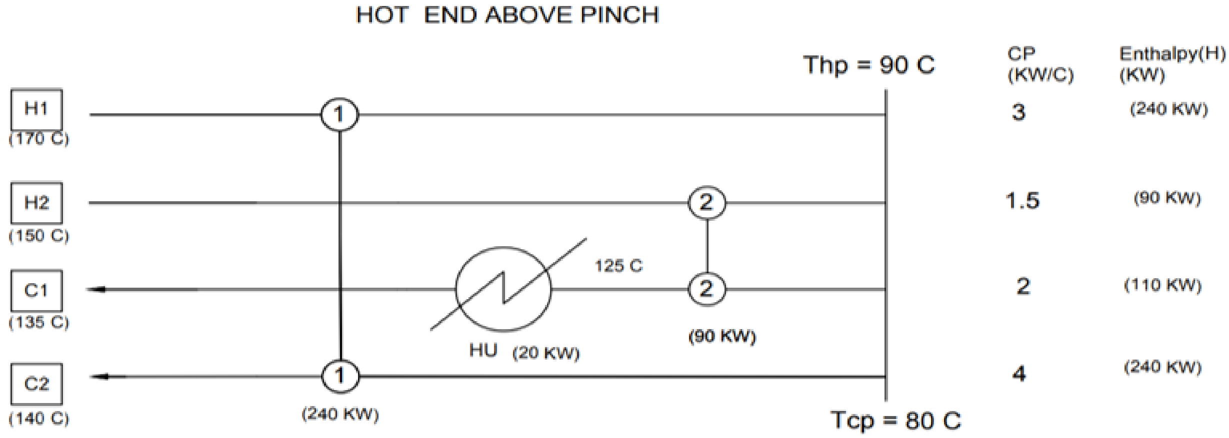

Figure 2.9: Above Pinch design for four-stream problem

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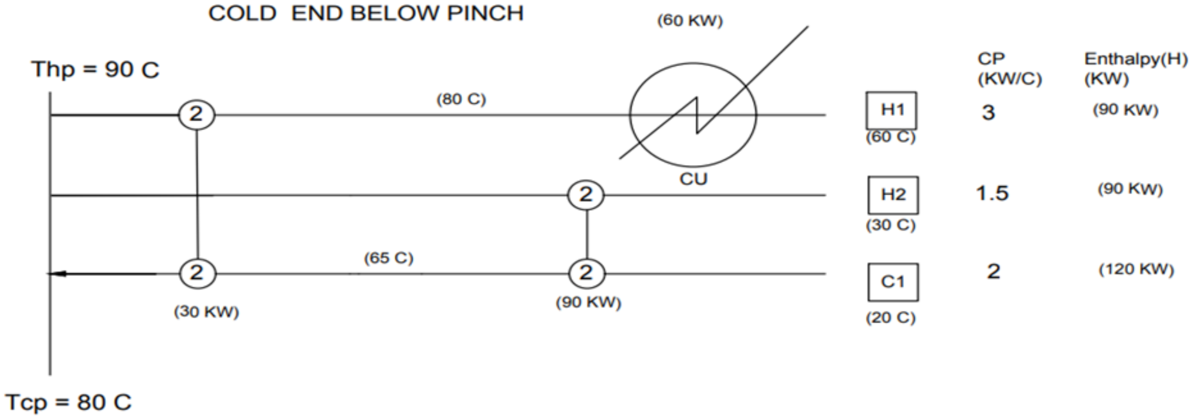

Figure 2.10: Below Pinch Design for four-stream problem

additional 20kW of hot utility to raise it to the required final temperature of 135°C. Finally, we add a cooler to stream 1 to account for the remaining 90kW required to bring it down to 60°C. The resulting design is shown as a network grid in Figure 2.9 and 2.10.

- **Loop Breaking and Path Identification**

In heat exchanger network design, loops and paths are important concepts that can help identify and address issues such as excess units and the need to restore driving forces. A loop is a set of connections that starts and ends at the same exchanger and can cause excess units. Heat loads can be shifted around the loop to break it, but this may violate the minimum temperature difference (ΔTmin).

