International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 5, May - 2014

MCT Logic: A mathematical Paradigm for Area Integration in Heat Exchanger Networks

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***Abstract*— Myriads of researchers have carried out the best possible heat integration networks for utilization of maximum heat loads and minimum area for heat exchange. Recently many new algorithms like SePTA, PTA and DE have been used to carry out the network synthesis for the best possible Heat Exchanger Network design with optimal area integration. With the approach of a sequential algorithm, i.e. SePTA, if a shift in minimum approach temperature is carried out, it is called Modification in Corrected Temperature, or MCT Logic. SePTA has been followed for the remaining calculations. The updated results obtained by using the above mentioned MCT Logic have led to a decrease in the integrated area for the network. Furthermore, these results were validated by considering the latest algorithms and it was found that our approach was effective. Modification in Corrected Temperature is a simple algorithm which can be executed using a spreadsheet and resulted reduction in area requirement.**

Keywords-HEN, Pinch Point, Minimum Approach Temperature (ΔT_{min}), MCT Logic

I. INTRODUCTION

The prime objective of every industry is to run a chemical plant economically. For achieving this purpose, many technological advances have been made over several decades. With healthy energy utilization in view, the concept of heat exchangers came into place which optimized plant economics by exchanging thermal energy between hot and cold streams. However, with industries getting bigger and more in number, maintaining economy of plants became increasingly important. Thus, the concept of Heat Exchanger Networks (HEN) came into picture, where, heat exchangers were optimally arranged between various hot and cold streams for minimum energy consumption.

For calculations pertaining to this discipline in plant economization, i.e. Pinch Technology, a heuristic approach is applied and rules of thumb are employed to optimize the best possible heat exchanger network. For this, it is necessary to find the pinch point, a point where the plant is most constrained. Energy transfer does not take place across this point and the heat exchanger network is also designed with this point under consideration.
In this report, Pinch Analysis is carried out by Segregated Problem Table Algorithm (SePTA)[1]. We will illustrate a modification, i.e. MCT Logic, which takes a different approach to the Minimum Approach Temperature (ΔT_{min}). This reduces the overall area of heat transfer in the network and distributes the available energy uniformly, thereby making it more efficient. ΔT_{min} is the maximum allowable deviation in the measured inlet and outlet temperatures of the heat exchangers in the network.

II. SEGREGATED PROBLEM TABLE ALGORITHM

SePTA is a numerical tool used for design of a heat exchanger network that maximises the energy efficiency and reduces the overall area, thereby increasing the economic feasibility. This method is used for simultaneous targeting of the energy profile to obtain optimum results.

SePTA is an extension of the Stream Temperature v/s Enthalpy Plot (STEP), which is a graphical tool for energy targeting. This method overcomes the limitations of the traditional pinch analysis method. The STEP plot is constructed on the basis of the profiles of continuous hot and cold stream, mapped on a graph of temperature v/s enthalpy that shows the pinch point and the heating and cooling loads. SePTA can complement this method on the basis of accuracy and speed, as it is based on linear algebraic calculations and can be easily programmed and simulated. The general procedure followed for configuration of HEN by means of SePTA can be explained with the help of a flow chart (Fig.3.1)

The main advantage of SePTA is that it can locate the pinch point, calculate the utility targets, and map the individual streams and its corresponding enthalpy and eventually perform the heat exchanger network design simultaneously. Along with speed, SePTA gives accurate results. It is based on simple numerical and algebraic formulae and thus, is easy to program on software like MS Excel.

Despite being easily programmable, the codes aren't fully automated and require manual input of certain values. Attempts are being made by researchers to fully automate the programming of SePTA. Due to its simplicity, reliable effectiveness and speed, we will use SePTA to carry out our calculations for configuration of HEN with an additional support of MCT Logic.

