CHEM-F266

Study Project Report

Heat Exchanger Network Analysis [HEN]

Submitted By

Aryan Choudhary	**2019A1PS1053G**
Satvik Sandeep Dhumale	**2019A1PS1061G**
Vedang Millind Phadke	**2019A1PS0701G**

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Abstract

This report covers the explanation of heat exchange network which exploits excess heat by integrating process hot and cold streams and improves energy efficiency by reducing utility usage and developed a code which performs first law analysis and pinch analysis on the input stream data and provides the necessary results for inferring the maximum heat recovery and minimum energy consumption in the effort to increase economic feasibility.

The generic assumptions and heuristics for the mathematical approach to heat exchange network analysis were assumed. Python was used to develop the code using the libraries - Pandas, NumPy, Matplotlib, SciPy and PyPinch. Pinch temperature, hot and cold utility and composite curves were assessed by the code. The mathematics required for building an optimization algorithm for solving the minimum matches problem to find the minimum number of heat exchangers was explained.

Introduction to Heat Exchangers

Heat exchangers are devices used to transfer heat from a hot fluid to a cold fluid. They are based on the principle of convective heat transfer. Convection is a mode of heat transfer by which heat is transferred between two flowing fluids due to the bulk fluid motion.

The basic types of heat exchangers are explained as follows:

1) **Double pipe heat exchanger**: The double pipe heat exchanger is, in its simplest form, one pipe held concentrically inside of a larger pipe (thus the name “double pipe”). The inner pipe acts as the conductive barrier, where one fluid flows through this inner pipe and another flows around it through the outer pipe, forming an annulus shape. The outside or “shell side” flow passes over the inside, or “tube side” flow, which will cause heat exchange through the inner tube’s walls.

2) **Shell and tube heat exchange**r: The main constituents of this type of heat exchanger seem to be the tube box, shell, the front rear end headers, and baffles or fins. The baffles are used to support the tubes, direct the fluid flow to the tubes in an approximately natural manner, and maximize the turbulence of the shell fluid. There are many various kinds of baffles, and the choice of baffle form, spacing, and geometry depending on the allowable flow rate of the drop in shell-side force, the need for tube support, and the flow-induced vibrations. There are several variations of shell-and-tube exchangers available; the differences lie in the arrangement of flow configurations and details of construction. In application to cool air with shell-and-tube technology (such as intercooler / Charge air cooler for combustion engines), fins

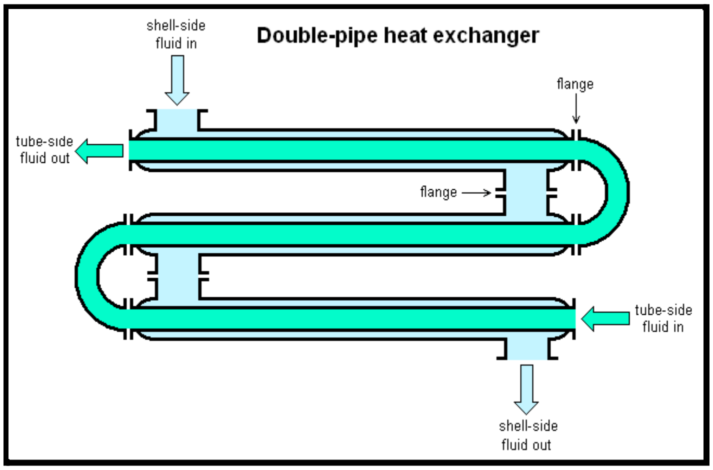
can be added on the tubes to increase heat transfer area on the air side and create a tubes & fins configuration.

3) **Plate Heat Exchanger** A plate heat exchanger contains an amount of thin shaped heat transfer plates bundled together. The gasket arrangement of each pair of plates provides two separate channel systems. Each pair of plates form a channel where the fluid can flow through. The pairs are attached by welding and bolting methods. The following shows the components in the heat exchanger. In single channels the configuration of the gaskets enables flow through. Thus, this allows the main and secondary media in counter-current flow. A gasket plate heat exchanger has a heat region from corrugated plates. The gasket functions as a seal between plates and they are located between frame and pressure plates. Fluid flows in a counter current direction throughout the heat exchanger. An efficient thermal performance is produced. Plates are produced in different depths, sizes and corrugated shapes. There are different types of plates available which include plate and frame, plate and shell and spiral plate heat exchangers. The distribution area guarantees the flow of fluid to the whole heat transfer surface. This helps to prevent stagnant areas that can cause accumulation of unwanted material on solid surfaces. High flow turbulence between plates results in a greater transfer of heat and a decrease in pressure.

4) **Condensers and Boilers Heat exchangers** using a two-phase heat transfer system are condensers, boilers and evaporators. Condensers are instruments that take and cool hot gas or vapor to the point of condensation and transform the gas into a liquid form. The point at which liquid transforms to gas is called vaporization and vice versa is

called condensation. Surface condenser is the most common type of condenser where it includes a water supply device.