A path is a connection between a heater and a cooler that allows for heat to be shifted along it. Load shifts along a path follow similar rules as those around a loop and can be used to restore driving forces. Operating temperatures and exchanger loads may be changed along a path**.**

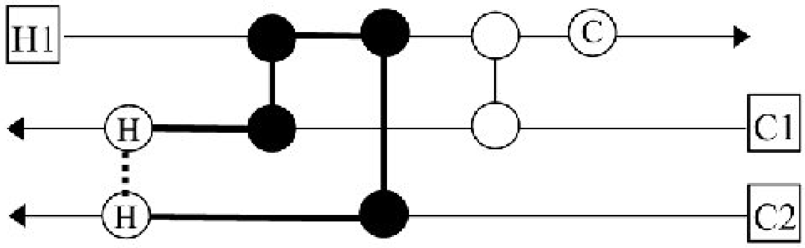

Figure 2.11: Identification of heat loop

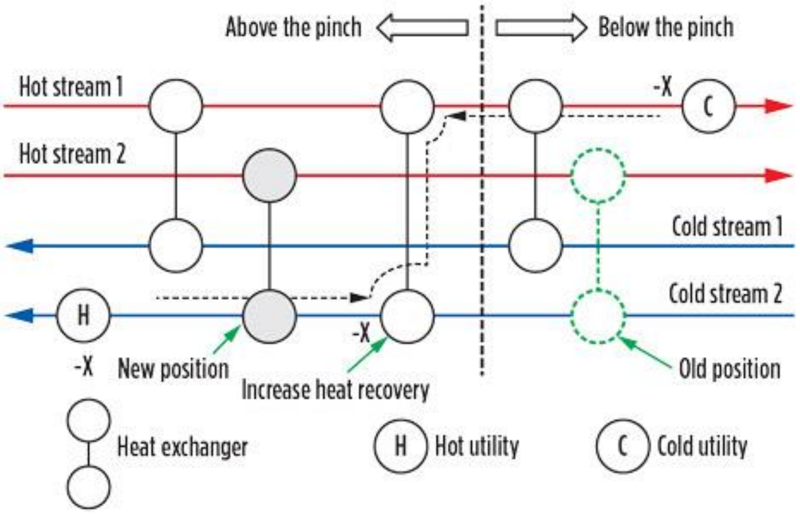

Figure 2.12: Loop breaking and path identification

2.2.6. Estimation of minimum energy cost target

Energy targeting is a method to identify energy savings in a process plant by evaluating the total energy that can be recovered and the amount of additional heating and cooling needed. It uses the hot and cold composite curves or problem table algorithms to assess energy saving opportunities prior to designing and retrofitting the heat exchanger network (HEN). Composite curves are graphical representations of energy recovery between process streams, plotted on a T-H diagram. By plotting temperature against enthalpy for individual streams, composite curves can be constructed to assess energy savings opportunities for the entire process. Energy targeting allows for plant-wide screening of processes to assess energy saving opportunities and evaluate both capital and energy costs for HEN design. By drawing the composite curves, we can estimate the Q_{Hmin} and Q_{Cmin} value which are the minimum energy targets.

2.2.7. Estimation of the capital cost target

The capital cost of HE is a measure of number of shells, heat exchanger type, heat exchanger area, and pressure rating. These factors can be extended to design of HEN with additional requirement such as number of units of HEs within a given network. The number units defined by independent loops (L) is, given by: $Nunits = S + L + C$**;** where $Nunits$ is the number of matches or units, S number of streams including utilities and C is the number of components.

Assume loop free network with single components, the equation becomes: $Nunits = S - 1$ can be applied to either side of the pinch point in the form below; $Nunits = [SABOVE\ THE\ PINCH - 1] + [SBELOW\ THE\ PINCH - 1]$.

In general, a HEN capital cost is minimized when the total number of HE units in the plant is kept at minimum number. The capital cost for a single HE is defined by the relationship below, $Installed\ Exchanger\ Capital\ Cost = a + bA$^c; where a, b, c are constants depending on material of constructions, rating and exchanger type respectively.

