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ENERGY SYSTEM ANALYSIS

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ENERGY SYSTEM ANALYSIS

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Keywords: Pinch technology, heat exchanger network, MATLAB, linear programming, genetic algorithm

Abstract

In the past decades, many synthesis of heat exchanger network is proposed to minimize the annual cost. The purpose of this thesis is to use a model to optimize the heat exchanger network for process industry and to estimate the minimum cost required for the heat exchanger network without compromising the energy demand by each stream as much as possible with the help of MATLAB programming software. Here, the optimization is done without considering stream splitting and stream combining. The first phase involves with deriving a simple heat exchanger network consisting of four streams i.e... Two hot streams and two cold streams required for the heat exchanger using the traditional Pinch Analysis method. The second phase of this work deals with randomly placing the heat exchanger network between the hot and cold streams and calculating the minimum cost of the heat exchanger network using genetic coding which is nothing but thousands of randomly created heat exchangers which are evolved over series of population.

Keywords:

Pinch technology, heat exchanger network, MATLAB, linear programming, genetic algorithm

Contents

1. Introduction:

In today's process industry, the importance of devouring energy is increased as the power demand for the world is increased. To reduce the energy utilization or devouring, it became necessary to pay attention to the heat exchanger network design. This is because the rate of consumption of fossil fuels increases and as a result the cost and emissions such as CO_2 etc. are also increased (Akbarnia et al., 2009). In the process industry, there are many streams which needed to be heated or cooled. This heating and cooling can be achieved by external utilities such as heaters and coolers respectively. The energy analysis or integration helps to find thermodynamically possible stream matches which is followed by introducing heat exchangers and thereby reducing the energy consumed by other utilities (Gu and Vassiliadis, 2014). The energy integration or heat integration uses different approaches such as insight based methods and optimization based methods. To calculate the energy targets the insight method uses the graphical tools such as grand composite curve whereas the optimization method uses mathematical programming to minimize or maximize an objective function such as cost or profit based upon the constraints related to the heat exchanger (Bonhivers et al., 2014).

The commonly used heat exchangers in industrial practice are multipass heat exchangers as they have advantages such as easy mechanical cleaning, allowance for thermal expansion, longer flow paths for given heat exchanger length, as well as good heat transfer coefficient. In the last few decades' notable research efforts on the synthesis of the heat exchanger network (HEN) have been performed. Despite that, most of the published methods for the synthesis heat exchanger network are related to single pass heat exchangers. One of the most widely used method is called pinch technology, which was developed by Bodo Linnhoff and his collaborators at ICI, Union Carbide, and the University of Manchester. The pinch technology is based upon first and second law of thermodynamics. It is possible to design multipass heat exchanger network based upon the concepts of pinch technology (Sun and Luo, 2011). The pinch analysis do not give any global optimal solution but it is widely used due to its simplicity of the concepts (Bonhivers et al., 2014).

2. Background:

2.1 Pinch analysis:

Pinch analysis or technology is an energy saving methodology used in process industry by calculating possible energy targets based upon laws of thermodynamics.

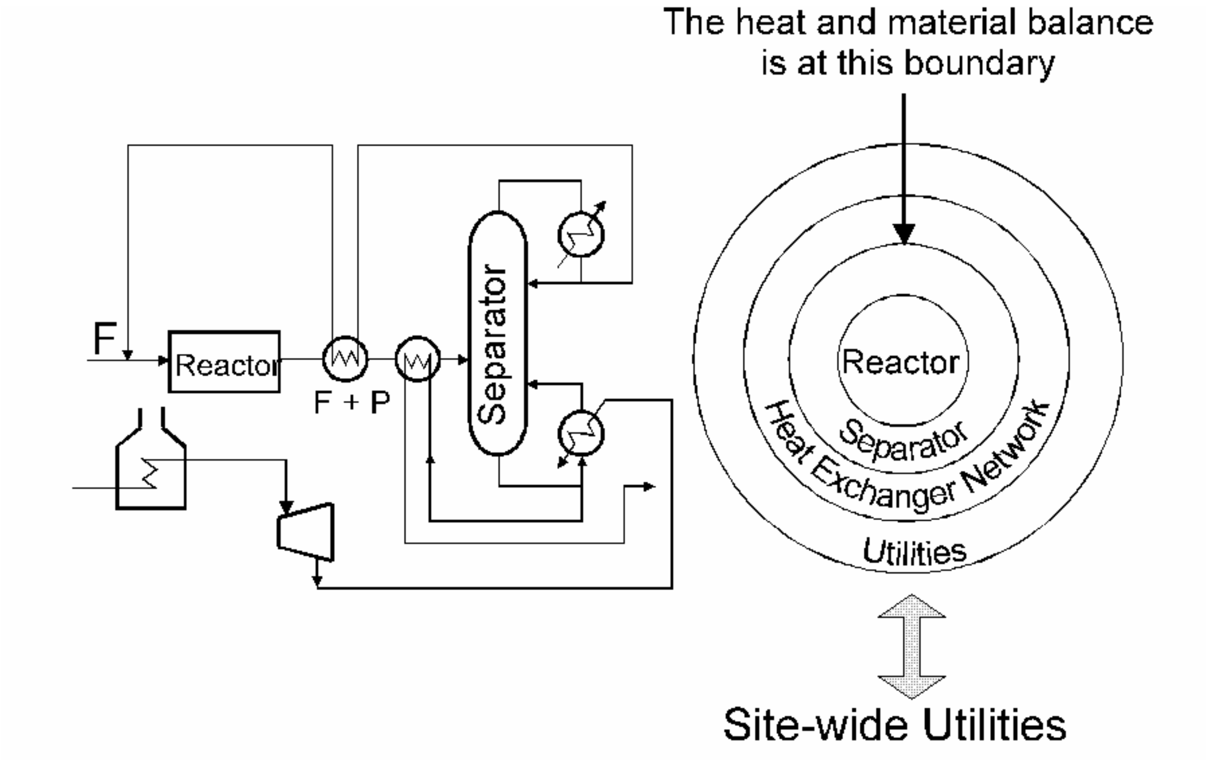
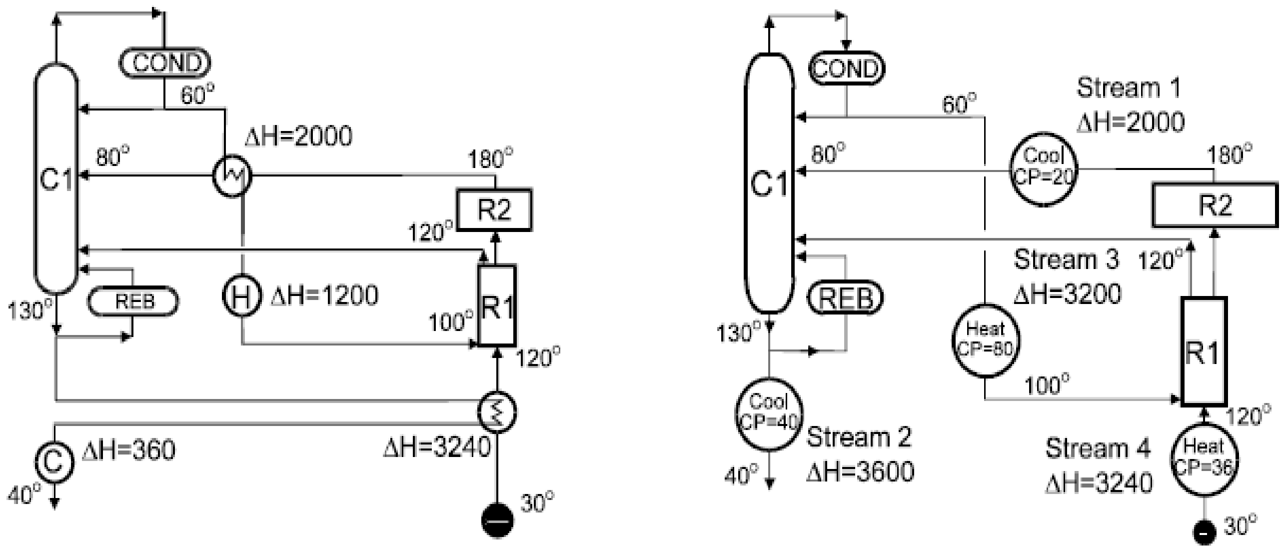


Fig – 1. 'Onion diagram' hierarchy in process design (March, 1998)

The figure above is the overall view of the process industry which explains the role of pinch technology. In the above onion diagram the design starts with a reactor at the core or centre which produces energy once fossil fuels or any other type of fuel is fed. The second layer in the onion diagram is the separator which can be designed once the concentrations of recycle and feed are known. The heat exchanger network is the third layer in the onion diagram which is designed based upon the heat and material balance. The final layer is the heating and cooling utilities which is a part of site wide utilities.

By using pinch technology, heat and material balance is calculated. Energy can be saved in onion layers one and two by pinpointing changes in the core condition. In order to have appropriate heat exchanger network, suitable energy saving targets are achieved using pinch analysis. The site's wide energy consumption can also be minimized using pinch analysis based upon the loads on various steam mains. Therefore the pinch technology provides an energy saving solutions for the entire plant from hot and cold utilities to heat exchanger network (March, 1998).

2.1.1 Data extraction:



(a) Process flow sheet (b) Data extraction flow sheet

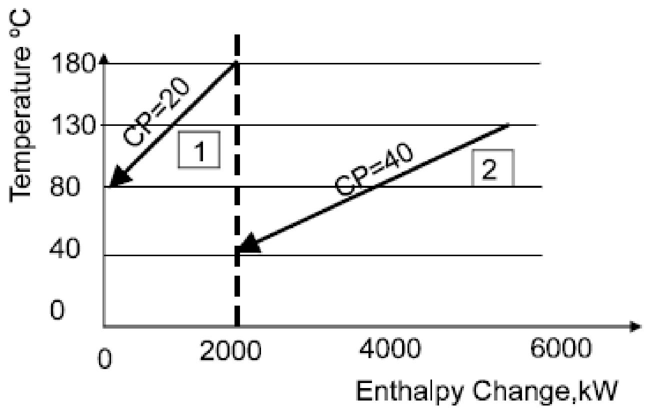
Fig – 2. Data extraction for Pinch Analysis.(March, 1998)

Data analysis or extraction is a step used to collect data from an existing plant to supply the information required for the Pinch Analysis. The above fig-2(a) is an example of process flow sheet for Pinch Analysis which has a two stage reactors with a distillation column and has a heat recovery unit with two process heat exchangers. A heat demand of 1200units for hot utility and 360 units for cold utility is observed in this process.

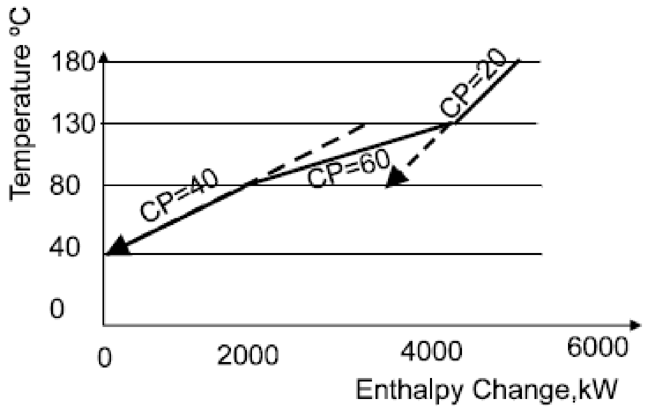
Fig-2(b) shows the data extraction flow sheet which focuses on heating and cooling demands of each steams. For simplicity the reboiler and condenser duties have been excluded, but are included in the actual study.(March, 1998)

2.1.2 Energy targets:

The energy targets obtained by Pinch Analysis provides the minimum energy consumption by the process. These targets are obtained by using "composite curves". The composite curves are graphical representation of the heat demand in the process (the cold composite curve) and the available heat in the process (the hot composite curve). These curves consists of temperature-enthalpy profiles.



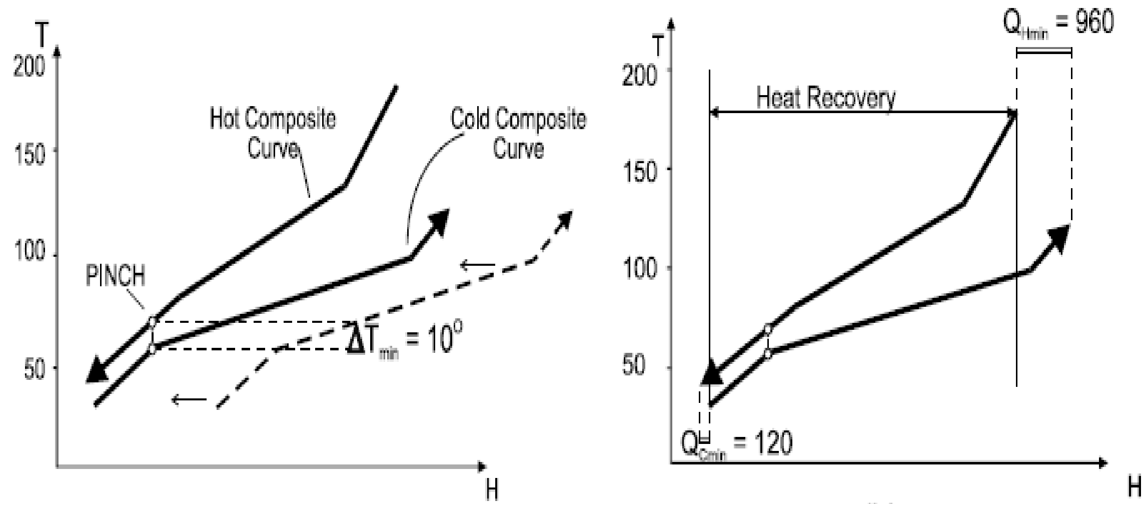
(a) T-h representation



(b) composite representation

Fig – 3. Construction of two hot composite curves (March, 1998)

Fig – 3 is the construction of two hot composite curves. Fig – 3(a) shows curves of individual hot streams and fig – 3(b) represents the composite curves of the two hot streams. Stream 1 is cooled from 180 º C to 80 º C by releasing heat of 2000kW with CP of 20kW/ºC. Stream 2 is cooled from 130 º C to 40 º C by releasing heat of 3600kW with CP of 40kW/ºC. In fig – 3(b) the hot composite curve is constructed by adding the change in enthalpies of each hot stream with their respective temperature intervals. Streams 1 and 2 are present in the temperature interval from 180º C to 130º C so the hot composite CP is equals to the sum of the CP's of stream 1 and stream 2 that is 20 + 40 = 60kW/ºC. The cold composite curve is constructed in a similar manner.(March, 1998)



(a) minimum temperature difference (b) minimum hot utility requirement

Fig – 4. Combined composite curve to determine energy targets (March, 1998)

The composite curve determines the minimum energy targets which is achieved by combining both curves. Fig – 4(a) shows the separation between the hot and cold composite curves using a specified minimum temperature difference DT_{min} (in this case 10º C was used). Fig – 4(b) indicates the maximum possible heat recovery process that is the minimum cold utility and hot utility requirements for the process for the chosen DT_{min}. In the existing process the energy consumption was 1200 units and after using the Pinch Analysis the minimum hot utility consumption is 960 units. The total energy saved is therefore 240 units by using the same DT_{min} as the existing process.