Given below is a schematic diagram of common heat exchangers→



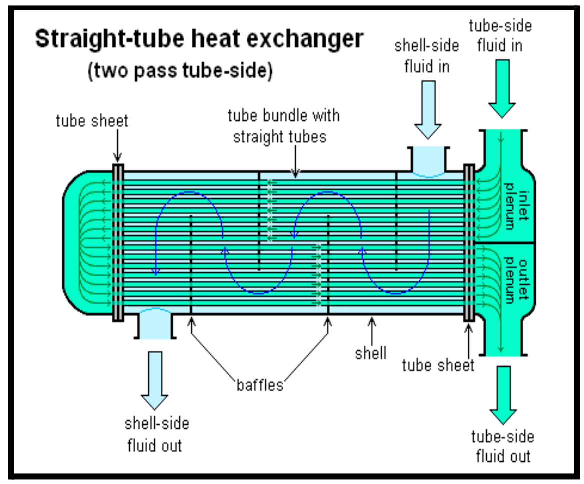


Fig 1: Double Pipe HE

Fig 2: Shell & Tube HE

Heat Exchanger Network

Heat exchanger networks are a series of heat exchangers used to transfer a large amount of heat energy from multiple hot streams to multiple cold streams.

Fig 3: Heat Exchanger Network

An in depth analysis of heat exchanger networks is needed to determine the following →

1) The heating and cooling requirements of the network
2) The pinch temperature
3) The number of heat exchangers.

The analysis is started by creating a table specifying the inlet and outlet temperatures of the hot and cold streams and their respective FCp values to calculate the heat transferred to/from each stream. This is followed by a first law analysis to determine the actual amount of heat needed to be supplied/extracted from the HEN. But First – law calculation does not consider the fact that we can transfer heat from a hot stream to a cold stream only if

Temperature of hot stream > Temperature of cold stream.

Hence, we need to keep a constant temperature difference between the two streams.

The *first step* is to plot the hot and cold streams for the HEN on a graph. The arrows should point in the direction in which the stream is traveling.

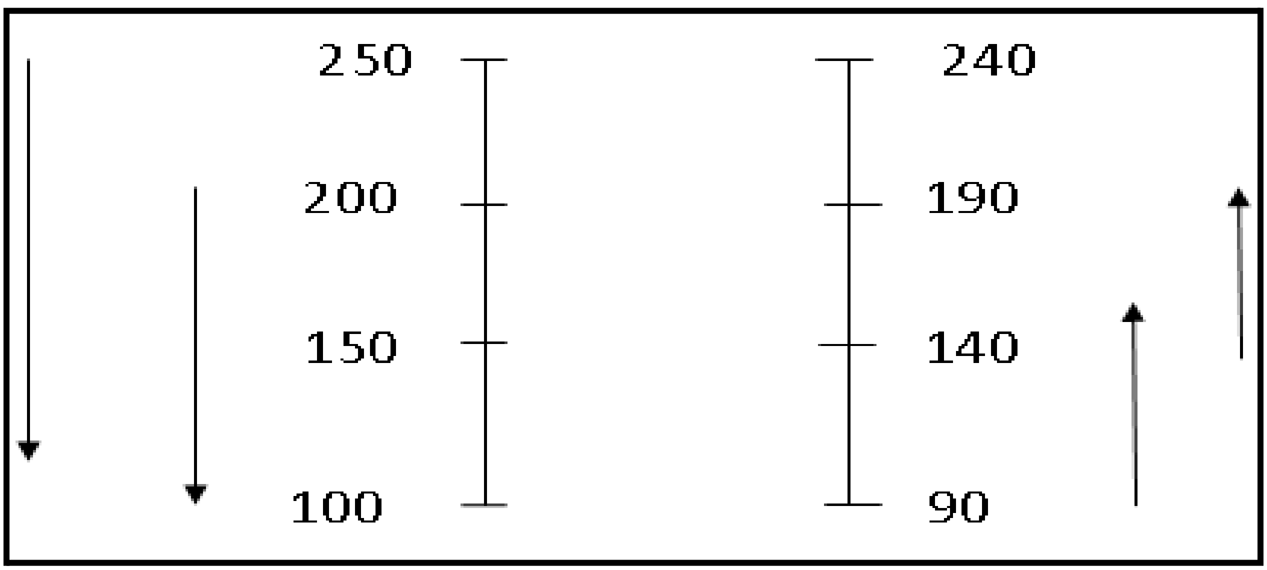


Fig 4: Hot and Cold streams plot

The *next step* is to establish a series of temperature intervals that correspond to the heads and the tails of the arrows on a graph i.e. inlet and outlet temps of the hot and cold streams given.