2.2.8. Identification of the optimum ΔTmin value

The economics of trade-off is important in determining the optimal value of the minimum temperature difference ($\Delta Tmin$) required for a feasible heat exchanger network (HEN) design. The value of $\Delta Tmin$ affects the amount of energy recovery and the size of the heat exchanger. Balancing the capital and operating costs is important as recovering all unused heat energy is not practical. Therefore, an optimal design with a feasible trade-off between capital and operating costs, including utility usage costs, is necessary.

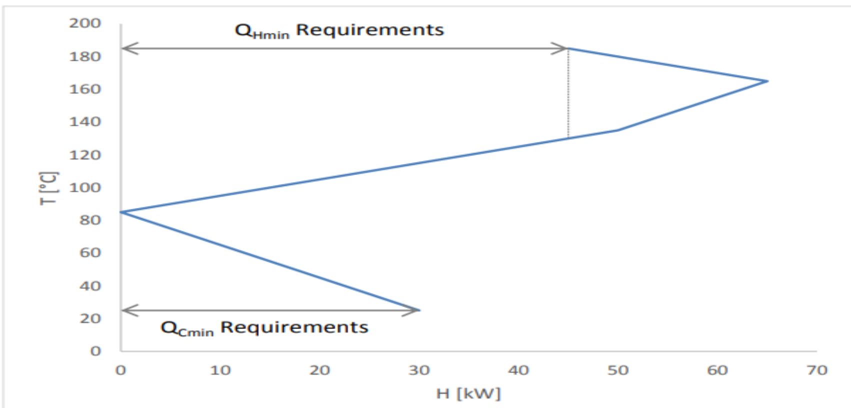

Figure 2.13: Identification of optimum $\Delta Tmin$ value

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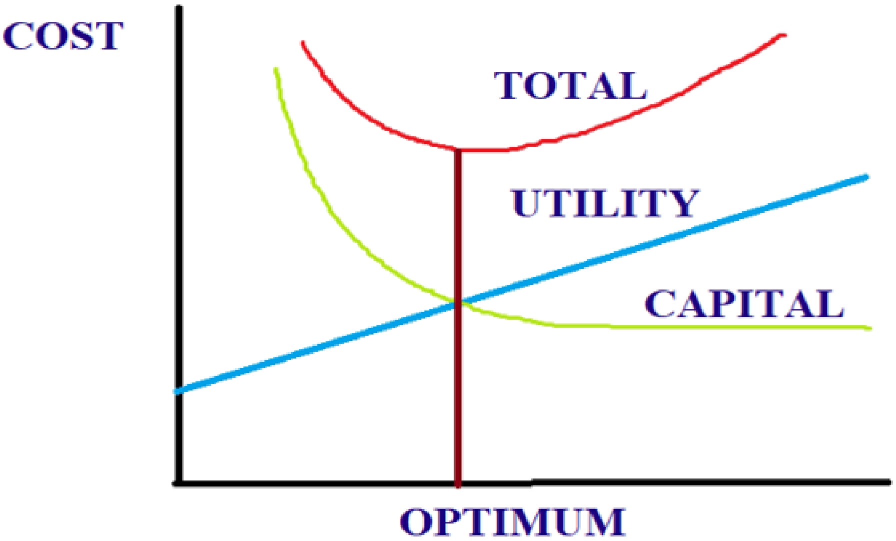


Figure 2.14: Trade-off between cost and optimum $\Delta Tmin$ value

A trade-off exists where the value of $\Delta Tmin$ for both energy and capital is at their minimum point; this point is regarded as the desirable $\Delta Tmin$ for HEN design. In above fig, the desirable $\Delta Tmin$ corresponds to the point of intersection between the line describing the cost of energy and that of the capital cost.

2.2.9. Design of the optimum Heat Exchanger Network [HEN]

Following trade-off optimization to identify the minimum temperature difference required for the design of cost-effective HEN, the network design using $\Delta Tmin$ which correspond to the minimum optimum temperature difference between the hot and cold composite curves can be formed.

III. THRESHOLD PROBLEM

Threshold problem only need a single thermal utility (either hot or cold but not both) over a given range of min. temperature difference (**ΔTmin**) ranging from zero to threshold temperature (T threshold).