Therefore the Pinch Technology helps in reducing the energy consumption by targeting minimum energy requirements which is based upon heat and material balance information.(March, 1998). The point where DT_{min} is noted is known as the pinch point. The process involving pinch can be separated into two possible separate systems that is one above and one below the pinch point.

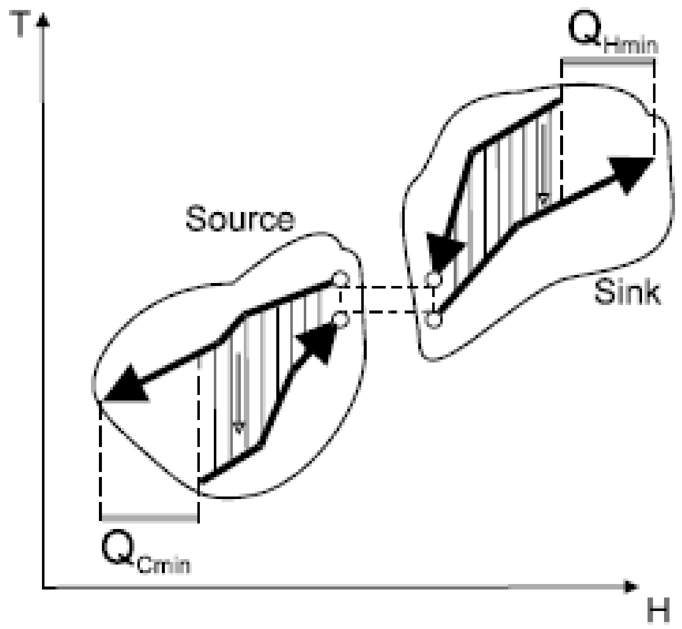


Fig – 5. The pinch divides the problem into source and sink (March, 1998)

The fig – 5 shows that the point below the pinch rejects the heat and the point above the pinch requires heat. Therefore, the point below the pinch is net heat source and the point above the pinch is heat sink.

So, to summarize the understanding of pinch and to achieve the minimum energy targets three rules must be obeyed which is

- heat must not be transferred across the pinch
- there must be no external cooling above the pinch
- there must be no external heating below the pinch

These above rules must be followed to achieve the minimum temperature difference that is the pinch point. These rules are basis in the construction of network design. If one of these rules is violated, it will results in an increase in the energy requirements beyond the minimum. If these rules are implemented in a retrofit plant the design procedure corrects the heat exchangers which are passing the heat through the pinch temperature. (March, 1998)

2.2 Methods:

There are few groups of methods which are used to achieve optimal heat exchanger configuration and to achieve economical design. They are

2.2.1 Thermodynamic approach:

The designing of power plants are done in a traditional way in order to maximize the thermal efficiency of the power plant. The analyses made by traditional methods are based on the first and second law of thermodynamics. These analyses display the various thermal inefficiencies of the system and sub systems of the plant. Certain heuristic rules are applied as soon as the inefficiencies are identified. Once the best thermally efficient design is achieved the capital cost of the plant is assessed.

The above approach lacks accuracy at it cannot give an optimal configuration or solution since it did not take in to consideration of the complex interaction between the subsystems. (Zhu, 1998)

2.2.2 Thermo-economic approach:

The thermo-economic approach is an extension of the thermodynamic approach where the prices of each streams in the unit along with capital cost is included in the analysis. This approach tries to give the best capital expenditure without compromising the thermal efficiencies. In order to find the most economical operating cost this model uses NPL (Non-Linear Programing) – optimisation. When this method is used in an existing process or plant it still uses the trial and error method for addressing the structural changes.(Zhu, 1998)

2.2.3 Mathematical optimisation:

By using the mathematical optimisation method it is possible to have a super structure which contains all the possible options such as exploring the benefits of both changes in parameters and structural changes in the process. But there are few drawbacks in this optimisation process that is this process needs a good initial starting value and also good feasible boundary conditions for variable in order to achieve good solution. Also, the formulation is non-convex and non-linear for a power plant process which interferes with optimisation process. Therefore a better superstructure optimisation is required in order to satisfy all the conditions in a systematic way.(Zhu, 1998)

2.2.4 New methodology:

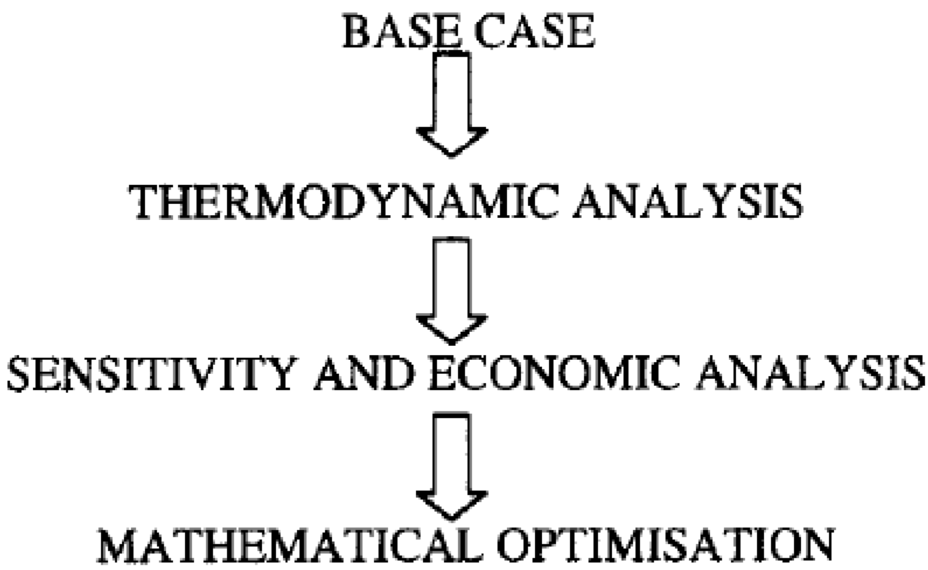


Fig – 6. Procedure for new methodology. (Zhu, 1998)

Fig – 6 shows the procedure for the new methodology which is the combination of benefits of thermodynamic, thermos-economic and mathematic optimisation. There are two types of design process in this design task which are analysis stage and design stage. The analysis stages includes thermodynamic analysis, sensitive analysis and economic analysis respectively. The function of analysis stage is to choose the best promising design options and then evaluate them on the basis of thermal and economical performance of the plant. In the design stage these promising designs are then implemented in a super structure. This supers-structure to find out the best optimal configuration and parameters for the plant. (Zhu, 1998)

2.2.5 Enthalpy table algorithm method:

The enthalpy table algorithm method is a combination of pinch design method (PDM) and problem table algorithm (PTA). The key feature of this technique is to design sub-networks of heat exchangers. These sub-networks are placed on each enthalpy intervals of hot and cold composite curves. These sub-networks are joined together to form into a single heat exchanger network which is later simplified using pinch technology. This method follows few steps to calculate the optimal solution. (Anastasovski, 2014)

<u>Step 1: determination of enthalpy and temperature intervals:</u>

Table 1: stream data used for the enthalpy table algorithm (Anastasovski, 2014)

Stream name	S-1	S-2	S-3	S-4
Mass flow [kg/s]	1	2	1	2
Supply temperature [°C]	20	40	100	80
Targeting temperature [°C]	50	70	30	20
Heat capacity [J/kg °C]	4000	4000	2000	2000
Pipe diameter [m]	0.30	0.30	0.30	0.30
Conductivity [J/m°s°K]	0.03	0.03	0.03	0.03
Density [kg/m^3]	1000	1000	1000	1000
Viscosity [Pa°s]	0.21	0.21	0.21	0.12
Velocity [m/s]	2	2	2	2
Heat transfer coefficient (HTC) [W/m^{2}°K]	39.26	39.26	54.00	48.10
Heat capacity flowrate [kW/K]	4	8	2	4
Enthalpy [kW]	120	240	140	240

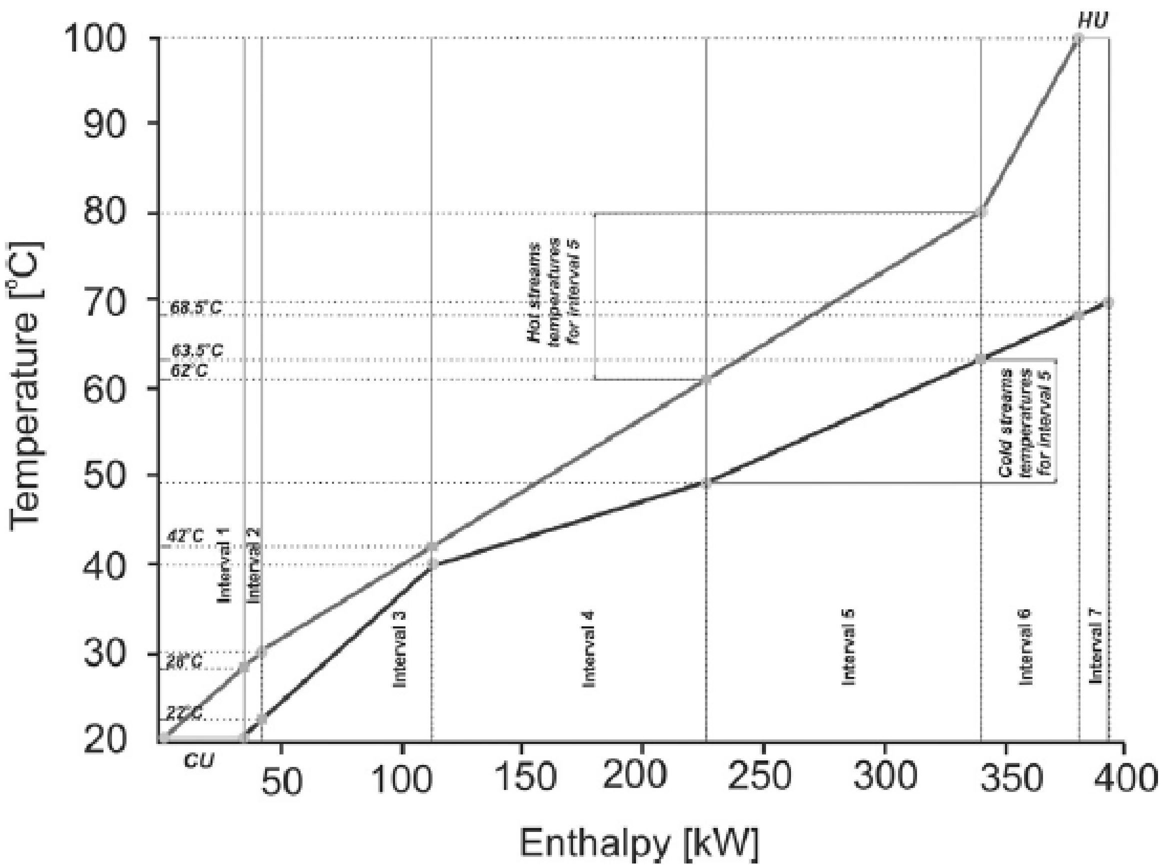


Fig – 7. Composite curve with enthalpy intervals (Anastasovski, 2014)

Table1 shows the enthalpy intervals and temperature intervals and fig – 7 shows that the break points in the composite curve determines the enthalpy difference. One enthalpy interval determines two different temperature intervals; one hot stream temperature interval and one cold stream temperature interval. A linear interpolation was used to determine the missing temperatures. The supply value of cold utility will be first temperature value for cold streams at zero enthalpy. The hot and cold composite curve gives the known temperature values at the next breaking point. In a situation where the hot stream temperature is unknown if the that temperature is coming from cold stream's target temperature, the breaking point of the cold composite curve and the cold utility supply temperature gives the value.