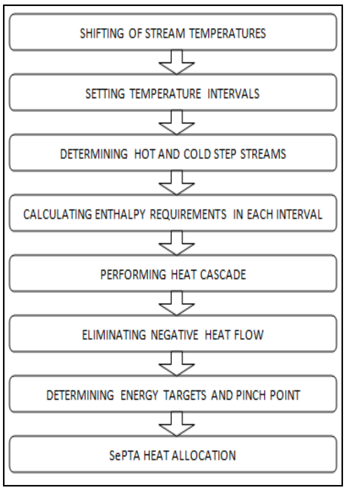


Fig.1- General Procedure for SePTA

III. MODIFICATION IN CORRECTED TEMPERATURE LOGIC (MCT LOGIC)

As stated earlier, Minimum Approach Temperature (ΔT_{min}) is an allowable deviation in the measured inlet and outlet temperatures of a heat exchanger in a HEN. This is accounted for the process to withstand conditions where variables may change. By using ΔT_{min}, we can obtain the corrected temperatures of each stream.

For hot streams,

$$T = T - \frac{\Delta Tmin}{n} \qquad (1)$$

For cold streams,

$$T = T + \frac{\Delta Tmin}{n} \qquad (2)$$

Where n is the stream splitting factor.

Now, Minimum Area of the HEN is calculated as:

$$A_{min} = \sum_i \left[\frac{1}{\Delta T_{lm}} \sum_j \frac{q_j}{h_j} \right] \qquad (3)$$

Clearly, for the same amount of energy required, if the value of log mean temperature difference increases, minimum area required for HEN will effectively get reduced. This reduction in area will in turn, ensure that the overall energy distribution in the network is uniform, thus making it more efficient. Modifying the corrected temperatures in the initial stage can hence, change the dynamics of area requirement and consequentially, efficiency of the HEN.

We aim to apply this logic in a number of case studies and design a compact multi-stream heat exchanger network and compare the results.

IV. CASE STUDY

For the given problem, with two hot streams and cold streams each, values of inlet and outlet temperatures, specific heat flow-rates and the resulting enthalpies are given as (Table 1):

Stream	T_{in} (^oC)	T_{out} (^oC)	FC_p (MW /^oC)	Mass Fl Rate (kg/sec)
H1	80	55	0.6279	0.15
H2	95	65	0.4186	0.1
C1	30	45	0.8372	0.2
C2	10	25	1.2558	0.3

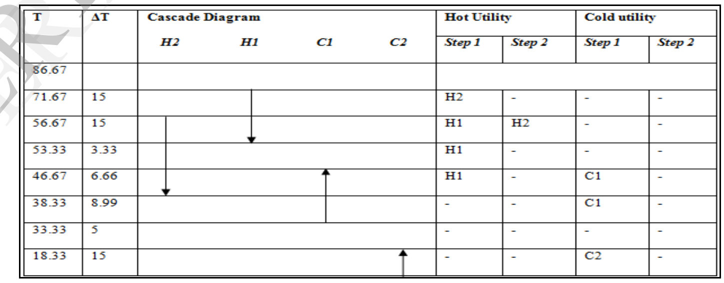
Table 1- Case Study

We can shift the inlet and outlet temperatures with the help of MCT Logic (Table 2):

Stream	Ti	To	FC_p	T_{Mi}	T_{Mo}
H1	80	55	0.6279	71.66667	46.66667
H2	95	65	0.4186	86.66667	56.66667
C1	30	45	0.8372	38.33333	53.33333
C2	10	25	1.2558	18.33333	33.33333

Table 2- Shifting of temperatures using MCT logic

Using these temperature values, we make a cascade diagram for hot and cold streams. We first arrange the hot and cold streams in decreasing order of their specific heat flow-rates respectively. We then allocate these streams to different steps in each interval as shown in Table 3.