CASE 1: WHEN COLD UTILITY IS ZERO

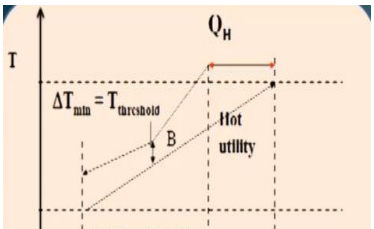


Figure 3.1. shows it requires only one utility i.e., hot utility of Q_H amount at **ΔTmin=T threshold**.

Figure 3.1: When Cold Utility Is Zero

Once **ΔTmin > T threshold** the hot and cold utility demand increases and is a function of **ΔTmin**. Physically it is shown by the position of the cold composite curve at "C" and "D".

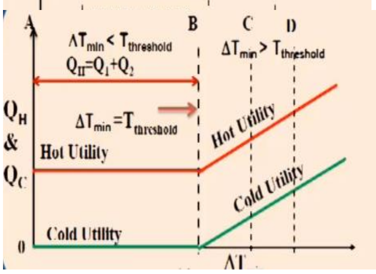


Figure 3.2: Threshold Temperature when Cold Utility Is Increasing (ΔT min > ΔT threshold)

CASE 2: WHEN HOT UTILITY IS ZERO

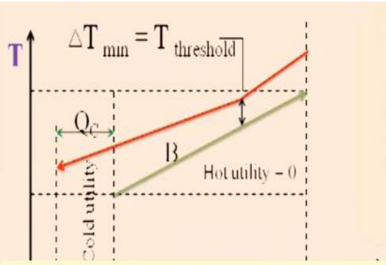
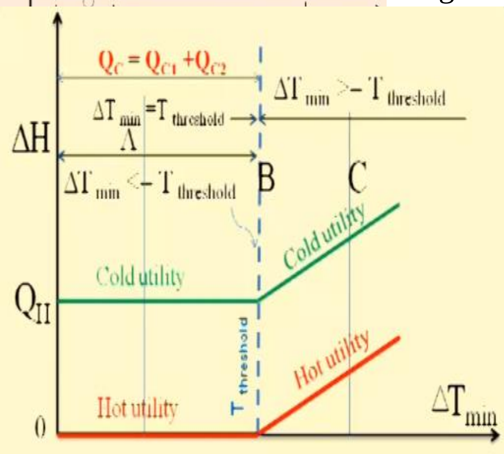


Figure 3.3. shows a threshold problem for which hot utility is zero. It only demands cold utility up to **T threshold**.

Figure 3.3: When HOT Utility Is Zero



At position "B" which is at **ΔTmin = T threshold** the hot utility demand is zero whereas the cold utility demand is Q_C. When the cold composite is shifted to position "A" where **ΔTmin < T threshold** it demands Q_{C1} cold utility at a higher level and Q_{C2} cold utility at a lower level. Where the sum of Q_{C1} and Q_{C2} being equal to Q_C. For the "C" position where, **ΔTmin > T threshold** the process demands both cold and hot utilities. Thus, in this case also for Δ**Tmin < T threshold** the cold utility demand is constant and hot utility demand is zero.

Figure 3.4: Threshold Temperature when Hot Utility is Increasing (ΔT min >ΔT threshold)

IV. APPLICATION OF PINCH ANALYSIS TECHNIQUE: A CASE STUDY

Application of Pinch technique on a case study with a plant flowsheet shown in Figure 4.1, 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.

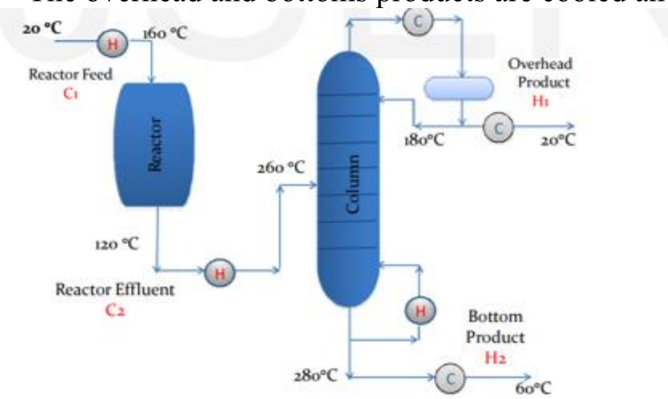


Figure 4.1: Typical Plant Flowsheet of the Case Study

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ISSN: 0970-2555
Volume : 53, Issue 2, No. 5, February : 2024