$H_{interval} = \Delta T_{interval} * m * C_p$ ------------------------------- (eq – 1)

The above equation gives the enthalpy change where $\Delta T_{interval}$ is interval temperature difference of hot or cold stream, m is the total mass flow rate in the segment and C_p is the average specific heat in that segment. (Anastasovski, 2014)

Step 2: creating a table of streams present in respective temperature intervals:

Table 2 – Heat capacity flow rates of energy streams. (Anastasovski, 2014)

Hot streams temperature intervals [°C]	Cold streams temperature intervals [°C]	Hot streams temperature difference [°C]	Cold streams temperature difference [°C]	Heat capacity flowrate for stream S-1 [kW/°C]	Heat capacity flowrate for stream S-2 [kW/°C]	Heat capacity flowrate for stream S-3 [kW/°C]	Heat capacity flowrate for stream S-4 [kW/°C]
100–140	68.5–70	40	1.5	–	8.0	–	–
80–100	63.5–68.5	20	5	–	8.0	2.0	–
62–80	50–63.5	18	13.5	–	8.0	2.0	4.0
42–62	40–50	20	10	4.0	8.0	2.0	4.0
30–42	22–40	12	18	4.0	–	2.0	4.0
28–30	20–22	2	2	4.0	–	–	4.0
20–28	4–20	8	16	–	–	–	4.0

Table2 shows the stream present in each temperature intervals. In table 2 it can be noted that there are empty spaces which means that there are no stream present in those intervals. The top row of streams can in this case be matched with hot utilities as it only contains cold streams. Correspondingly, the bottom rows of hot streams can be satisfied with the cold utilities. Hot or cold utilities are needed to be added if there are any unbalanced temperature intervals. (Anastasovski, 2014)

Step 3: Construction of heat loads:

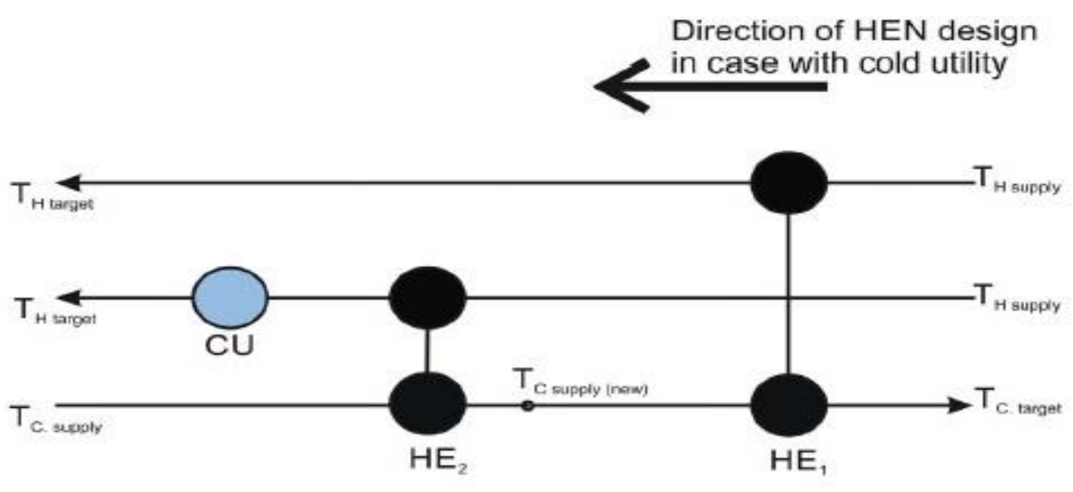
Table 3 – Heat content of energy streams present in certain temperature intervals. (Anastasovski, 2014)

Hot streams temperature intervals [°C]	Cold streams temperature intervals [°C]	Hot streams temperature difference [°C]	Cold streams temperature difference [°C]	Heat of stream S-1 [kW/°C]	Heat of stream S-2 [kW/°C]	Heat of stream S-3 [kW/°C]	Heat of stream S-4 [kW/°C]	Heat balances for every interval [kW]
100–140	68.5–70	40	1.5	–	12	–	–	12
80–100	63.5–68.5	20	5	–	40	–40	–	0
62–80	50–63.5	18	13.5	–	108	–36	–72	0
42–62	40–50	20	10	40	80	–40	–80	0
30–42	22–40	12	18	72	–	–24	–48	0
28–30	20–22	2	2	8	–	–	–8	0
20–28	4–20	8	16	–	–	–	–32	–32

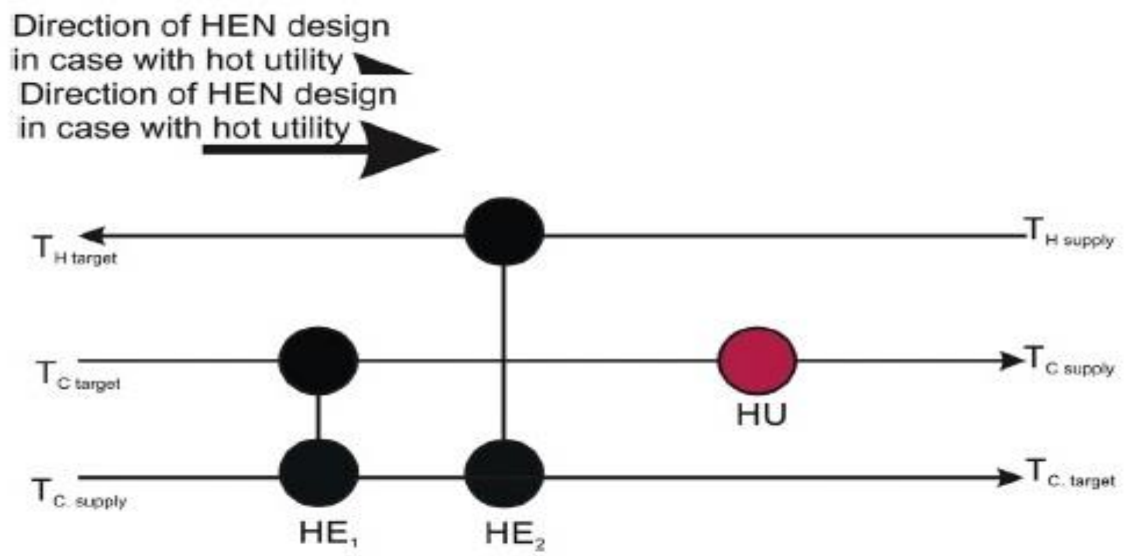
Table-3 shows list of streams based upon heat content of streams which is present in certain energy intervals. From the previously mentioned eq 1 the enthalpy are calculated and are written in columns for all four streams. Heat balances for every stream is represented in the last column, in which all balances are zero except the ones in the top and bottom. The heating and cooling demands are represented by the heat values in those positions. Negative sign is given to hot streams since they give out heat or energy and cold streams with positive sign since they accept heat. (Anastasovski, 2014)

Step 4: design of a primary heat exchanger network:

In table – 5 almost all the enthalpies are balanced and the places where the enthalpies are not balanced are represented by hot and cold utilities. The sub networks are independent problems so their starting point in the design can be from any interval. All sub-networks are connected in the same way as it represented in the combined composite curve. The heat load of each stream is compared to the highest of all its values. The streams which have the same heat load values are paired. If a single heat exchanger is added between the hot and cold streams, it can be noted that there is no violation of ΔT_{min}. The problem comes in by pairing a second heat exchanger which is placed between the non-paired parts of the stream fragments where the possibility of series connection must be checked. Series connection means that heat from one hot stream is transferred to more than one cold stream. The design direction can be started from right side to left side or from left side to right side. The new supply temperature must be determined if the design direction starts from right side to left side. The new supply temperature is determined by the value of heat that is transferred from hot stream to cold stream. If the streams are connected from left side to right side, the new supply temperature for the cold stream must be higher than or equal to cold streams target temperature.



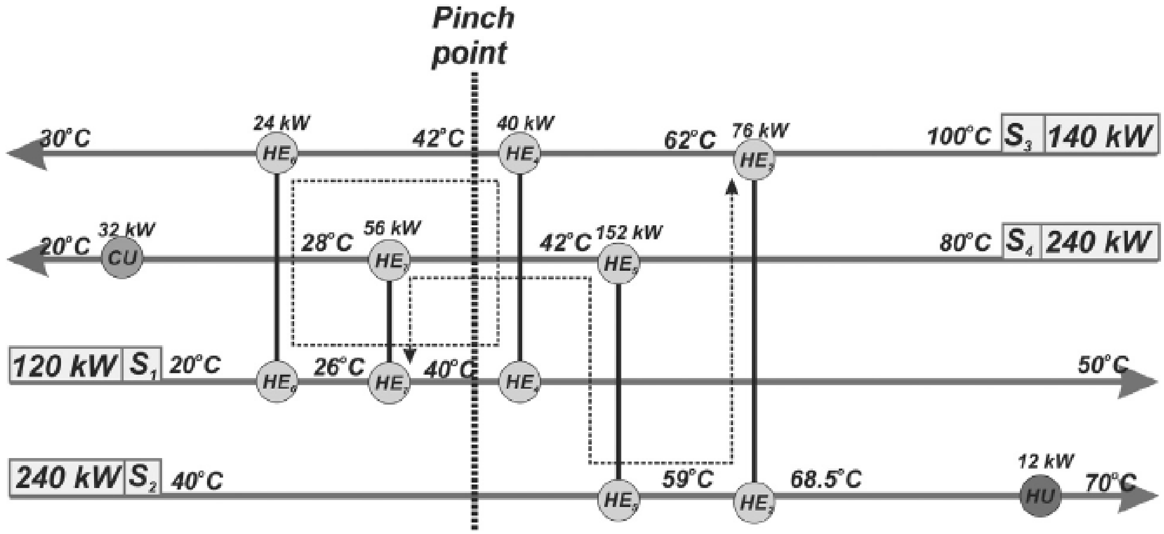
(a) Left to right direction design for cold utility demand.



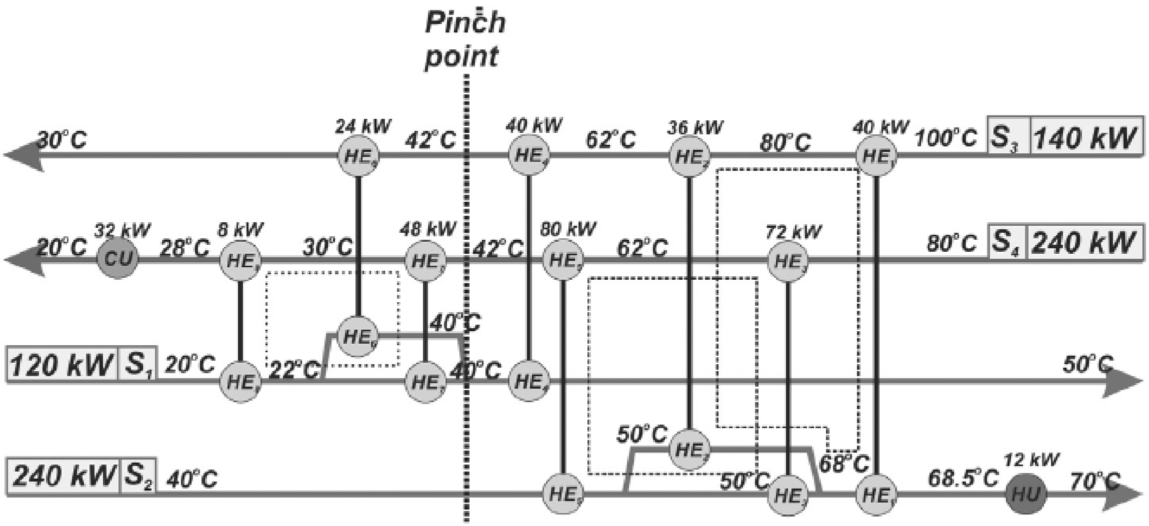
(b) Right to left direction design for hot utility demand.

Fig – 8. Direction of heat exchanger network design for unbalanced enthalpy intervals (Anastasovski, 2014)

Fig – 8 shows the sub-networks that demands utilities in which for cold utility the direction of design starts from right side end to left side and for hot utility the direction of design starts from left side end to right side. To make a simple loop repetition of same combination of streams are taken in to consideration. From table-3 the heat exchanger network is designed. The hot stream temperature interval is 42º C - 62º C and cold stream interval is 40º C - 50º C which is the first enthalpy interval above the pinch point contains fragments of all the four streams. The two streams S_1 and S_3 can exchange heat as S_3 contains extra heat of 40kW which is needed by stream S_1. Similarly, streams S_2 and S_4 can exchange heat as stream S_4 contains the heat needed by stream S_2. Streams $S_{2,}$ S_3 and S_4 are present in the second enthalpy interval above the pinch. In this enthalpy interval, the stream S_2 need a heat demand of 108kW which is satisfied by streams S_3 and S_4. There are two possible enthalpy solutions in this enthalpy interval which are design of heat exchanger network connected in series and designs of heat exchanger network with connections between S_2 branches. The criteria for serial connection need to be taken in to consideration as the design of heat exchanger networks in series can violate the concept of temperature crossing and ΔT_{min}. (Anastasovski, 2014) *step 5: simplifying of networks to the final design of heat exchanger network:*



(a) The case with branching of stream fragments with marked loops according to pinch technology rule



(b) Cases with marked loops and paths that are going through the pinch point

Fig – 9. Grid diagram of designed heat exchanger networks. (Anastasovski, 2014)

In fig – 9 there can be noted some loops and paths to get a new form, in which there is loop between the path that connects heaters and cooler and heat exchangers HE4 and HE6. the heat exchangers HE3 and HE5 are second loop and heat exchangers HE7 and HE8 are third loop. By summing the heat load of every heat exchanger of that loop, new heat exchangers are created.