T	ΔT	Cascade Diagram				Hot Utility		Cold utility	
		H2	*H1*	*C1*	*C2*	*Step 1*	*Step 2*	*Step 1*	*Step 2*
86.67									
71.67	15					H2	-	-	-
56.67	15					H1	H2	-	-
53.33	3.33					H1	-	-	-
46.67	6.66					H1	-	C1	-
38.33	8.99					-	-	C1	-
33.33	5					-	-	-	-
18.33	15					-	-	C2	-

Table 3- Step Selection

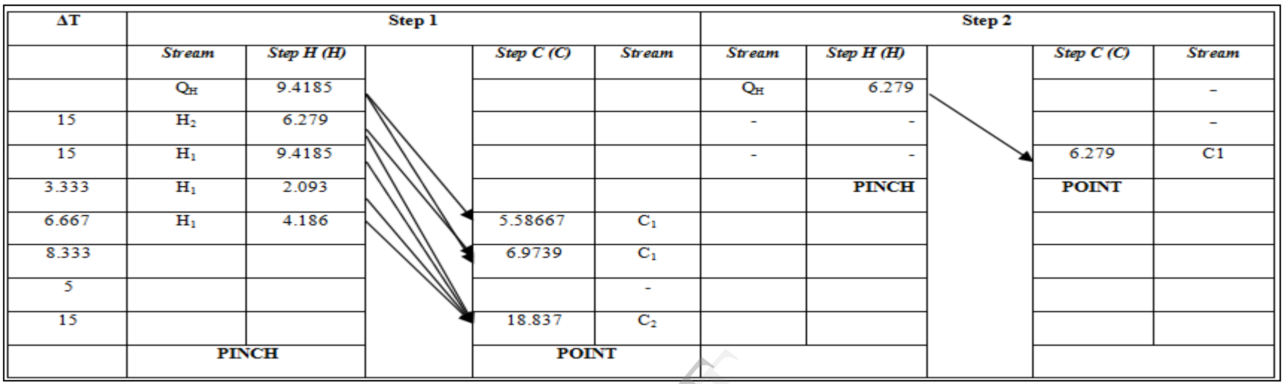
From the cascade diagram, we obtain stepwise stream allocation for each interval. Using this data, we can find the energy requirements of each interval with respect to individual steps and can thus, calculate cumulative enthalpies at each interval.

The minimum values in these columns are the heating loads which are then supplied to the top interval and added individually to every interval to obtain the feasible enthalpies. From here, the value of the bottom most enthalpy obtained is the cooling load. The point across which net heat transfer is zero is the Pinch Point. For both steps, Pinch Point should be obtained at the same interval. This process is illustrated in Table 4.

After obtaining the feasible energy, we carry out SePTA Heat Allocation (SHA) process, where heat is cascaded by starting from the top of the Q_f column and moving downwards from hot to cold streams. No heat transfer occurs across the Pinch Points (this being a case of multiple pinch points), thus indicating minimum utility requirement as shown in Table 5.

			Step Selection (H)		Step Selection (C)		FCp		Q		Q cum		Q rev	
TC	DT		Step 1	Step 2	Step 1	Step 2	Step 1	Step 2	Step 1	Step 2	Step 1	Step 2	Step 1	Step 2
86.666667														
71.666667	15		0.4186	0	0	0	0.4186	0	6.279	0	6.279	0	15.6975	0
56.666667	15		0.6279	0.4186	0	0	0.6279	0.4186	9.4185	6.279	15.6975	6.279	25.116	6.279
53.333333	3.33333		0.6279	0	0	0	0.6279	0	2.093	0	17.7905	0	27.209	0
46.666667	6.66667		0.6279	0	0.8372	0	-0.2093	0	-1.39533	0	16.3952		25.8137	
38.333333	8.33333		0	0	0.8372	0	-0.8372	0	-6.97667	0	9.4185		18.837	
33.333333	5		0	0	0	0	0	0	0	0	9.4185		18.837	
18.333333	15		0	0	1.2558	0	-1.2558	0	-18.837	0	-9.4185		0	

Table 4- Stream Temperature v/s Enthalpy Plot



ΔT	Step 1					Step 2				
	Stream	*Step H (H)*		*Step C (C)*	*Stream*	*Stream*	*Step H (H)*		*Step C (C)*	*Stream*
	Q_H	9.4185				Q_H	6.279			-
15	H_2	6.279				-	-			-
15	H_1	9.4185				-	-		6.279	C1
3.333	H_1	2.093					**PINCH**		**POINT**	
6.667	H_1	4.186		5.58667	C_1					
8.333				6.9739	C_1					
5					-					
15				18.837	C_2					
	PINCH			**POINT**						

Table 5- SePTA heat allocation

V. PROPOSED DESIGN

For a system containing two hot streams and two cold streams, we have proposed a design which is illustrated as follows.