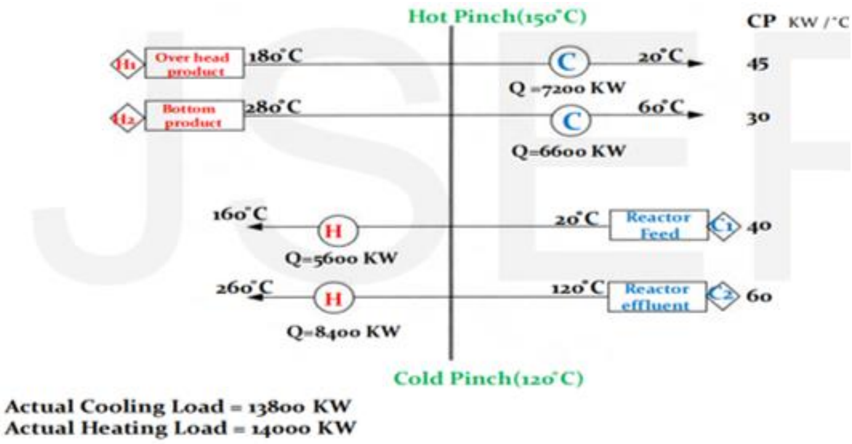

Figure 4.2: Grid Diagram of the Flowsheet

Beginning for HEN design I represent the streams in the form of grid diagram as shown in where the actual consumption of external utilities is:

Heating load = 14000 Kw

Cooling load = 13800 Kw

First the heat content of each stream is determined using the formula **mCpΔT**.

Heating load and Cooling load is determined by adding the heat contents of hot and cold streams respectively.

Table 4.1: Thermal and Physical properties of Streams

Stream No.	**Stream Name**	**T_s°C**	**T_t °C**	**CP (kW/°C**
C1	Reactor Feed	20	160	40
C2	Reactor Effluent	120	260	60
H1	Overhead Product	180	20	45
H2	Bottom Product	280	60	30

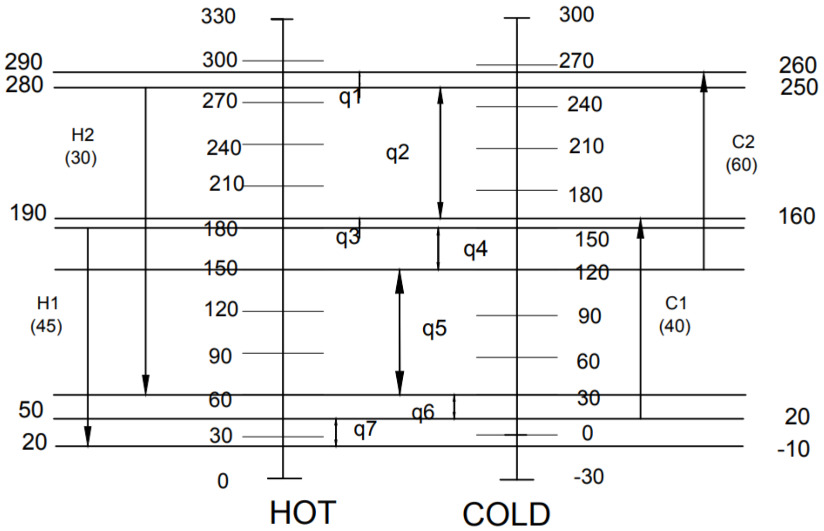

Figure 4.3: Temperature Interval (TI) Diagram for Given Case

Temperature Interval (TI) diagram is drawn with two scales, one for hot stream and other for cold stream. Both temperature scales should be shifted by temperature equal to $\Delta Tmin$ i.e., if $\Delta Tmin$ is 'x' ºC then starting temperature scale for hot stream scale should be more by 'x' ºC than that of cold stream scale. Then both hot and cold streams are drawn on their respective scale side with head and tail. Difference between two horizontal lines is the temperature interval. Heat content of each temperature interval is calculated using the formula, $[\Sigma(mCp)_{hoti} - \Sigma (mCp)_{coldi}] \times \Delta Ti$

Next, the **cascade diagram** is drawn to find the minimum hot utility (QHmin) and minimum cold utility (QCmin) as well as pinch temperature.