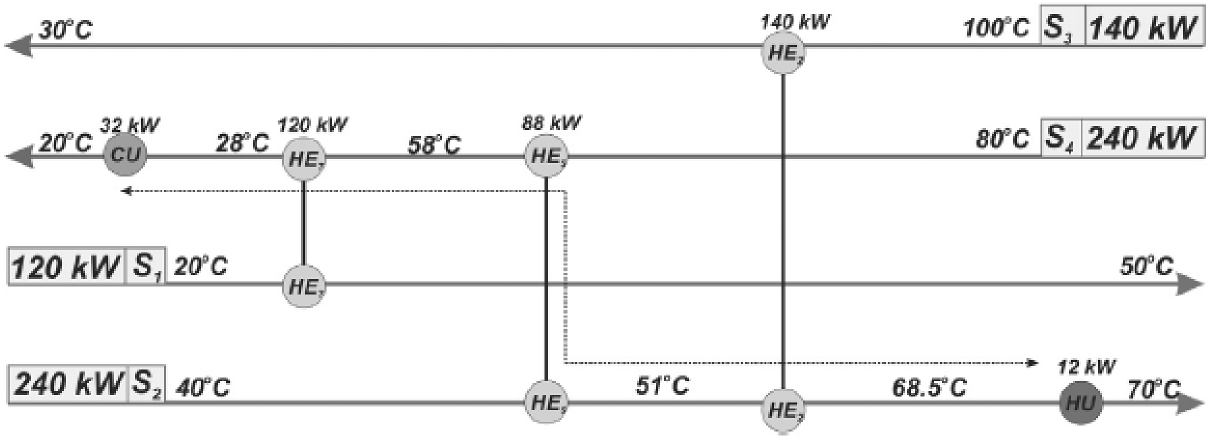


Fig – 10. Heat exchanger network after using of rule for loops through the pinch point. (Anastasovski, 2014)

From fig – 10 it can be noted that there is a reduction in the energy required by the hot and cold utility. There will be a violation of ΔT_{min}, if the path that goes to heat exchanger 5 is broken.

This is technique can be used in threshold problems or multiple pinch problems. This technique divides the networks in to sub-networks and the break points in the hot and cold composite curve determines the number of sub-networks. This method gives the continuity of process streams in the network design as there is a possibility of pairing up of already paired stream combinations. There is a possibility of increasing the number of loops which gives a simple solution.

There are some drawbacks in this method as it depends on the designers ability to solve the problem and creativity of the designer. (Anastasovski, 2014)

2.2.6 The extended pinch analysis method for sub ambient process:

The extended pinch analysis deals with exergy analysis which has the advantages of including all the stream properties such as temperature, pressure and composition. The methodology of this process is the combination of the pinch analysis and exergy analysis to find the minimum annual cost with the use of mathematic programming. Situations such as when supply pressure (P_s) greater than the target pressure (P_t) a favourable design procedure was developed. In this method, the compression and expansion work is optimised together with the work needed to create the cooling utilities. In a sub-ambient process the temperature of a stream is decreased when the stream is expanded as the pressure is reduced and at the same time cooling duty of the stream is increased. Thus, some of the original pressure based exergy is converted to temperature based exergy. (Aspelund et al., 2007)

EXERGY CALCULATION:

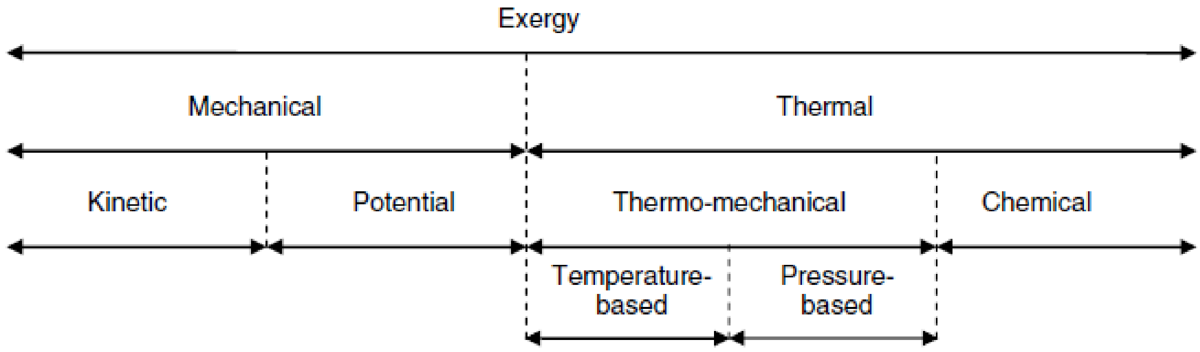


Fig – 11. Exergy components. (Aspelund et al., 2007)

Fig – 11 shows the different types of individual exergies available in the system or stream but this problem focus on thermos-mechanical exergy; the sum of temperature based exergy and pressure based exergy.

$e^{(tm)} = (h - h_o) - T_0 (s - s_o)$……………………………(eq – 2)

where,

$e^{(tm)}$ is the thermo-mechanical exergy,

h and h_o are inlet and exit enthalpies respectively,

s and s_o are inlet and exit entropies respectively,

T_o is the ambient temperature.

The eq – 2 was obtained from first and second law of thermo-dynamics. In this problem, chemical and mechanical exergies were not included since there is no chemical reactions and the mechanical exergy was assumed negligible.

$e^{(T)} = h(T, P) - h(T_o, P) - T_o(s(T, P) - s(T_o, P))$…………………………(eq – 3)

$e^{(P)} = h(T_o, P) - h(T_o, P_o) - T_o(s(T_o, P) - s(T_o, P_o))$…………………………(eq – 4)

The Eqs (3) and (4) constitute the thermos-mechanical exergy consisting of temperature T and pressure P. When the stream is brought from current temperature T to ambient temperature T_o at constant pressure P, temperature based exergy $e^{(T)}$ is obtained. Similarly, at constant temperature T_o, if the stream is brought from initial pressure P to ambient pressure P_o, pressure based exergy $e^{(P)}$ is obtained.

$$E_{c.min} = \Delta E_c = \Delta E_{(TH - \Delta T)}$$

$$= \dot{m}C_p \left[T_{H.s} - T_{H.t} - T_o \ln\left((T_{H.s} - \Delta T) / (T_{H.t} - \Delta T)\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots (eq – 5)$$

Eq – 5 shows the minimum amount of exergy $E_{c.min}$ required to cool down a hot stream at constant ΔT by heat transfer. Where, $T_{H.s}$ and $T_{H.t}$ are the hot stream at sub-ambient supply temperature and hot stream at sub-ambient target temperature respectively. (Aspelund et al., 2007)

The overall design procedures are, (Aspelund et al., 2007)

- The total exergy of hot and cold streams is calculated to check whether it is possible to have a process without utilities or not. If the calculated exergy is above 100% minimum energy required is found.
- After finding out the minimum temperature differences and equipment efficiencies establish an initial estimate for the irreversibility's.
- To find the pinch point and minimum amount of heat required by hot and cold utilities, develop the hot and cold streams composite curves.
- After the expansion and compression process of the process stream, develop the pinch curves.
- Calculate new exergy efficiency.
- Compare the new exergy with the old one and develop the current design with new exergy efficiency.
- This procedure does not guarantee global optimal solution.

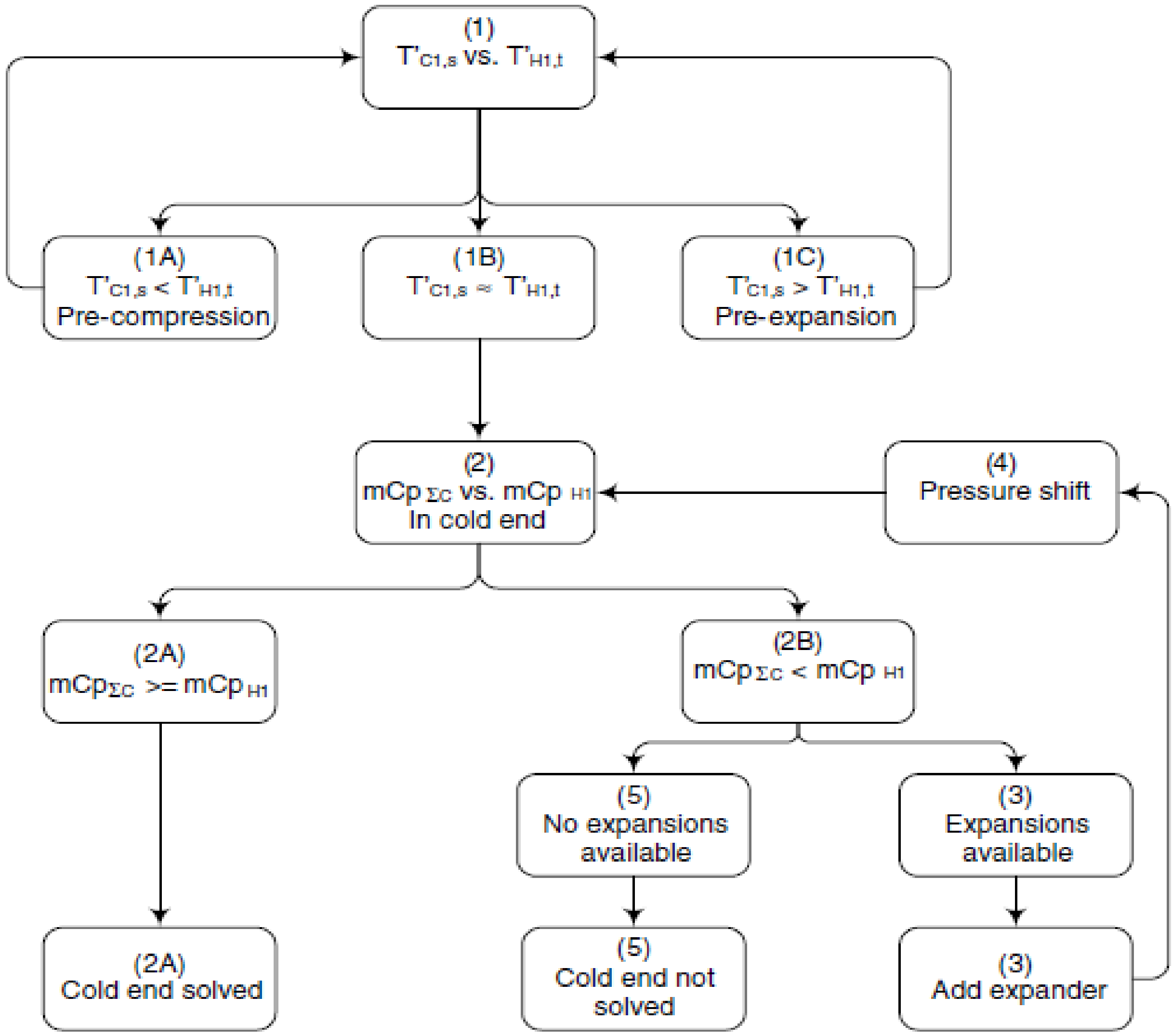


Fig – 12. Procedure for cooling a hot stream by utilizing pressure based exergy in a cold stream. (Aspelund et al., 2007)

A simplified version of the procedure for cooling a hot stream by using exergy in a cold stream is shown in fig – 12. The first step is to modify the hot and cold stream temperature using the Pinch Analysis. The hot and cold stream temperatures are adjusted by subtracting half of ΔT_{min} for hot stream and adding half of ΔT_{min} for cold stream. The cold stream is compressed to reach the hot stream target temperature if the original cold stream is colder than the hot stream target temperature. This process helps to reduce the exergy loss. While compressing the cold stream, some work is needed, which is recovered by expansion by producing additional cooling at high temperature. In some cases, the cold stream is expanded if the cold stream supply temperature is higher than the hot stream target temperature. (Aspelund et al., 2007)

In step (2) the heat capacity flow rates of hot and cold streams are compared. In this step the hot stream target temperature is higher than the new cold stream temperature. The composite curve will diverge and the cross-over in the cold region is avoided if the flowrate of the total heat capacity of the cold stream is equal to or larger than that of the hot stream in the cold region. To increase the total heat capacity flow rate of the cold stream, the cold stream is expanded several times. Depending on the total enthalpy changes and the energy content of the stream, external heating and cooling systems are added.

In the step (3) one more expansion is done, if there is any pressure available in the cold stream. To make the composite curve diverge at least one more sub-stream is needed in the cold end.

In step (4) to maintain equal pressure ratio over the expanders. But by following this step the inlet temperatures must be increased to obtain the target outlet temperature if the pressure ratio across the expanders are decreased. Step (5) indicates the need for external cooling utility if the cold end cannot be solved due to lack of expanders.