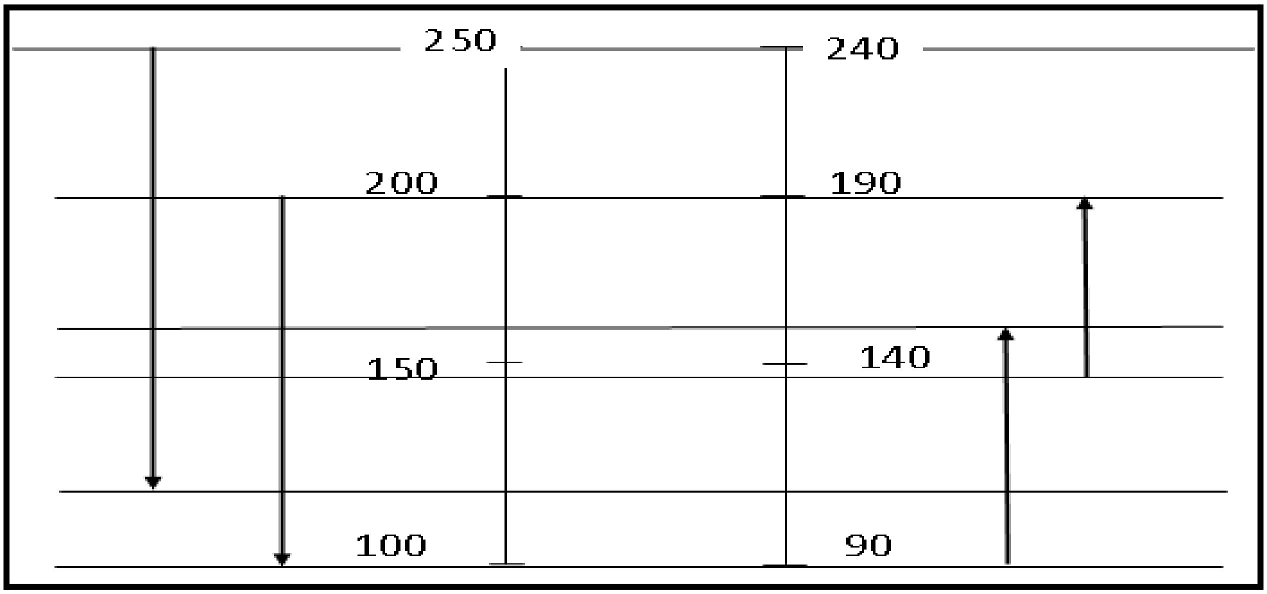


Fig 5: Temperature Interval Diagram

Next, we create a cascade diagram and plot the heat transfer between all the intervals. This is needed to determine the cooling and heating requirements. The temperature interval where no heat transfer occurs is classified as the pinch temperature. Its value is the average value of the hot and cold streams. The pinch temperature is extremely important in HEN analysis as the network is divided into two parts. One part above the pinch interval and the other part below the pinch temperature. **NO HEAT IS TRANSFERRED ACROSS THE PINCH.** The heat transferred above and below the pinch is recorded.

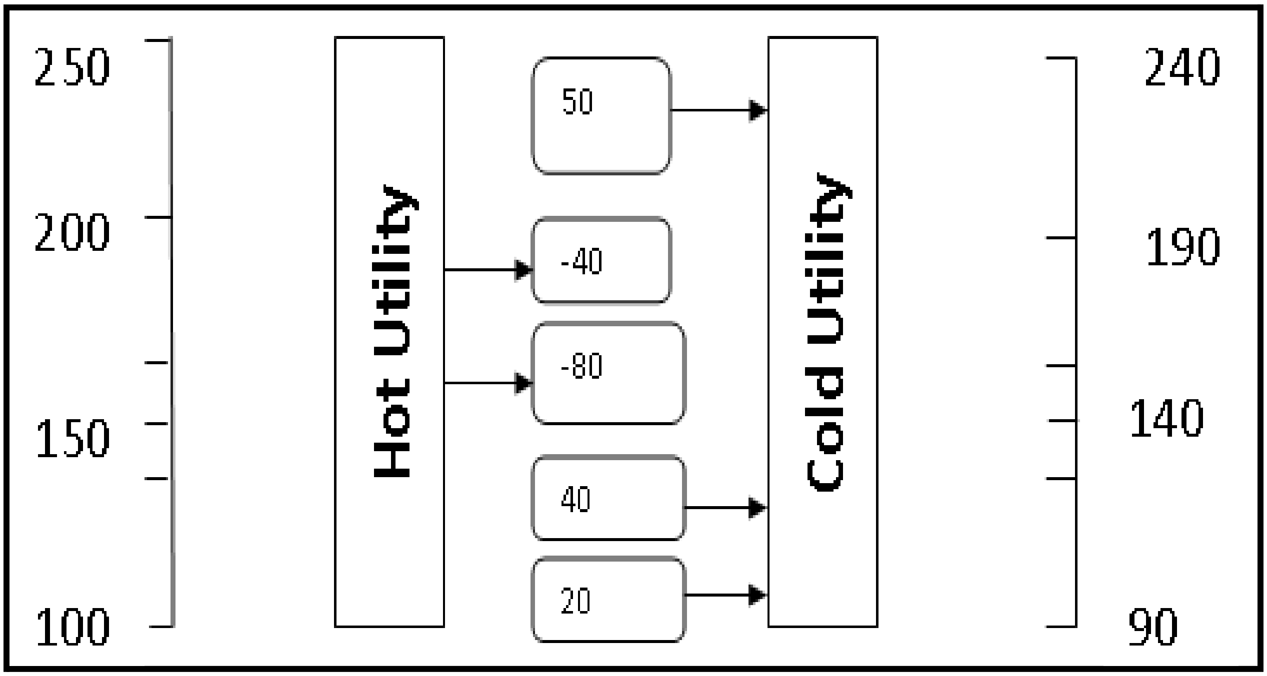


Fig 6: Heat cascade diagram

Next step is plotting a grand composite curve. Within each temperature interval, the grand composite curve provides a graphical representation of the extra heat accessible to a process. We cascade heat to lower temperature intervals in intervals where there is a net heat excess. Once we've met the demand for heat at lower temperatures, we use cooling utilities to remove the leftover heat at regular times. We utilise the excess heat from higher temperature periods first in intervals where there is a net heat deficit. We employ heating utilities just when we've exhausted heat surpluses from higher temperature intervals.