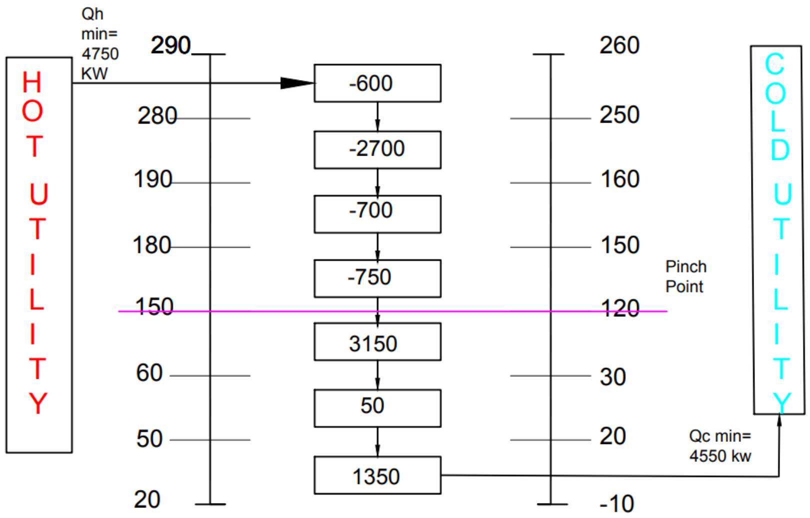

Figure 4.4: Cascade Diagram for Given Case

Pinch temperature is the temperature at which there is no heat transfer taking place.

$Q_{H\ min}$ = 4750 kW; $Q_{C\ min}$ = 4550 kW

Pinch temperature: Hot pinch = 150°C; Cold pinch = 120°C; Average pinch = 135°C

- **Finding pinch, QHmin and QCmin from Grand Composite Curves (GCC)**

Grand Composite curves can be drawn using Temperature Interval (TI) Diagram

Table 4.2: Data for Hot Temperature Enthalpy Curve

	X	Y
	0	20
	1350	50
	1800	60
Hot T-E Curve	8550	150
	10800	180
	1100	180
	3800	280
	3800	290

Table 4.3: Data for Cold Temperature Enthalpy Curve

	X	Y
	4550	-10
	4550	20
	4950	30
Cold T-E Curve	8550	120
	11550	150
	12550	160
	17950	250
	18550	260

Table 4.4: Data for Cumulative Temperature Enthalpy Curve

Average Temperature (Ti)	**Cumulative Enthalpy (H cum)**
5	4550
35	3200
45	3150
135	0
165	750
175	1450
265	4150
275	4750

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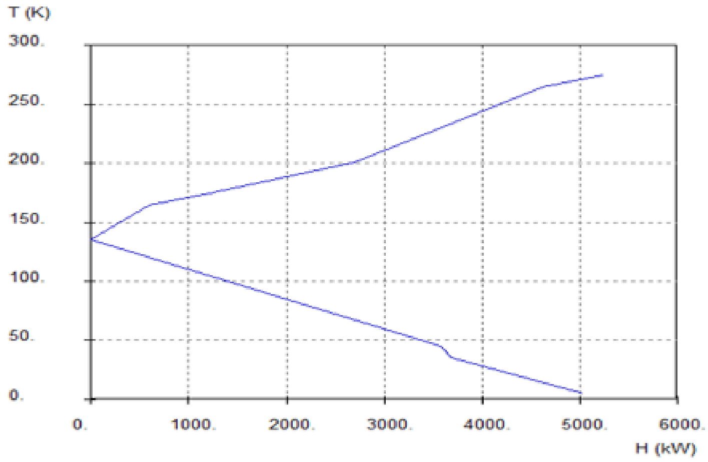

Figure 4.5: Grand Composite Curve

By applying pinch technique sequences for HEN designing alternate designs are drawn taking into consideration the steps and rules required to design a network. One of such alternative design of HEN is shown below in figure 4.6. It satisfies minimum utility target