The above method is a promising tool to achieve an optimal solution to develop the energy intensive process. This methodology uses both the traditional pinch analysis and exergy analysis to give an optimal solution in a transparent way. (Aspelund et al., 2007)

2.2.7 A graphical method for pinch analysis:

In this method, a graph is constructed for representing an existing heat exchanger network by plotting the temperatures of process hot streams versus temperatures of cold streams. Straight lines are drawn to represent the existing heat exchanger. From these straight lines slopes are drawn which is proportional to the ratio of heat capacities and flow. The conventional method is has some difficulty in matching the existing temperatures with the target values of the curves. But by using the new graphical method it’s easier to achieve the energy targets and in estimating the performance of the heat exchanger network. (Gadalla, 2015)

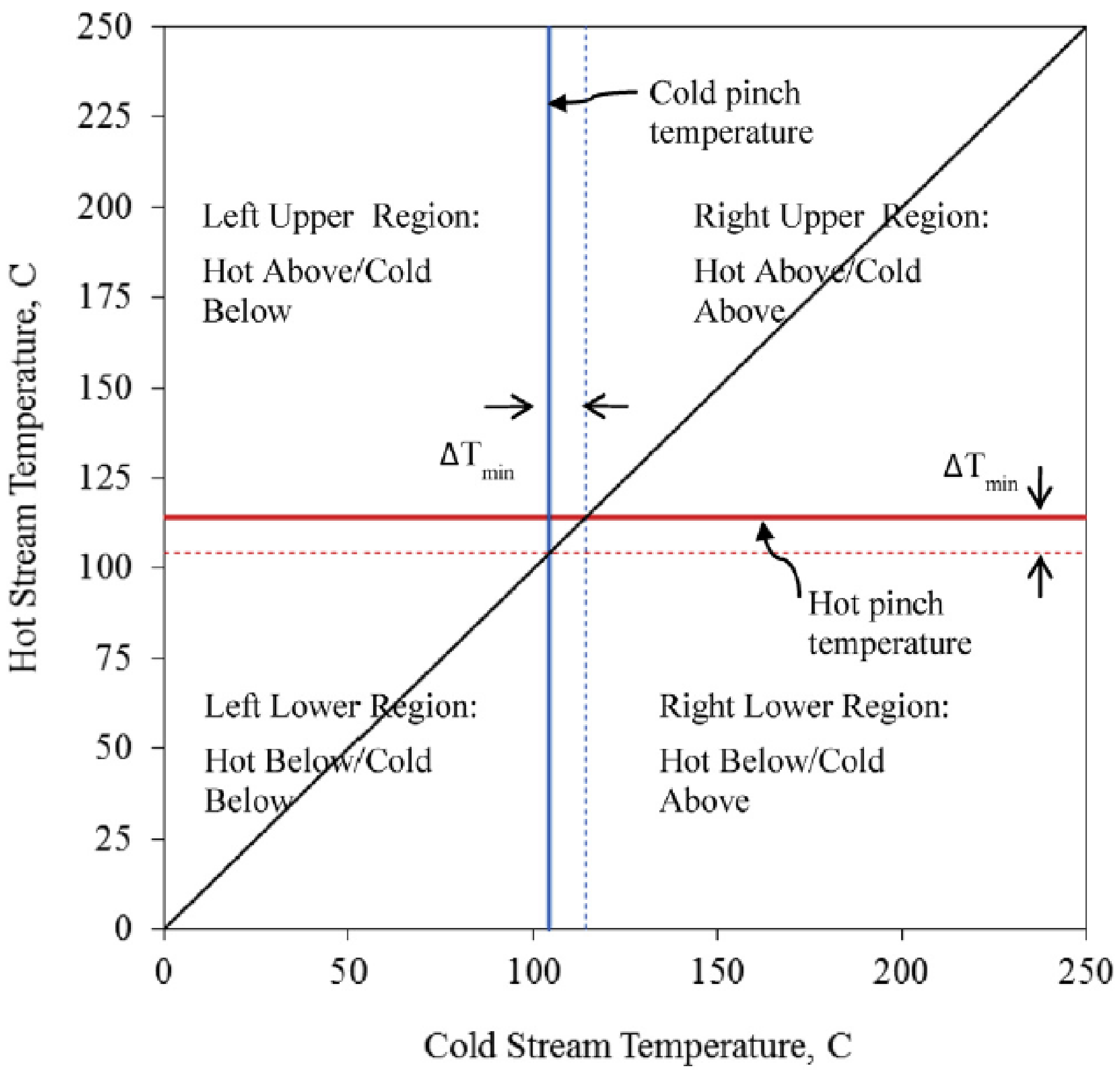


Fig – 13. A graphical representation for energy analysis. (Gadalla, 2015)

From fig – 13 the temperatures of the hot stream to and from the heat exchanger are plotted against the cold stream temperatures. In the figure, x-axis represents the cold stream temperatures and the y-axis represents the hot stream temperature. The two horizontal lines on the figure represent the hot stream supply temperature of the stream is denoted by the upper horizontal line and the target temperature is denoted by the lower horizontal line. Correspondingly, the two vertical lines denotes the cold stream supply temperatures are denoted by left side vertical line and the target temperatures are denoted by right side vertical line. In the same way, the pinch temperatures for hot and cold streams are denoted by horizontal and vertical lines respectively. It can be noted in the figure that the hot and cold pinch temperatures divide the graph into four different regions that is left and right upper regions and left and right lower regions. These regions represent the possible exchanger matches within the heat exchanger network, which are as follows, (Gadalla, 2015)

- The left upper region shows that there is heat exchange between the hot streams above the pinch point and the cold stream below the pinch point.
- The right upper region shows that there is heat exchange between hot streams above the pinch point and the cold streams above the pinch point.
- The left lower region shows that there is heat exchange between hot streams below the pinch point and the cold streams below the pinch point.
- The right lower region shows that there is heat exchange between hot streams below the pinch point and the cold streams above the pinch point.

The graphical method shows the following features from fig – 13,

- The two temperature coordinates that is the temperature of hot stream (T_h) and cold stream temperature (T_c) defines any point located on the graph.
- When the hot stream temperatures are equal to the cold stream temperatures, the graph is represented by a diagonal line which divides the graph into two regions that is feasible energy integration above the diagonal and infeasible energy integration below the diagonal. Below the diagonal there is infeasibility because the heat sources present there are colder than the heat sinks and therefore, exchangers are not possible there and must lie above the diagonal.
- In the right upper region, only heaters are allowed as there is energy balance with external hot utilities.
- Similarly, in the left lower region only coolers are allowed as there is energy balance with external cold utilities.
- Though, the left upper region violates the principles of the Pinch Analysis as heat is transferred across the pinch, the heat integration in this region is still feasible.
- The exchangers placed in the two right upper and left lower region is the place where heat recovery should takes place. In some real plants several exchangers are present in

the left upper region, which indicates inefficient heat recovery designs. As the result of the inefficient design more fuels and utilities are consumed.

- The heat exchanger matches that touch the pinch temperatures signifies that the energy integration takes place across the pinch temperatures.

The graphical method can represent the heat exchangers as temperatures of hot streams plotted against the temperatures of cold streams. This method can evaluate the performance of existing heat exchanger networks with respect to pinch analysis by identifying the inefficiencies of the process. Further, this method reduces the energy demand by the utilities by shifting heat graphically between heat exchanger loops. (Gadalla, 2015)

2.2.8 Biogeography – based optimization method:

Simon proposed the biogeography algorithm method which is a new and powerful optimization technique. The study of geographical distribution of biological organisms is called biogeography. The geographical areas which are suitable for the biological species said to have a high habitat suitability index (HSI). There certain variables called suitability index variables (SIVs) which characterize the habitability of species. The HSI and SIV are considered as dependent and independent variables respectively. A higher habitat suitability index, means a lager the number of species. The habitats having higher HSI are more stable than the habitats with lower HSI. This technique is based upon migration and mutation. The mathematic representation of migration and mutation are as follows, (Hadidi and Nazari, 2013)

Migration:

This method is similar to that of other population optimization technique. The solutions of candidate are represented as vector of real numbers in which each real numbers are considered as one SIV in the array. In biogeography based optimization (BBO), the quality of each candidate solution is found using HSI. Higher the HSI solution, better the quality of solution and lower the HSI solution, lower the quality of solution. To share information between habitats probabilistically, the rates of emigration and immigration of each solution is used. Each solution is modified using habitat modification probability. To modify suitability index variable, immigration rate (λ_s) of each solution is used. To select which population set will migrate, emigration rates (μ_s) are used probabilistically. The migration process brings changes within the existing solution. (Hadidi and Nazari, 2013)

Mutation:

Some changes can occur suddenly due to natural calamities in the HSI of natural habitat which causes some changes in the equilibrium value of the habitat. This process is called mutation. The mutation rates are determined by species count probabilities.

$P^h_s = - (\lambda_s + \mu_s)P_s + \mu_{s+1}P_{s+1}$ $S = 0$,---------------------------------------(eq – 6)

$P^h_s = - (\lambda_s + \mu_s)P_s + \lambda_{s-1}P_{s-1} + \mu_{s+1}P_{s+1}$ $1 \leq S \leq S_{max} - 1$,------------------(eq – 7)

$P^h_s = - (\lambda_s + \mu_s)P_s + \lambda_{s-1}P_{s-1}$ $S = S_{max}$-----------------------------------(eq – 8)

The above differential equations are used to calculate the probability of each species count. Where,

P_s is the probability of habitat containing exactly S species,

P_{s+1} is the probability of habitat containing S+1 species,

P_{s-1} is the probability of habitat containing S-1 species,

λ_s, μ_s is the immigration and emigration rate of habitat containing S species,

λ_{s-1}, μ_{s-1} is the immigration and emigration rate of habitat containing S-1 species,

λ_{s+1}, μ_{s+1} is the immigration and emigration rate of habitat containing S+1 species,

S_{max} is the maximum species count.

Higher the probability of the solution, lower the chance of mutation and similarly, lower the probability of the given solution, higher the chance of mutation. So better values are obtained with medium HSI solution.

Based on this method there was reduction in capital cost up to 14% and savings in operating costs up to 96%. So the over decrease of total cost was up to 56.1% by using the biogeography based optimization. (Hadidi and Nazari, 2013)

2.2.9 Particle swarm optimization (PSO):

The particle swarm optimization is based upon superstructure simulation optimization model by including steam splitting to minimize the total annual cost and energy cost of utilities. This method was developed by Kennedy and Eberhart in 2001, where they got stirred by the social behaviour of bird flocking or fish schooling. The technique used in the PSO process is stochastic optimisation technique. The procedure provided by particle swarm optimization is population based search procedure in which the particles change their position or state with time. Each particle in the PSO system fly's around in a multi-dimensional search space where the position is adjusted according to its own experience and the experience of the neighbouring particles to make sure the possible best position is occupied by all particles. In most of the research and application areas the PSO is implemented successfully. In the PSO, only few parameters are need to be adjusted and therefore it became attractive in different research areas. The objective function used in this case is as follows (Silva et al., 2009)

Minimize $C_{global} = (C_{HU} \,.\, HU + C_{CU} \,.\, CU) + \Sigma\,(a + b.\, A_k^{c})$……………….(eq – 9)

Where, HU, CU, C_{HU} are hot and cold utilities and the cost associated to them a, b and c which are constants that depend on the equipment used, A is the area of heat exchanger.

$\upsilon_{k+1}^{(i)} = \omega_k \upsilon_{k+1}^{(i)} + c_1 r_1 (p_k^{(i)} - x_k^{(i)}) + c_2 r_2 (p_k^{global} - x_k^{(i)})$………………………..(eq – 10)

$x_{k+1}^{(i)} = x_k^{(i)} + \upsilon_{k+1}^{(i)}$………………..(eq – 11)

Where,

$x_k^{(i)}$ and $\upsilon^{(i)}$ are position and velocity vectors of the particle i, respectively,

ω_k is the inertia weight,

c_1 and c_2 are constants,

r_1 and r_2 are two random vectors,

k is the iteration number,

$p_k^{(i)}$ is the position with best result of particle i,

p_k^{global} is position with best result of the group.

According to eq – 5 and eq – 6, the particles and the velocity of each particle are actualised. At the beginning of the optimization, the variables are randomly generated and then the location is modified. The particles are formed based on variables such as number of stages, heat exchanged in each equipment, fraction of cold stream splitting and fraction of hot stream splitting. The hot and cold utilities demand and the heat exchangers areas are calculated after the generation of the particle. The hot and cold utilities demand and the heat exchangers areas are calculated after the generation of the particle The objective function is penalized, if the particle is not a solution of the problem or if the particle violates any constrains. (Silva et al., 2009)

2.2.10 The R-curve analysis method:

Kimura and Zhu developed the R-curve analysis method to determine the most economic modifications to existing utility systems. The R-curve is a curve which indicates of exixting plant can be improved without any capital investment. By converting the fuel energy into heat (Q_{heat}) and power (W), a target for the efficiency of utility system is provided by the R-curve. A heat sink is required for the production of shaft work from fuel energy; this fact determines the shape of the R-curve. The ratio of useful part of energy and the integrated energy consumption (Q_{fuel}) is the fuel utilisation efficiency or integrated energy efficiency. The process plant acts as the heat sink for power generation in an integrated site. The overall generation becomes more efficient if the heat demand to power demand is large.

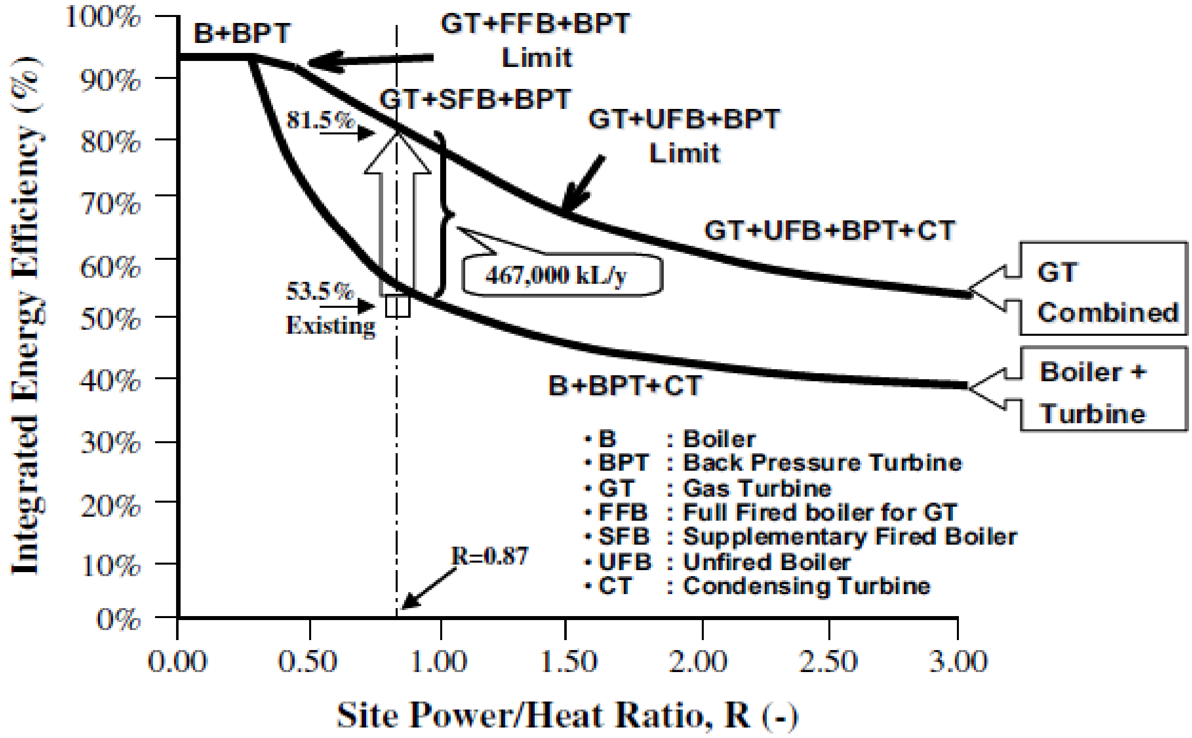


Fig – 14. Theoretical limit lines of two energy curve. (Matsuda et al., 2009)

Fig – 14 determines the theoretical lines of the two energy systems. In the above figure the two energy systems used are gas turbine combined system and boiler and turbine conventional system. Maximum achievable efficiency is shown by the R-curve for the given R-ratio. The R-ratio is the ratio of power to the heat demand from the process. A scope of improvement in the design is revealed in the difference between the existing efficiency and maximum efficiency. To determine complex wide opportunities of multiple sites, the power and heat demand of multiple sites are combined to form the R-curves. The R-curve is applied on the basis of minimum energy requirement balance in a conventional approach. The R-curve analysis estimates the amount of theoretical energy that can be saved and also estimates the present condition of the utility systems.(Matsuda et al., 2009)

2.3 Genetic algorithm:

The optimization process consists of forming an initial basic concept and improving the concept based upon gained information to find the maximum or minimum output results. In the optimization process the input may be a variable or functions such as objective function or cost function or fitness function (Haupt and Haupt, 2003).