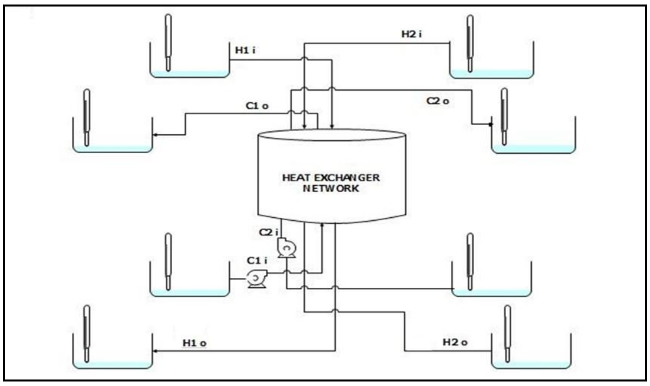


Fig 2- Proposed design

This is a compact heat exchanger network, where more than two streams interact in a compact environment. From this design, we have three possible contacting patterns: H_1 & C_2, H_2 & C_1 and H_2 & C_2.

After the Heat Allocation is carried out, we can combine all the energy transfers taking place between all streams and consecutively, design the Network Diagram, which gives us the final network and the area required by each stream individually for each interaction. Thus, with the help of the network diagram, we can calculate the overall area required for the network. The network diagram for the system is shown in Fig. 3

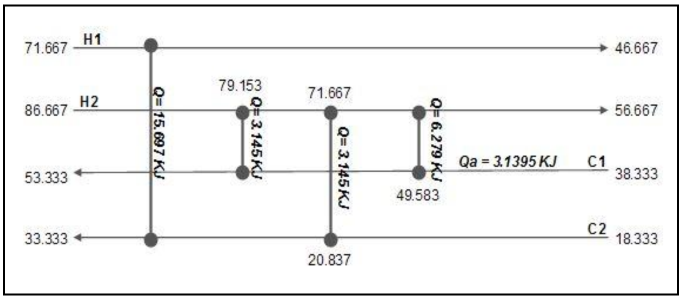


Fig 3- Network Diagram

VI. RESULTS

I. AREA

By correcting the stream temperatures with the MCT Logic, area required for the network is calculated as shown in the following table.

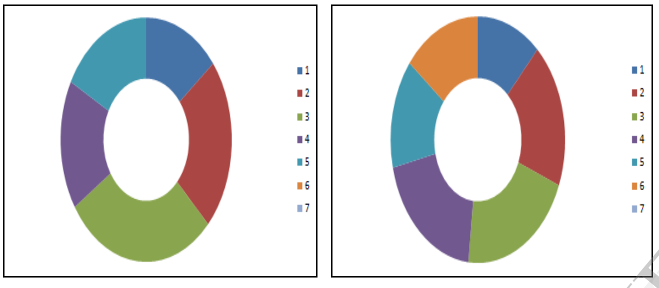
Stream	ΔT_1	ΔT_2	ΔT_{lm}	Q	U	Area
H1 & C2	38.33333	25.83333	31.6733	15.6975	240.9956	0.002056
H2 & C1	33.33333	29.58333	31.42105	3.1395	178.1765	0.000561
H2 & C2	58.33333	53.33333	55.796	3.1395	207.6238	0.000271
H2&C1(Q)	22.08333	14.58333	18.07473	6.279	178.1765	0.00195