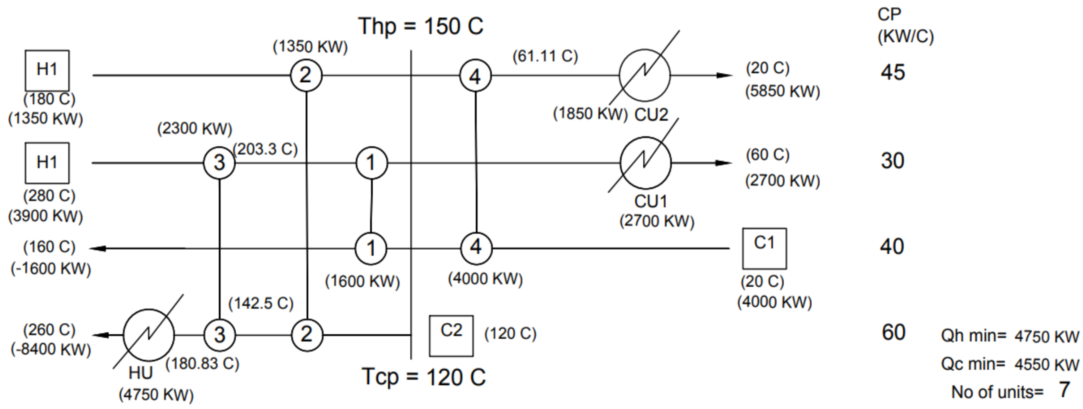

Figure 4.6: HEN above and below Pinch Satisfying Minimum Utility Target

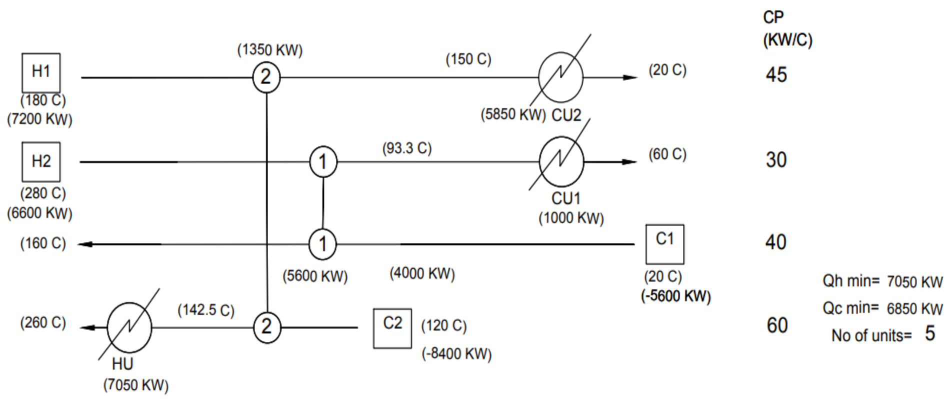

Figure 4.7: Modified HEN with minimum number of HEx after loop breaking

The design achieved minimizing of utilities and as a result of combination; loops appear due to match repeating between the same streams as represented. In this case, modification of design by breaking the loop is required by replacing two heat exchangers with one to minimize the units 'number and so on reduce capital cost as shown in figure 4.7

V. ECONOMIC ANALYSIS OF HEN DESIGN

Annual overall cost of HEN = Annualised capital cost + Annual operating cost
Where;
*Annualized capital cost = Capital cost of units / life time
* Capital cost of units = 8600 + 670 (Area)$^{0.83}$ m^2

Area = $\frac{Q}{U*\Delta TLm}$ Where: Q = Heat load of unit; kW
U = Heat transfer coefficient, kW/m^2 °C
$\Delta T L_m = (T1 - t2) - (T2 - t1) / \ln [(T1 - t2) / (T2 - t1)]$

Where: T1 = Inlet temperature of hot stream; T2 = Outlet temperature of hot stream
t1 = Inlet temperature of cold stream; t2 = Outlet temperature of cold stream

Life time = 6 years
Cost of piping = 8% of installed cost equipment.