There are different types of optimization technique but the most commonly used technique to find the global minimum or maximum is genetic optimization. In 1960, Genetic Algorithm (GA) was invented by John Holland and later in the year 1960s and 1970s the algorithm was developed by Holland and his students and colleagues at the University of Michigan. Original goal was to design an algorithm to understand the phenomenon of nature adaptation and to find ways to implement this process into computer systems (Mitchell, 1996). Generally speaking, genetic algorithms are probabilistic optimization methods in which the concept of evolution is used to improve the solution to find better global minimum or maximum value (Bodenhofer, October,2003).

In the genetic algorithm, to a given problem or process each individual represents a possible solution where the individuals are determined randomly from search space. The fitness function or objective function determines the result of the variable that needs to be optimized to find the fitness of the solution. The next generation of population is determined by the individuals that has the best fitness solution within the previous population. An optimal solution is obtained for a given problem from the group of possible solutions. (M.A.S.S.Ravagnani, June, 2005)

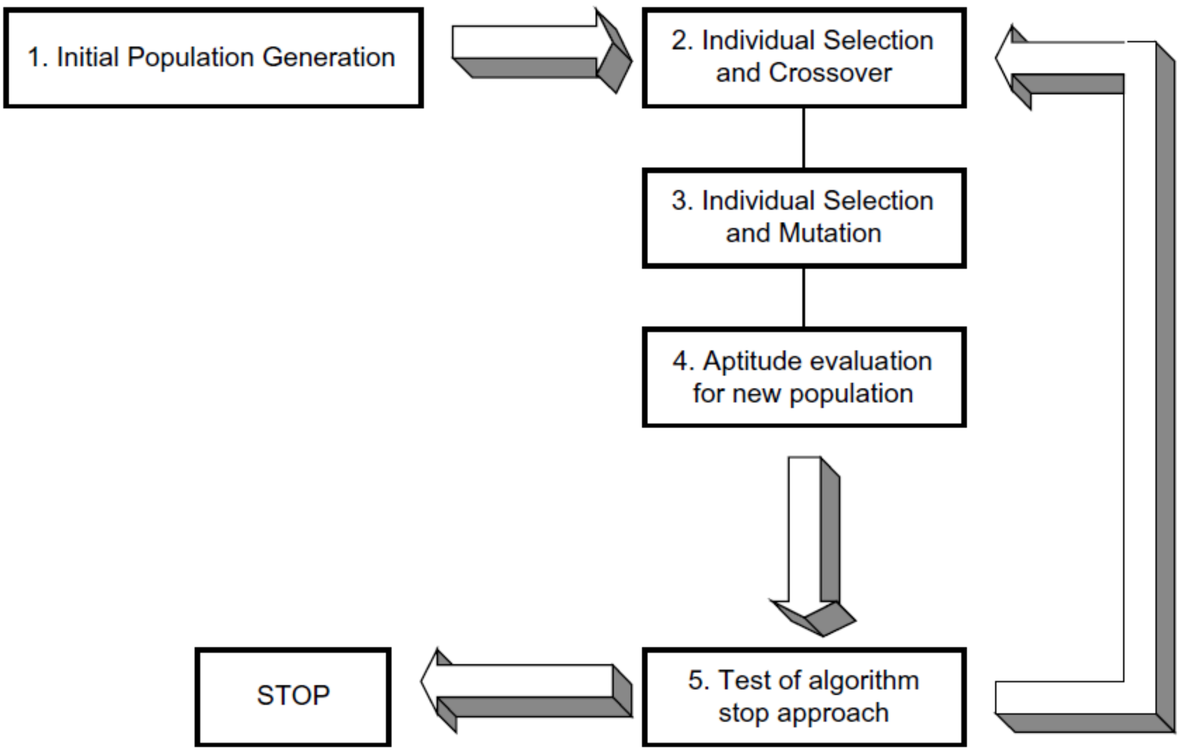


Fig – 15. Genetic operation for each generations.(Ravagnani et al., 2005)

Fig – 14 shows a simplified flow-chart about different operations in a genetic algorithm. In the genetic algorithm, the transition from one generation to next generation consists of three basic process; which are,

- <u>Selection:</u>

  In the selection process, per the fitness or objective function value, individuals are selected for reproduction.

- <u>Cross-over:</u>

  Two individual containing genetic information or coding are merged together to produce good children or solution in this process.

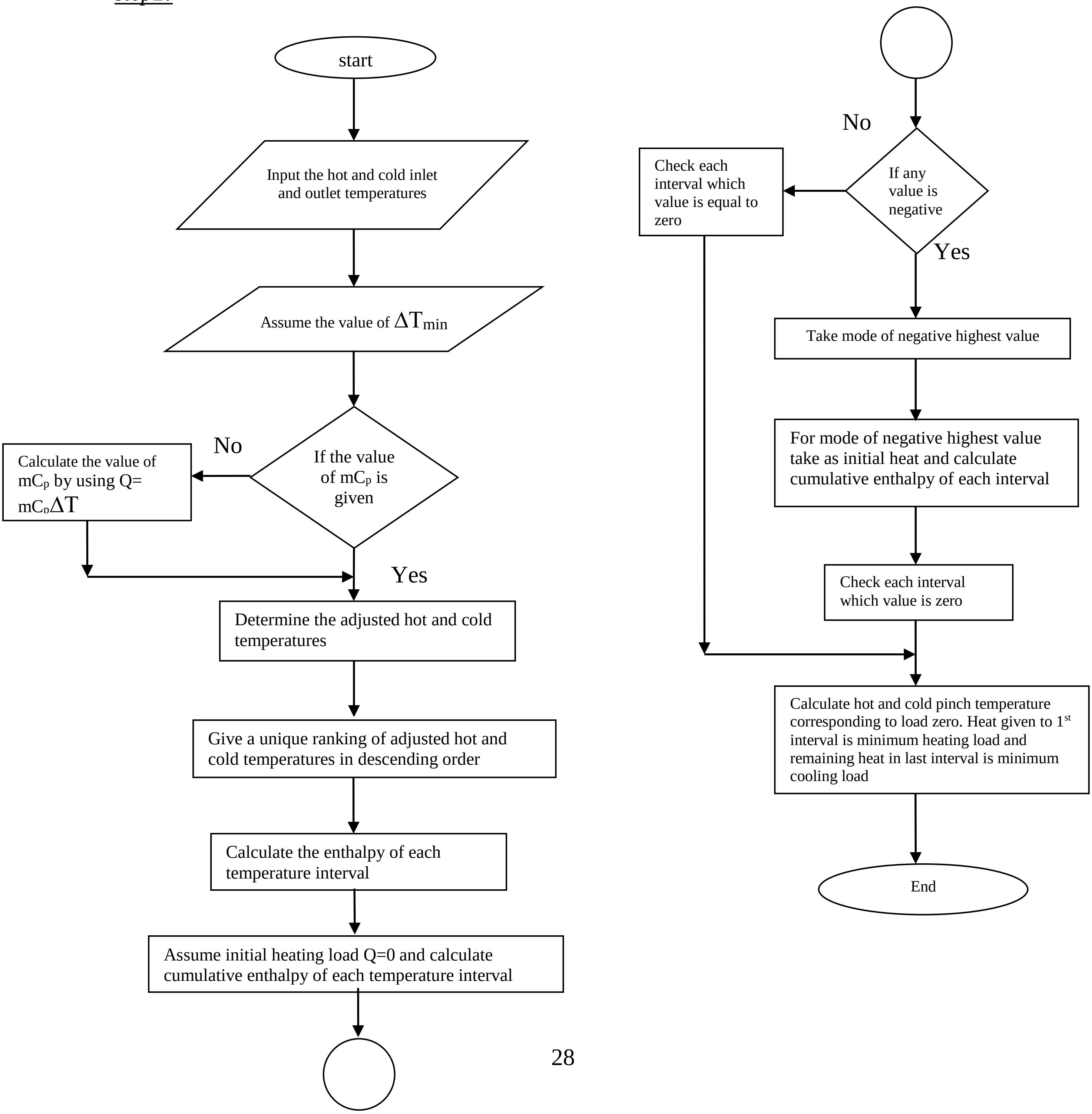
- <u>Mutation:</u>

  The mutation is the process in which random deformation of strings occurs with a certain probability to avoid local maxima. (Bodenhofer, October,2003)

3. Analytical method:

The methodology implemented in this thesis consists of two distinct stages. In the first stage, Pinch Analysis is used to find the pinch temperature or pinch point and in the second stage the heat exchangers are placed between the cold and hot streams using genetic coding to find the optimal solution that is optimal operating cost of the plant. The tool used here for optimization is MATLAB. The below steps explains the process of energy analysis done in this thesis

step1:



The above flow chart explains the steps in Pinch Analysis (Tewari et al., 2015). In the Pinch Analysis step, the actual steam temperatures are converted to interval temperatures using the below equations,

Hot streams $T_{int} = T_{act} - \Delta T_{min}/2$………………(eq – 12)

Cold streams $T_{int} = T_{act} + \Delta T_{min}/2$………………(eq – 13)

Where, T_{int} is the interval temperature, T_{act} is the actual temperature, ΔT_{min} is the minimum temperature difference. The minimum temperature difference is assumed and interval temperature is calculated.

From appendix–1 shows the codes which are used to in the construction of hot and cold composite curve to implement the Pinch Analysis in MATLAB. The initial heating value is assumed to be zero. After finding the temperature intervals, there will be some duplicate temperatures, which are arranged in the order of magnitude. Heat balance is carried out for streams within each temperature intervals. There will be few negative values which are eliminated by introducing some heat.

The pinch analysis is used as a function file which will be used later for heat exchanger network synthesis. The minimum temperature difference is added manually to find the possible pinch temperatures. A grand composite curve is then constructed from merging the hot and the cold composite curve in one graph. From the grand composite curve the pinch temperature is determined.

Step2:

The equation for area of heat exchanger and cost function or objective function to run the gene coding is implemented as a function in MATLAB. The equation for calculating area is given below,

$Q = UA\Delta T_{lm}$ W……………………………………(eq – 14)

$Q = \dot{m}C_{p,h} (T_{h,in} - T_{h,out}) = \dot{m}C_{p,c} (T_{c,in} - T_{c,out})$ W……………………………………..(eq – 15)

$\Delta T_{lm} = [(T_{h,in} - T_{h,out}) + (T_{c,in} - T_{c,out})]/[\ln((T_{h,in} - T_{h,out})/ (T_{c,in} - T_{c,out}))]$……………(eq – 16)

Where,

Q is the heat transfer rate (W),

U is the overall heat transfer co-efficient (W/Km^2), A is the surface area of the heat exchanger (m^2),

ΔT_{lm} is the logarithmic mean temperature difference (K),

$T_{h,in}$ is the inlet temperature of hot stream (K),

$T_{h,out}$ is the outlet temperature of hot stream (K),

$T_{c,in}$ is the inlet temperature of cold stream (K),

$T_{c,out}$ is the outlet temperature of cold stream (K),

$\dot{m}$ = mass flow rate of fluid (kg/sec),

$C_{p,h}$ and $C_{p,c}$ is the specific heat capacity of hot and cold fluid respectively (J/kg.K).

To calculate the area, heat transfer rate is calculated using eq-15. After finding the heat transfer rate, it is substituted in eq-14 followed by the logarithmic mean temperature difference and overall heat transfer co-efficient. The above equations are then implemented as a function so that they can be used by the gene coding for optimization.

The objective function is the cost equation which is also used as a function file along with area in MATLAB. The cost function used is as follows,

Cost of heat exchanger = $A_1 + A_2\,[\text{area}]^{A_3}$ \$/yr

Where A_1, A_2 and A_3 are constants in the cost function.