Developing the Code

1. **Importing Libraries and Module**

   Pandas, NumPy, Matplotlib and SciPy libraries are imported along with the PyPinch module.

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy import interpolate
from PyPinch import PyPincha
```

2. **Providing Data and Specifications**

   - The data is provided by the relative path of the CSV file.
   - The '*draw*' is specified for PyPinch to draw Matplotlib based plots.
   - An *input_table* variable is created using Pandas for Pinch Analysis.

```
options = {'draw'}
pinch = PyPinch('./streams/streams.csv', options)
input_table=pd.read_csv('./streams/streams.csv', skiprows=1)
```

The data is provided in the following format to PyPinch and *input_table* →

Tmin	10	
FCP	**TSUPPLY**	**TTARGET**
1000	250	120
4000	200	100
3000	95	150
6000	130	190

Table 1: Sample data

Tmin is the minimum temperature difference decided for pinch analysis.
FCP is the flow rate of the stream.
TSUPPLY is the supply temperature of the stream.
TTARGET is the target temperature of the stream.

3. Formating *input_table*

The data is formatted for proper analysis of *input_table*

```
input_table["Stream Type"] = \
np.where(input_table[" TSUPPLY"]>
input_table[" TTARGET"],"HOT","COLD")

input_table["Heat Capacity Flowrate(kW/K)"] =  \
round(input_table["CP"],2)

index=[]
```

```
for n in range(1,len(input_table)+1):
    index.append(n)

input_table["Stream Number"] = index
Input_table = input_table.set_index('Stream Number')
Input_table = input_table.rename(columns={" TSUPPLY": "Ts",
" TTARGET": "Tt", "Heat Capacity Flowrate (kW/K)":"FCp"})

hot_streams=input_table[input_table["Stream Type"]=="HOT"]
cold_streams=input_table[input_table["Stream Type"]=="COLD"]

Tmin=20    # explicitly mentioned for analysis
```

The formatted table looks as follows →

Stream Number	CP	Ts	Tt	Stream Type	FCp
1	1000	250	120	HOT	1000
2	4000	200	100	HOT	4000
3	3000	90	150	COLD	3000
4	6000	130	190	COLD	6000

Table 2: Formatted input_table

4. **Plotting the temperature Interval**

The PyPinch method is called to construct the temperature interval diagram.

The *shiftTemperatures()* method is called to shift the supplied temperatures →

Hot Streams ($T_S > T_T$) shift by $-\ \Delta Tmin/2$

Cold Streams ($T_T < T_T$) shift by $+\ \Delta Tmin/2$

```
pinch.shiftTemperatures()
pinch.constructTemperatureInterval()
pinch.showPlots()
```

The resulting temperature interval plot (for data above[Table 2]) →

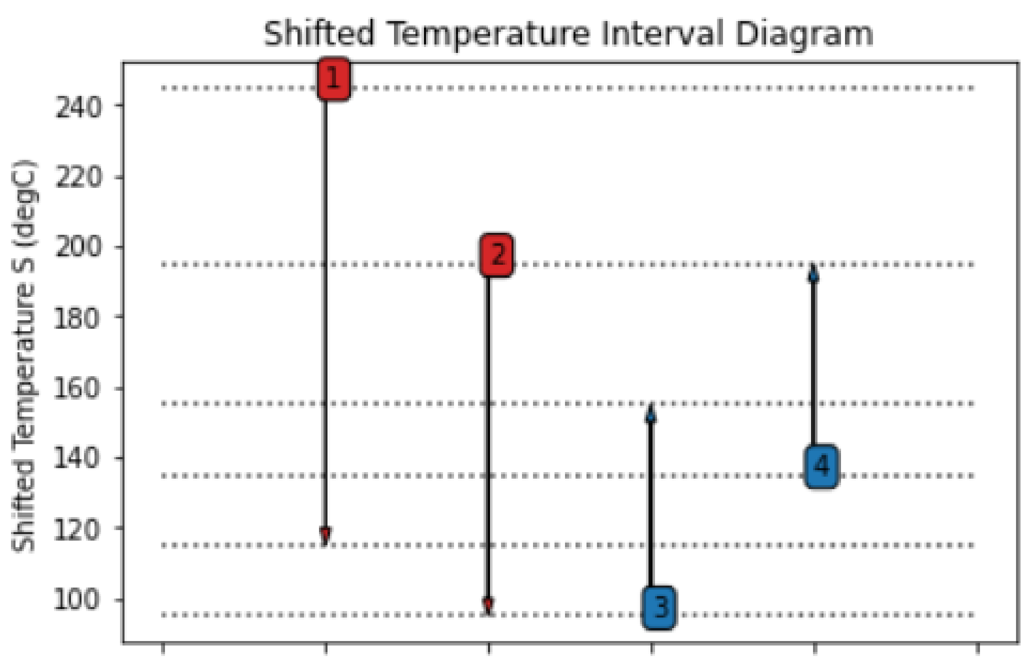


Fig 7: Temperature Interval Diagram(Program)

Here,

The streams 1 and 2 mark the hot streams.

The streams 3 and 4 mark the cold streams.

5. Creating the Problem Table/ First Law Analysis

The problem table calculates the enthalpy deficient/surplus for the intervals created in the temperature interval.