Table 6- Area Calculation

The total area obtained for the following network, inclusive of the excess area accounted for the excess load in the network, is Area required for a heat exchanger network designed by correcting the temperatures with MCT Logic is calculated to be **9.692×10^{-3} m^{2}**. This is inclusive of the design considerations, which is covered under the aegis of the correction factor. This value is lesser than the area required for the network designed by conventional correction factor, the value for which is **11.706×10^{-3} m^{2}**, including excess area of 30% which is the standard design consideration. This means that the application of MCT logic has ensured the area reduction by 20.81%, which is a considerable amount. If we take the cost factor into account, considering the fabrication costs, we observe a 22.83% reduction in the total costs, excluding the maintenance costs.

II. ENERGY DISTRIBUTION

When temperatures are corrected by using MCT Logic, the designed HEN has more uniform energy distribution as compared to other network. This can be shown with the help of the doughnut diagrams (Fig. 3):



4(a) 4(b)

Fig. 4: Energy Distribution in the Heat Exchanger Network

(a) By using conventional correction (b) By using MCT logic

We have applied the MCT Logic on 3 other case studies, taken from different research papers. There was a significant improvement in the uniformity of energy distribution all the networks that we had seen. There was a significant reduction in the area required for the network in all the case studies. Following is the table, where we have compared the areas obtained in the respective papers:

Case Study	No. of hot streams	No. of cold streams	Area obtained by the authors	Area obtained by MCT logic
Case Study 1[1]	3	3	5657.951m^{2}	4572.19 m^{2}
Case Study 2[2]	2	2	74.914 m^{2}	43.226 m^{2}
Case Study 3[3]	2	2	662.99 m^{2}	458.96 m^{2}

VII. CONCLUSION

As seen in the result comparison for all the case studies, the major differences that MCT Logic makes to the overall Heat Exchanger Network, is observed in the reduction in area and energy distribution in the network. By reducing the required area of the network it becomes economical. Also, with equal division of energy throughout the network, the whole system becomes more efficient. This also indicates that maximum energy is utilized within the network itself. These points can be noted as the major advantages of MCT Logic in Heat Exchanger Network Synthesis.

However, correction factor for heat losses and costing of individual units are not accounted for. Nevertheless, reduction in the required area and a more efficient energy balance in the network are complementary to reduced heat escaping and less energy wastage. The advantages, hence, more than compensate for these impediments as MCT Logic aids the economical functioning of a HEN by reducing its operational expenditures.

VIII. NOMENCLATURE

- MCT = Modification in Corrected Temperatures
- C_p = Specific Heat Capacity (MW kg^{-1O}C^{--1})
- FC_p = Specific Heat Flowrate (MW ^{O}C^{--1})
- T_{in} = Inlet Temperature (^{O}C)
- T_{out} = Outlet Temperature (^{O}C)
- $T_{i\,(mod)}$ = Corrected Inlet Temperature (^{O}C)
- $T_{o\,(mod)}$ = Corrected Outlet Temperature (^{O}C)
- ΔT = Difference in Temperature (^{O}C)
- i, j = Enthalpy intervals
- q_j = Enthalpy change in jth stream
- h_j = Heat transfer co-efficient of jth stream
- ΔT_{min} = Minimum Approach Temperature (^{O}C)
- ΔT_{lm} = Log Mean Temperature Difference
- ΔH = Change in Enthalpy (MW)
- Q_H = Heating Load (MW)
- Q_C = Cooling Load (MW)
- $Q_{cumulative}$ = Cumulative Heat (MW)
- $Q_{feasible}$ = Feasible Energy (MW)
- A_{min} = Minimum Area Required for HEN (m^{2})
- U= Overall Heat Transfer Coefficient(MW m$^{2\,o}$C^{-1})
- PTA = Problem Table Algorithm
- SePTA = Segregated Problem Table Algorithm
- DE = Differential Evolution
- STEP = Steam Temperature vs. Enthalpy Plot
- SHA = SePTA Heat Allocation
- HEN = Heat Exchanger Network

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