Capital cost = cost of heat exchangers + operating cost of heat exchangers + cost of hot utilities + cost of cold utilities \$/yr

step3:

The final step involves in forming a gene coding system to optimize the cost and reduce the energy usage. It is done by combining the pinch analysis along with the cost estimation in the gene coding. First the program is written in such a way that it should randomly place the heat exchanger between the hot stream from cold streams. The constraint used is that cold stream temperature is less than the hot stream temperature. The next step is to allot the number of heat exchangers and number of solutions to be saved. After allotting the number of heat exchangers and number of solutions, only possible random connections between the streams are made. After arranging the heat exchangers, the order of streams is corrected and the boundary conditions such as the lower limit and upper limits are set. And initial guesses are made. The MATLAB function 'fmincon' is used to find the minimum cost based upon the placement of heat exchangers. In this case the gene coding selects the individual streams based upon the cost function and place the heat exchanger between the hot and cold streams. In this particular case, cross-over is not included.

4. Results and discussion:

4.1 Case study - 1:

To test the coding designed, a simple case study was chosen from Gundersen model. The data's from Gundersen model is represented in the below table – 4,

Table – 4: problem data for case study (Escobar and Trierweiler, 2013)

Streams	T_{in} (ºC)	T_{out} (ºC)	$\dot{m}C_p$ (kW/ºC)	H (kW/m^2 ºC)
H1	270	160	18	1
H2	220	60	22	1
C1	50	210	20	1
C2	160	210	50	1
CU	15	20	-	1
HU	250	250	-	1

Cost of heat exchanger = $A_1 + A_2\,[\text{area}]^{A_3}$ \$/yr

$A_1 = 4000$

$A_2 = 500$

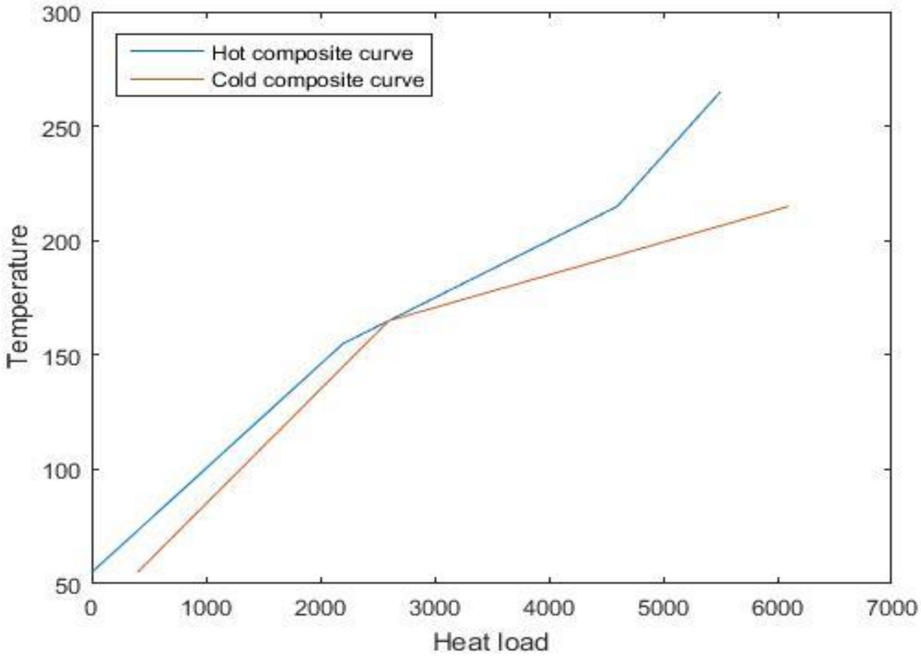
$A_3 = 0.83$

Cost of cold utility = 20 ($/kW.yr)

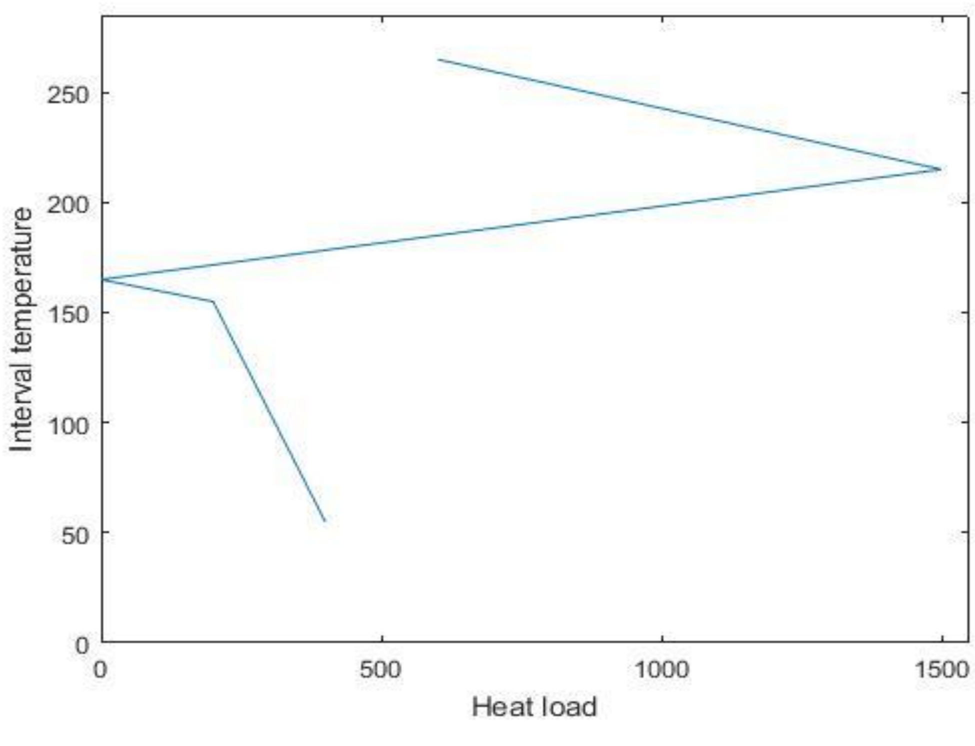
Cost of hot utility = 200 ($/kW.yr)

Number of heat exchangers = 6

The above values or data were implemented on program and it was compared with the original solution.



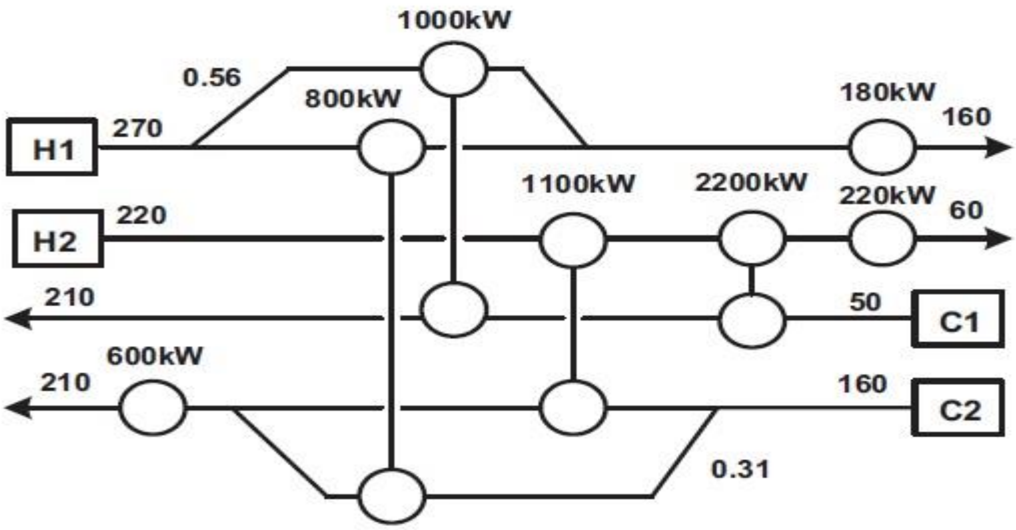
(a) Hot and cold composite curve obtained from MATLAB for the above data.



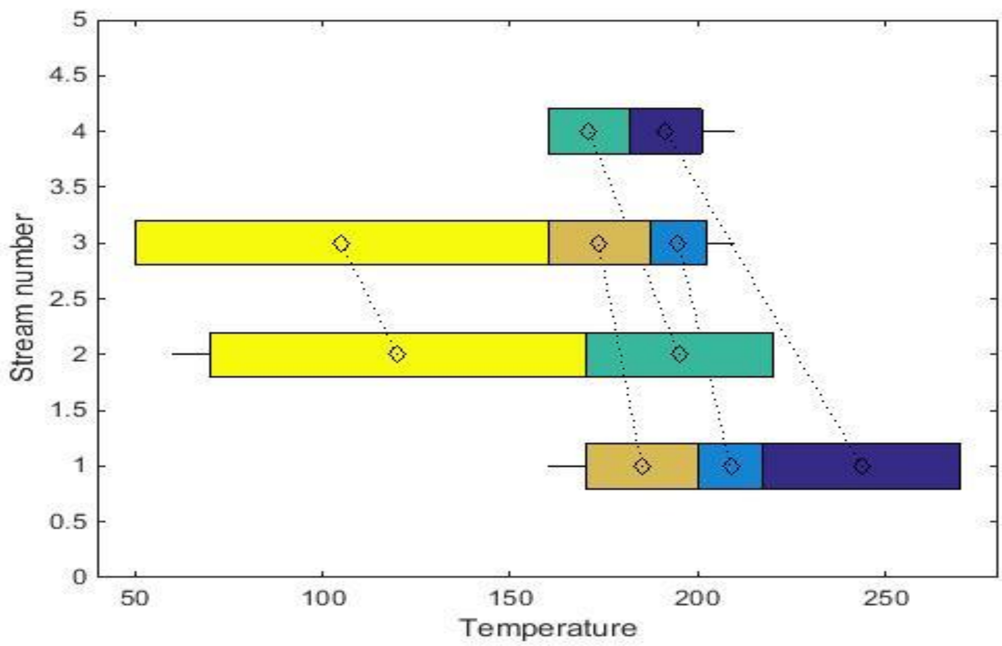
(b) Grand composite curve obtained from MATLAB for the above data.

Fig – 16. Composite curves obtained from above data.

From the data in table – 4, the hot and cold composite curve and the grand composite curve is constructed. The idea is that the user input stream data and the program calculates the minimum energy demand for cooling and heating as well as identifies the pinch point. In fig - 16 the x-axis heat load is plotted against the y-axis interval temperature to form the hot and cold composite curve. The pinch point obtained for this case study is165 ºC.



(a) Actual placement of heat exchangers from reference model. (Escobar and Trierweiler, 2013)



(b) Obtained placement of heat exchanger from MATLAB.

Fig – 17. Comparison between the actual and obtained heat exchanger network.

Table – 5: Comparing costs and utility demand:

cost and utility	Reference model	Obtained model
Operating cost ($/yr)	128000	128000
Min cold utility (kW)	400	400
Min hot utility (kW)	600	600
Capital cost ($/yr)	248387.2	270700

After the grand composite curve and the pinch temperature is found, the program is entering the gene coding stage where its find the best possible match between the streams and finds the optimal heat exchanger cost. From fig – 17 it can be see that the placement of heat exchangers is different between the obtained one and the actual reference model. From the table – 5, it can be noted that the operating cost and the hot and cold utility demand remains the same for both actual and obtained model. There is some difference in the capital cost between the actual and the obtained because the actual network model considered the steam splitting and steam combining in their heat exchanger network design. The obtained program cannot handle steam splitting and steam combining.

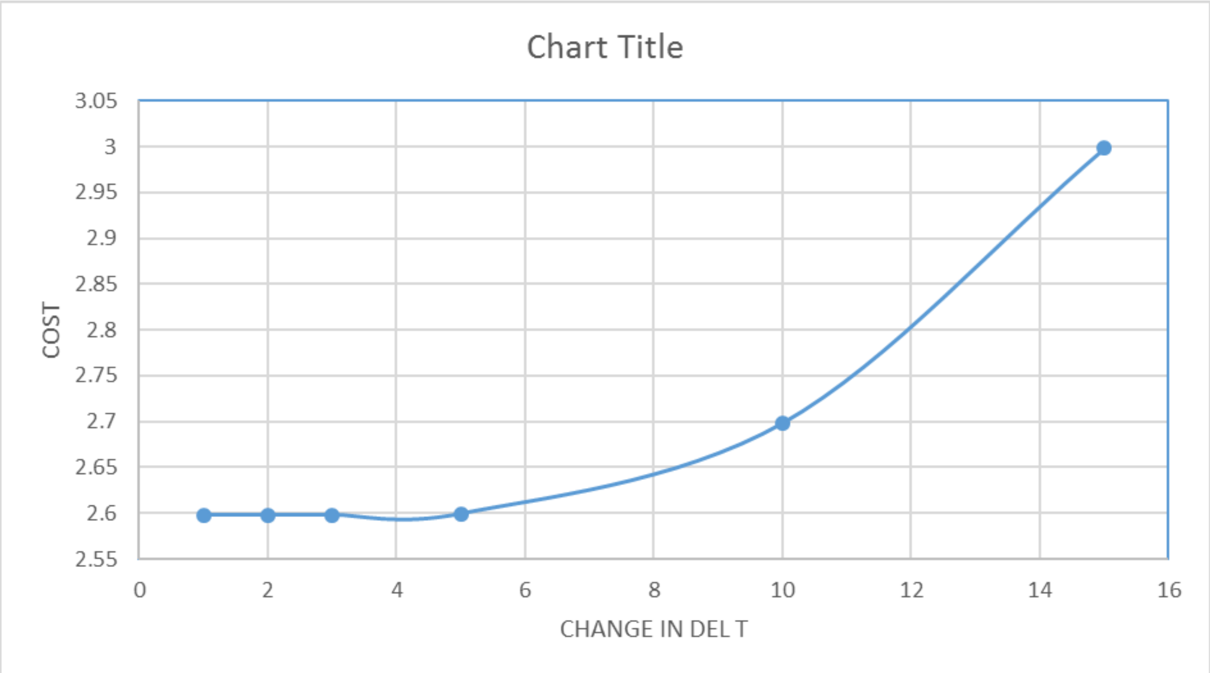


Fig – 18. A graph plotted between the ΔT_{min} and the capital cost.