```
pinch.constructProblemTable()
pinch.showPlots()
```

$Interval: S_i - S_{i+1}$	$\Delta S(°C)$	$\Delta CP(kW/°C)$	$\Delta H(kW)$	
1: 245.0 - 195.0	50.0	1000.0	50000.0	Surplus
2: 195.0 - 155.0	40.0	-1000.0	-40000.0	Deficit
3: 155.0 - 135.0	20.0	-4000.0	-80000.0	Deficit
4: 135.0 - 115.0	20.0	2000.0	40000.0	Surplus
5: 115.0 - 95.0	20.0	1000.0	20000.0	Surplus

Table 3: Interval Enthalpy Analysis

ΔS is the temperature difference for the interval

6. Cascade Analysis

PyPinch is used to perform cascade analysis.

```
pinch.constructHeatCascade()
pinch.showPlots()
```

Unfeasible Heat Cascade

		Hot Utility: 0
Interval	$\Delta H(kW)$	Exit H (total kW)
1	50000.0	50000.0
2	-40000.0	10000.0
3	-80000.0	-70000.0
4	40000.0	-30000.0
5	20000.0	-10000.0
		Cold Utility: -10000.0

Feasible Heat Cascade

		Hot Utility: 70000.0
Interval	$\Delta H(kW)$	Exit H (total kW)
1	50000.0	120000.0
2	-40000.0	80000.0
3	-80000.0	0.0
4	40000.0	40000.0
5	20000.0	60000.0
		Cold Utility: 60000.0

Table 4: Cascade Analysis (Program)

Here,

The *Unfeasible Heat Cascade table* shows the enthalpies for the intervals as per the temperature interval diagram excluding the heat utility requirements.

The Feasible Heat Cascade table shows the enthalpies for the intervals as per the temperature interval diagram including the heat utility requirements that need to be fulfilled.

7. **Finding Pinch Temperature**

The pinch temperature is saved in the *pinch.pinchTemperature*

```
pinch.pinchTemperature
```

For data from Table 1 the pich temperature was found to be 135 C.

8. **Pinch in Grid Representation**

The *Pinch_in_the_grid_representation()* is used to display the pinch position in the interval diagram [the function code is included in the file attached]

The following diagram is for the data given above(Table 2) →

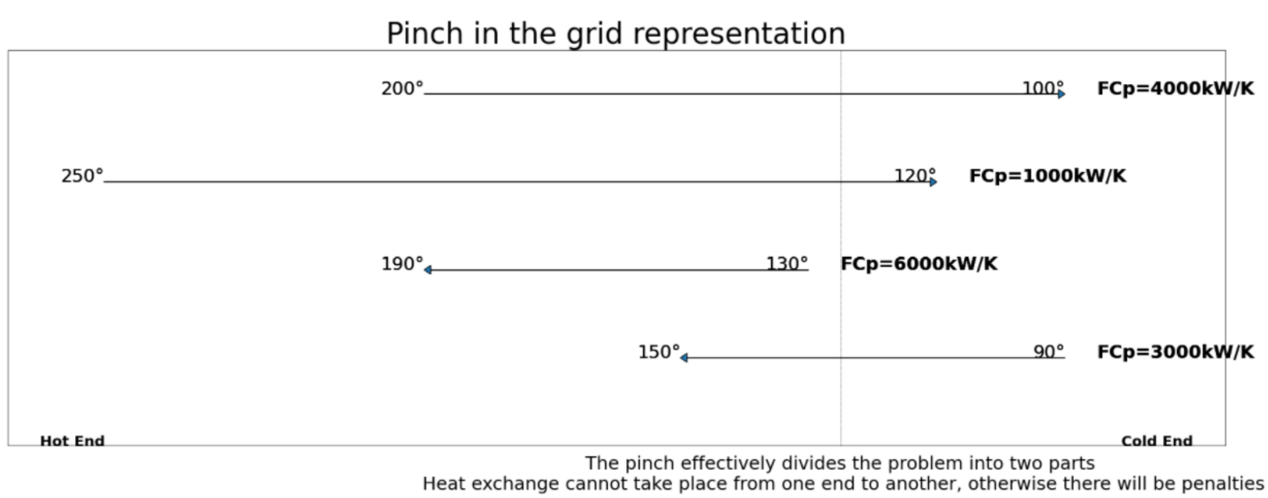


Fig 8: Pinch in Grid Representation

This graph visualizes the location of the pinch as per the temperature interval diagram.

9. Constructing Composite Curves