Data: Cooling water (CW): Ts = 10°C, Tt = 30°C, Price = Rs. 0.0001/kg
Steam: Ts = 300°C, Tt = 300 °C, Price = Rs. 0.04/ kg, λ = 2257 kJ/kg
Overall heat transfer coefficient: $U_{exchanger}$ = 0.2kW/m^2°C; Operating Hours = 8500 Hrs/Year

Before Loop breaking

Revamped HEN		
	Before Loop Breaking	**After Loop Breaking**
Capital cost (₹)	**₹ 10,11,469.98**	**₹ 9,16,003.64**
Operating cost (₹/yr.)	27,41,735	40,72.840
Total Annualized Cost(₹/yr.)	29,10,313.98	42,25,507.64

Table 4.5: Cost estimation of HEN before loop breaking

After Loop Breaking

Table 4.6: Cost estimation of HEN after loop breaking

Heat Exchanger	Area of HT (m^2)	Capital Cost (₹)
1 – 1	295.76	83927.67
2 – 2	200.83	63228.90
Heater	1370.58	277570.99
Cooler	295.50	83872.70
Cooler	2202.89	407403.38
	TOTAL	**₹ 9,16,003.64**

Revamping of the Case Study through Heat Recovery Technique

As a new design for the case study; the 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 the cost. The modification is adding of four heat exchangers of 1350 KW, 2300 KW, 1600KW, 4000KW. Maximum energy recovery realized where external heating reduced from 13800 to 4750 KW and external cooling reduced from 14000 to 4550 KW.

Table 4.7: Cost Equating before and after addition of Heat Exchanger

	Existing System of Heating and Cooling	**Revamped HEN (Before Breaking Loop)**
Hot Utility (kW)	13800	4750
Cold Utility (kW)	14000	4550
Cost of Hot Utility (₹/yr.)	92,33,580	25,75,985
Cost of Cold Utility (₹/yr.)	4,74,320	1,65,750
Operating Cost (₹/yr.)	97,07,900	27,41,735
Saving on Operating Cost (₹/yr.)	----------	**69,66,165**
Capital Cost (₹)	----------	**10,11,469.98**
Total Annualized Cost (₹/yr.)	----------	**29,10,313.98**

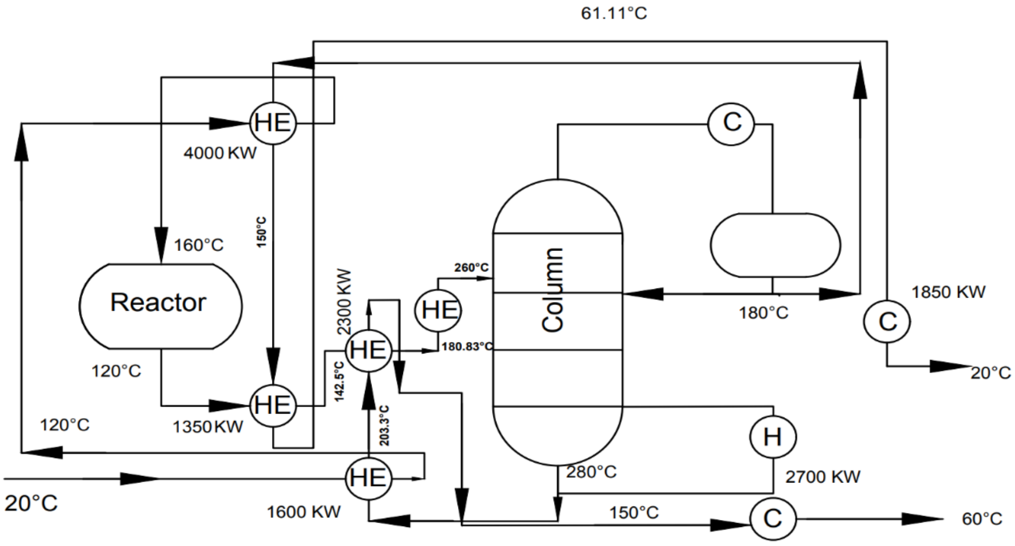

Figure 4.8: Redesigned problem flow sheet after HEN among process streams

VI. 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 proved its validity through its application to a case study where percentage of utilities' saving reached to 65.7 % & 67.5% for hot utility and cold utility respectively. Maximum energy saving is realized where external heating reduced from 13800 to 4750 kW and external cooling reduced from 14000 to 4550 kW. Further heat loop can be broken to decrease number of heat exchangers in HEN and thus reduces capital cost, however increases utility requirement and hence its cost.

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