From fig – 18 it can be noted a graph is plotted between change in ΔT_{min} and capital cost to find the effects of ΔT_{min} on the cost. From the graph, as ΔT_{min} increases the cost increases but below $\Delta T_{min} = 6$ the cost is constant or there are only minor changes in the value of cost. The reason why a cost increase is not seen for small values of ΔT_{min} in this optimization is that the program optimizes with the target of minimizing the cost with a temperature difference of at least $\Delta T_{min,}$ but it does not require the specific temperature difference to be achieved.

4.2 Case study – 2:

In this case study the coding is tested against a complex design to check the capability the coding against multiple heat exchangers and the time the MATLAB program took to find an optimal solution. Same data from the Gunderson model were chosen but the number of heat exchangers were increased.

Table – 6: Impact on cost due to number of heat exchangers and the time it took to find solution:

Number of heat exchangers	Elapsed time (sec)	Operating cost ($/yr)	Capital cost ($/yr)
8	246.1173	128000	269810
10	373.2784	128000	269810
12	403.3831	128000	270700
20	947.1394	128000	270700

From table-6 it can be noted that as the number of heat exchangers increases the time to find the optimal solution also increases. The capital cost also increases as the number of heat exchangers increases but becomes constant after adding more heat exchangers but the operating cost remains the same.

4.3 Case study – 3:

In case study- 3 the compatibility of the program is tested against a model containing more number of streams. In this study data from Bjork and Pettersson is used.

Table – 7: Problem data for case study (Pettersson, 2005)

Streams	T_{in} (ºC)	T_{out} (ºC)	$\dot{m}C_p$ (kW/ºC)	H (kW/m^2 ºC)
H1	180	75	30	2
H2	280	120	15	2.5
H3	180	75	30	2
H4	140	45	30	2
H5	220	120	25	1.5
H6	180	55	10	2
H7	170	45	30	2
H8	180	50	30	2
H9	280	90	15	2
H10	180	60	30	2
H11	120	45	30	2
H12	220	120	25	2
H13	180	55	10	2
H14	140	45	20	2
H15	140	60	70	2
H16	220	50	15	2.5

H17	220	60	10	2.5
H18	150	70	20	2
H19	140	80	70	2
H20	220	50	35	2
H21	180	60	10	2
H22	150	45	20	2.5
C1	40	230	20	1.5
C2	120	260	35	1
C3	40	190	35	1.5
C4	50	190	30	2
C5	50	250	60	2
C6	40	150	20	2
C7	40	150	20	2
C8	120	210	35	2.5
C9	40	130	35	2.5
C10	60	120	30	2.5
C11	50	150	10	3
C12	40	130	20	1
C13	120	160	35	1
C14	40	90	35	1.75
C15	50	90	30	1.5

C16	50	150	30	2
C17	30	150	50	2
CU	25	40	-	2
HU	325	325	-	1

Cost of heat exchanger = $A_1 + A_2\,[\text{area}]^{A_3}$ \$/yr

$A_1 = 8000$

$A_2 = 800$

$A_3 = 0.80$

Cost of cold utility = 10 (\$/kW.yr)

Cost of hot utility = 70 (\$/kW.yr)

$\Delta T_{min} = 5$

The above values or data were implemented on program and it was compared with the original solution.

Table – 8: Comparing costs and utility demand:

cost and utility	**Reference model**	**Obtained model**
Operating cost (\$/yr)	709000	715600
Cold utility (kW)	11740	11833
Hot utility (kW)	8460	8532.5
Capital cost (\$/yr)	1998000	2723200

From table – 8, it can be noted that the operating cost and the hot and cold utility demand is higher compared to the reference model. There is also huge difference in the capital cost and the operating cost as the obtained program cannot handle steam splitting and steam combining. In the obtained model 50 heat exchangers were used as a starting value and the actual number of heat exchangers which were placed on the streams are 28.

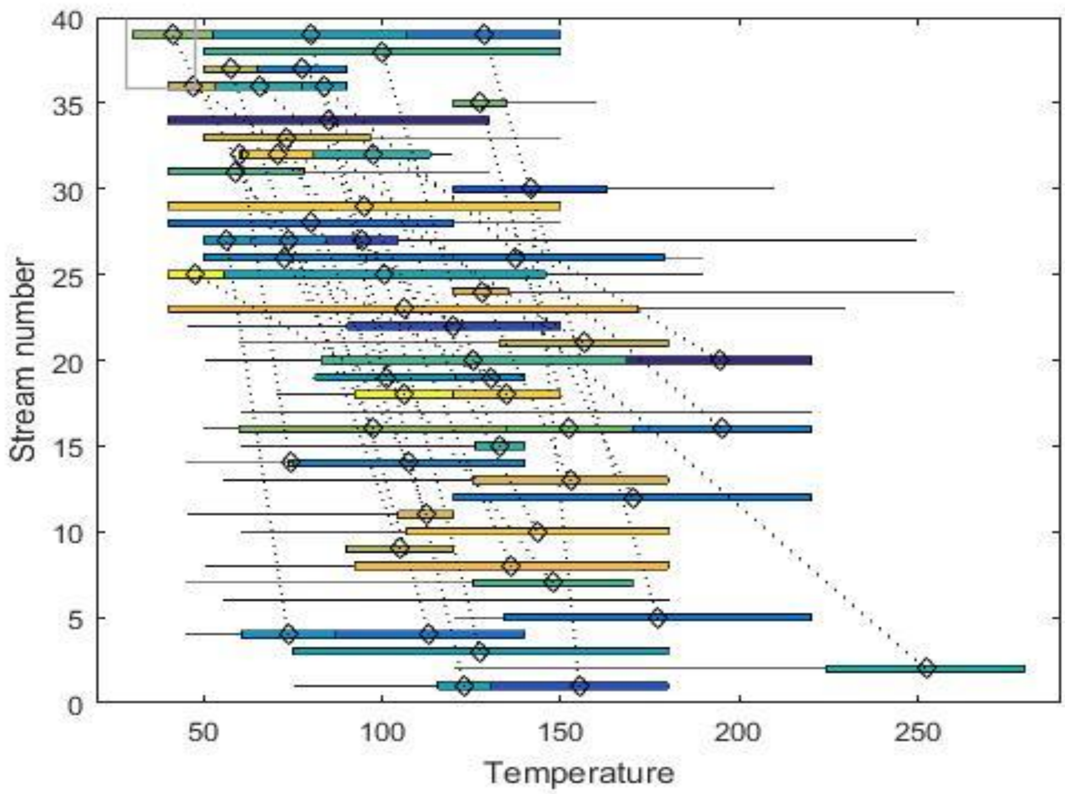


Fig – 19. Heat exchanger network for multiple streams.

From fig – 19 it can be noted that the coding can find an optimal solution for multiple streams in this case its 39 streams that is 22 hot streams and 17 cold steams.

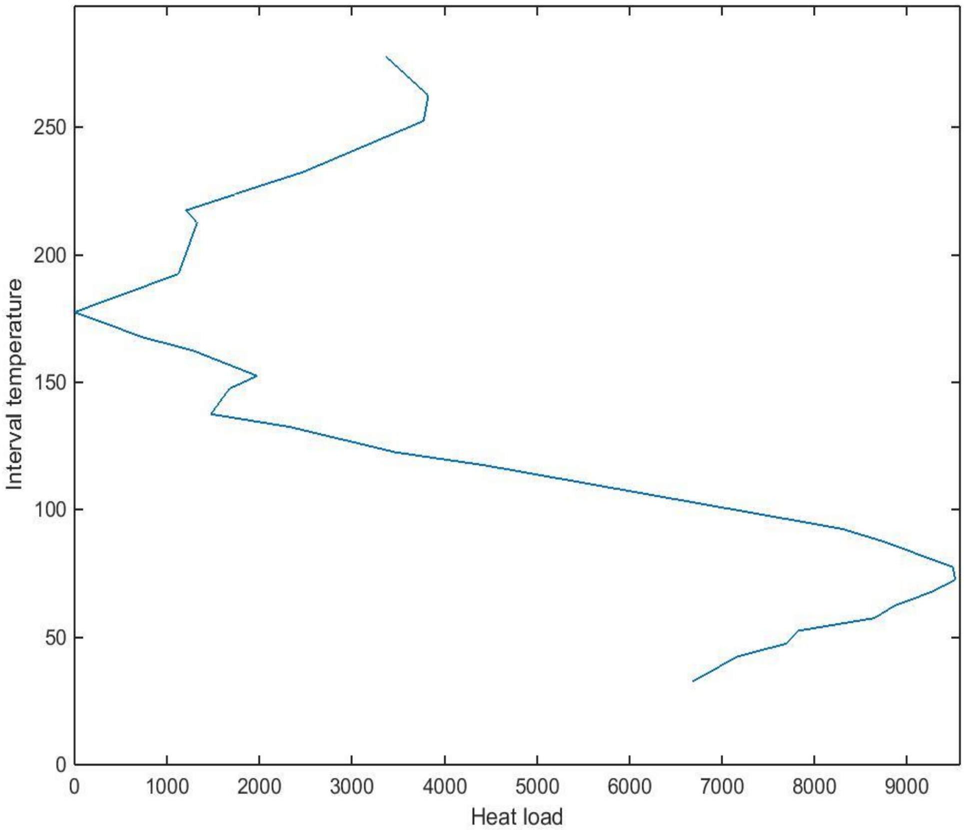


Fig – 20. Grand composite curve from above data.

Fig – 20 shows the grand composite curve for the multiple stream case. From the fig it can be seen that the minimum hot utility is 3375 kw and the minimum cold utility is 6675 kw.

5. Conclusions:

The most studied problems in the process synthesis is the heat exchanger network synthesis but finding a feasible solution even for a small-scale problem has been troublesome. In this work, the main optimization for the heat exchanger network and reduction of cost is carried out using genetic algorithm or gene coding. The coding method implemented is tested on a reference model which is simple that is consisting of four streams were chosen and the obtained results were compared with the actual one. In this synthesis, the algorithm can evolve towards the optimum solution by implementing a good starting point to start the program. The method used in this work cannot handle steam splitting and steam combining thus a perfect optimal solution was not found or the capital cost was not equal to the actual reference model. As the coding can handle complex cases such as increase in number of heat exchangers and number of streams, it can be used in finding optimal solution for process plants containing multiple heat exchangers and multiple streams.

Since due to the limited amount of time the optimization process in this work is not fully completed as this model or optimization process cannot handle steam splitting and combining. In the future, this step can be implemented in to this process to have a fully optimized process and the results obtained will be equal to the reference model.

Appendix 1:

```
number=size(Tin,2);
nh=0;
nc=0;
for i=1:number
    if Tin(i)>Tout(i)
         nh=nh+1;
         Tinterval(i,1:2)=[Tin(i) Tout(i)]-dT(i);
    else
        nc=nc+1;
        Tinterval(i,1:2)=[Tin(i) Tout(i)]+dT(i);
    end
end


%hot composite curve
T_h=sort([Tinterval(1:nh,1);Tinterval(1:nh,2)],1,'ascend');
nint_h=size(T_h,1);
dT_hot=T_h(2:nint_h)-T_h(1:nint_h-1);
heat_hot=zeros(nint_h,1);
hot_cascade=zeros(nint_h,1);
for i=2:nint_h
    for j=1:nh
        if Tinterval(j,1)>=T_h(i) && Tinterval(j,2)<=T_h(i-1)
            heat_hot(i-1)=heat_hot(i-1)+F(j)*dT_hot(i-1);
        end
    end
    hot_cascade(i)=hot_cascade(i-1)+heat_hot(i-1);
end

% Cold composite curve
T_c=sort([Tinterval(nh+1:nh+nc,1); Tinterval(nh+1:nh+nc,2)],1,'ascend');
nint_c=size(T_c,1);
dT_cold=T_c(2:nint_c)-T_c(1:nint_c-1);
heat_cold=zeros(nint_c,1);
cold_cascade=zeros(nint_c,1); %this will be adjusted later to match dT at the pinch
for i=2:nint_c
    for j=nh+1:nh+nc
        if Tinterval(j,2)>=T_c(i) && Tinterval(j,1)<=T_c(i-1)
            heat_cold(i-1)=heat_cold(i-1)+F(j)*dT_cold(i-1);
        end
    end
    cold_cascade(i)=cold_cascade(i-1)+heat_cold(i-1);
end

```

(a) Coding's used in construction of hot and cold composite curve.

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```matlab
%Grand composite curve

Tint=sort([Tinterval(:,1);Tinterval(:,2)],1,'descend');
n=size(Tint,1);
dTint=Tint(1:n-1)-Tint(2:n);
heat_load=zeros(n-1,1);
cascade=zeros(n,1);
for i=2:n
    for j=1:number
        if max(Tinterval(j,1:2))>=Tint(i-1)  && min(Tinterval(j,1:2))<=Tint(i)
            if Tin(j)>Tout(j)
                heat_load(i-1)=heat_load(i-1)+F(j)*dTint(i-1);
            else
                heat_load(i-1)=heat_load(i-1)-F(j)*dTint(i-1);
            end
        end
    end
    cascade(i)=cascade(i-1)+heat_load(i-1);
end

if min(cascade)<0
    cascade=cascade-min(cascade)*ones(n,1);
else
    cascade=cascade+min(cascade)*ones(n,1);
end

%Pinch temeprature
i=find(cascade==0);
T_Pinch=Tint(i);

%minimum heat requirement
MinH=cascade(1);
MinC=cascade(n);



%adjustment of compositie curve to pinch point and dT
cold_cascade=cold_cascade+MinC*ones(nint_c,1);

%plotting figures
figure (1)
plot(hot_cascade,T_h)
hold on
plot(cold_cascade,T_c)
```

(a) Coding for construction of grand composite curve.

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