```
pinch.constructShiftedCompositeDiagram()
pinch.constructCompositeDiagram()
pinch.constructGrandCompositeCurve()
```

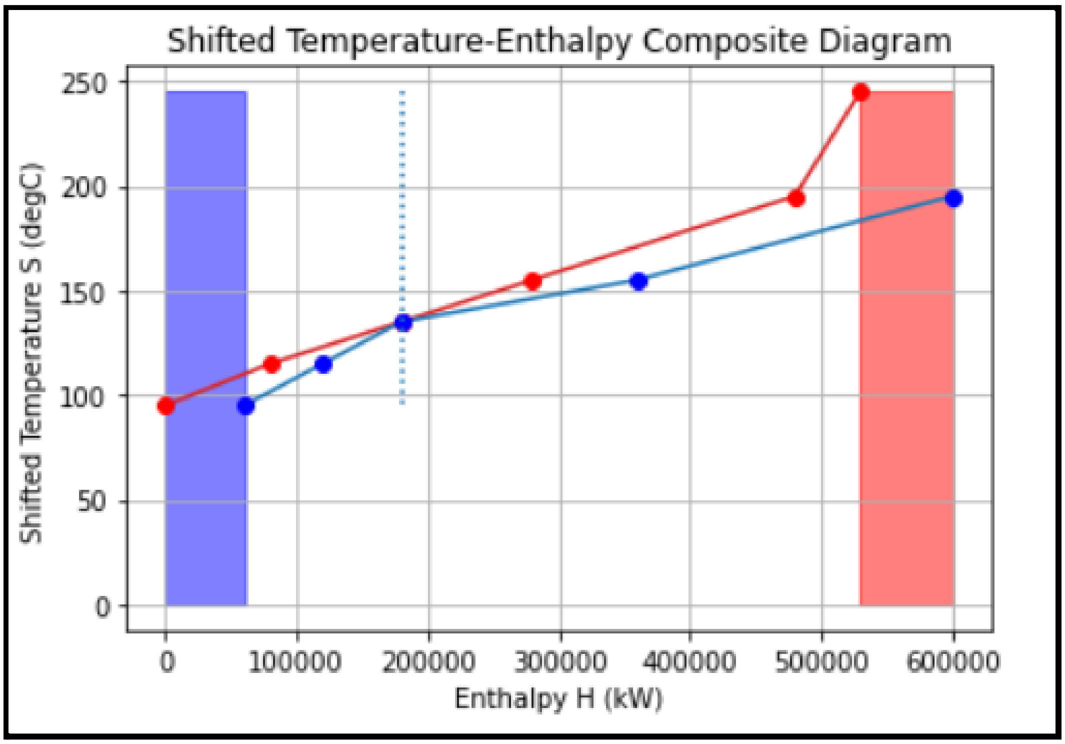


Fig 9: Hot Composite Curve

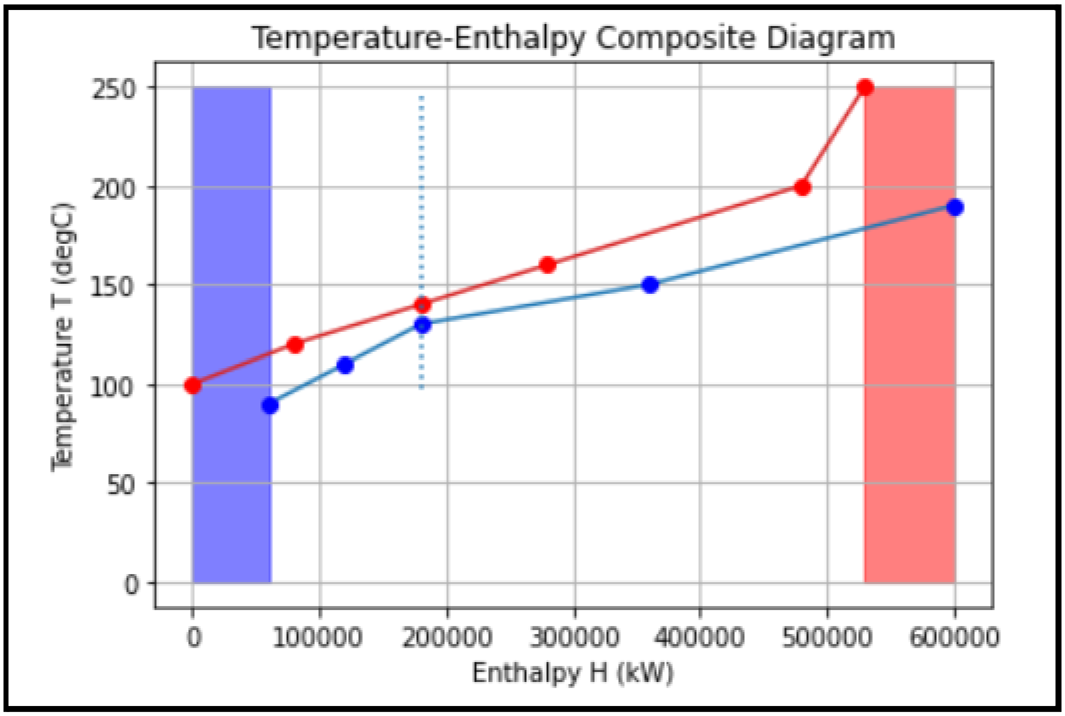


Fig 10: Cold Composite Curve

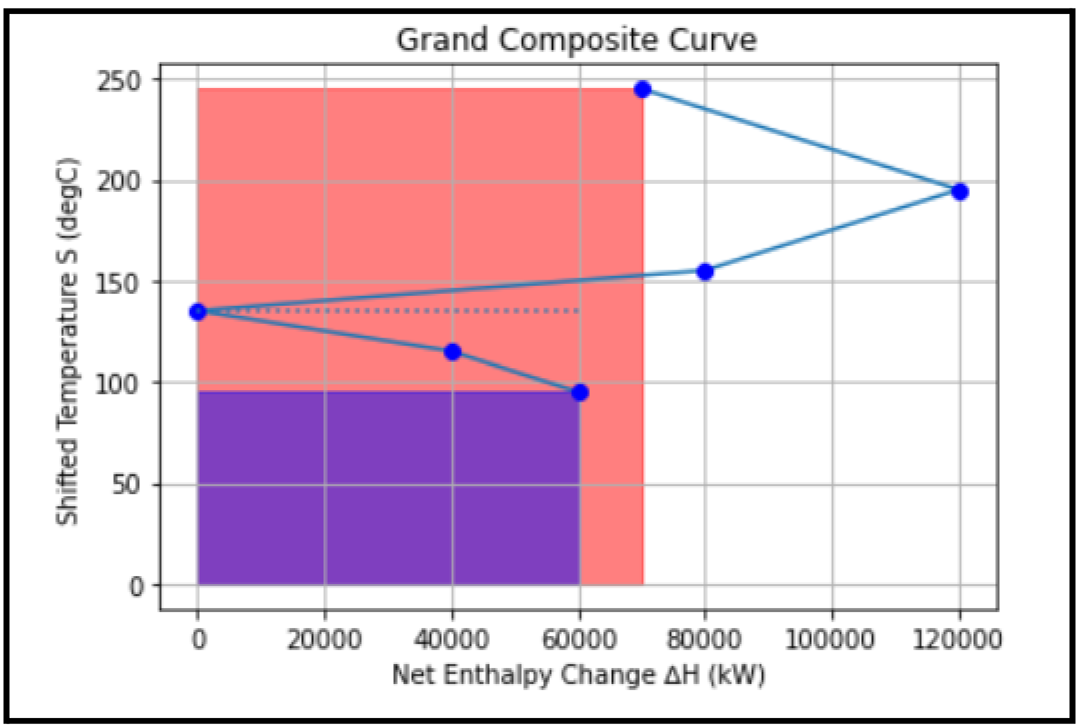
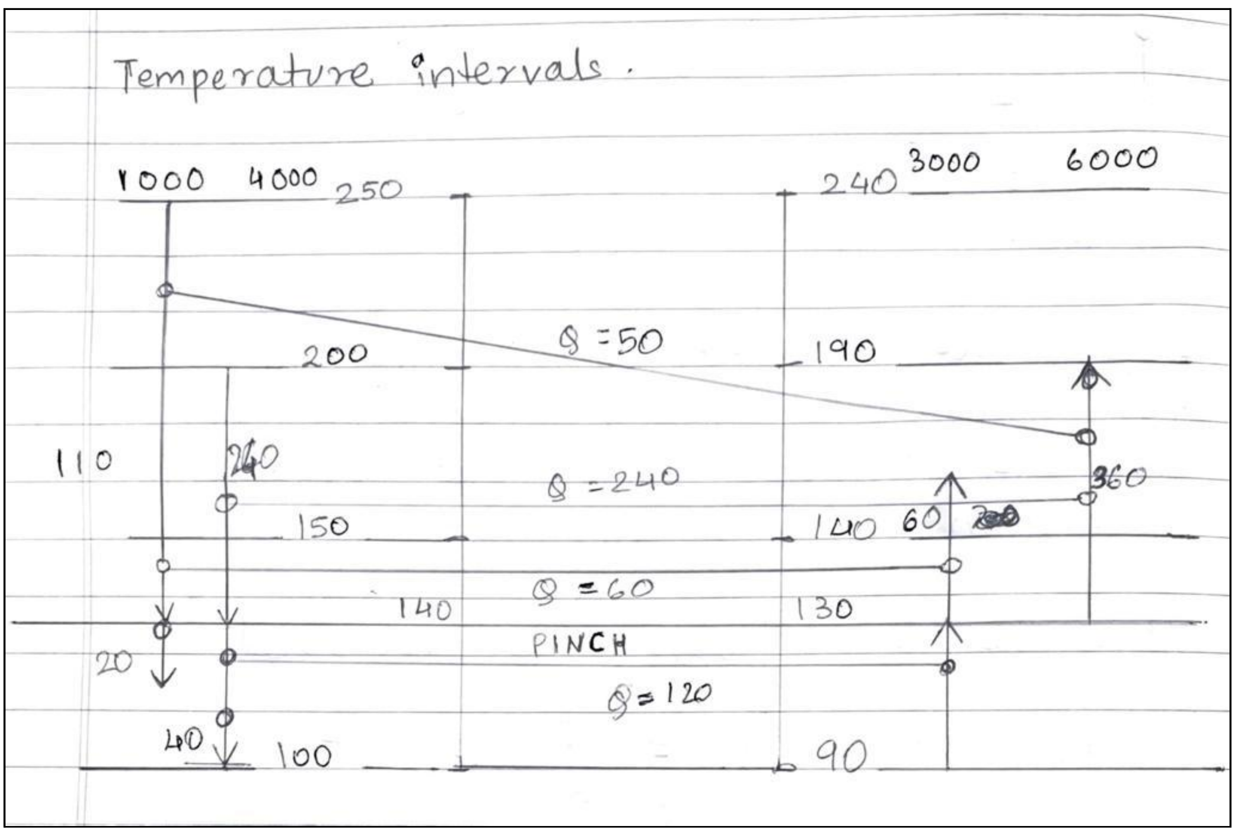


Fig 11: Grand Composite Curve

Finding the minimum number of Heat Exchangers

Determining provably good solutions to the minimum number of matches is the bottleneck of designing a heat recovery network.
MINLP (Mixed integral nonlinear programming) is the optimization method used to solve the minimum matches problem based on the mathematical model. (this report does not cover the algorithm but the explains the overall logic behind it)

Designing HEN is explained using the data from **Table 1** →
(Following analysis is done after completing the First Law and Pinch Analysis)



Matching streams

Above Pinch. FCp cold > FCp hot
(Streams 3 and 4 matched with stream 1)

∴ from stream 1, 60×10^3 kW to stream 3
From stream 1, 50×10^3 kW to 4

Remaining 310×10^3 kW in stream 4
240×10^3 kW comes from stream 2

And the rest 70×10^3 kW goes to hot utility.
∴ 4 Heat exchangers ABOVE PINCH

Below Pinch FCp hot > FCp cold.

20 kW from 1 to cold utility
120 kW from stream 2 to stream 4
and the remaining 40 kW to cold utility

Total cold utility → 60 kW

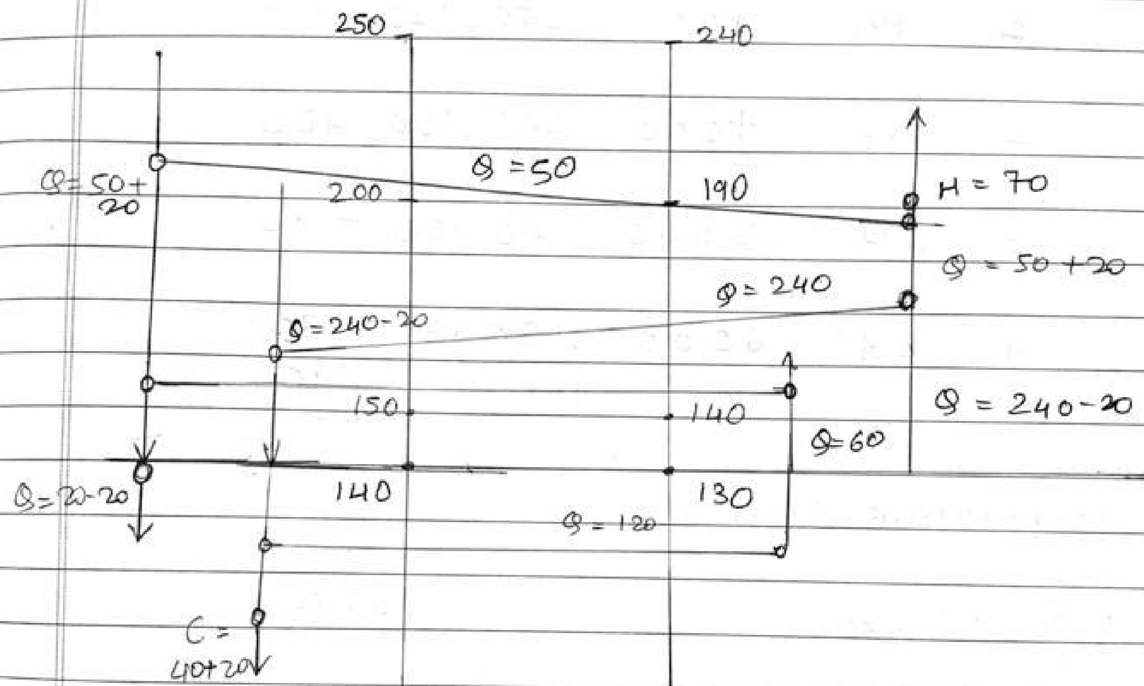
H.Es below pinch = 3

Total H.Es = 7

But we can see by tracing the path that loops are formed in the network.

3 loops are formed in the network.

Two of these loops pass through the cold utility and if one of them breake then other will also be broken.



Loops are removed by adding a heat source and shifting a heater along a path. This procedure decreases loops but increases energy consumption.

After the three loops are removed,

$$\text{No. of H.Es} = 7 - 3 + 1$$
$$= 5$$

5 is the minimum number of heat exchangers

As shown, for the given data the minimum number of heat exchangers were 5. We also observe that the presence of loops increases the minimum energy requirements for completing the heat exchange network.

The results can be further used for economic potential analysis in chemical plants and industry for feasibility studies.

Conclusion

Heat exchanger networks (HENs) are important to petroleum and petrochemical processes because they help save hot and cold utilities, resulting in reduction of operating cost.

From this project we have understood heat exchanger networks and how the hot utility, cold utility values will be obtained.Based on the calculated energy requirements, a Heat Exchanger network can be constructed which would achieve the maximum heat recovery. This would be based upon splitting the streams' energy changes above and below the Pinch Point, with no heat exchange over it.

We have also gained a considerable amount of understanding about the working of HEN and the simulation using Python.

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References

1. Lewin, Daniel R., et al. *Product and Process Design Principles: Synthesis, Analysis, and Evaluation*. John Wiley & Sons Incorporated, 2017.

2. Letsios, Dimitrios, et al. “Heuristics with performance guarantees for the minimum number of matches in heat recovery network design.” *Computers & Chemical Engineering*, vol. 116, 4 August 2018, pp. 422-450. *https://www.sciencedirect.com/*, https://doi.org/10.1016/j.compchemeng.2018.03.002.