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Energy Savings in Cement Industry: Use of Heat Integration Approach and Simulation Tools

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In thermo-chemical process industries, Heat Exchanger Network design and retrofit represent an important part of the plant design. The purpose of this network is to maximise heat recovery from process streams entering and exiting process equipment, thereby lowering the overall plant costs. The use of Pinch Technology in design ensures maximum heat recovery and minimum energy consumption resulting in minimum cost of hot and cold utilities. Energy Integration of cement industry was carried out using the principle of Pinch Technology. In present case study, Heat Exchanger Network was designed by use of methodology of Aspen Energy Analyser software V10.0 and Pinch Technology. The optimum minimum approach temperature of 11 °C was used to determine the energy target and the Pinch Point Temperature was found to be 994.5 °C. The utilities targets at Minimum Approach Temperature were found to be 1.594×10^7 kJ/h and 1.075×10^8 kJ/h for hot and cold utilities respectively. Pinch Analysis is best energy integration technique, which saves more energy and utilities cost than the traditional energy technique.

1. Introduction

The cement industry is an important part of big chemical family. Cement is mostly used as raw material for any construction and modern infrastructure needs. Also the cement industry is an energy intensive industrial sector, where the energy requirement is approximately 40 % of total cost of production. The cement industry sector consumes 15-20 % energy among all the energy consuming sectors in India (Verma and Kumar, 2017) cement industry sector is one of the highest greenhouse gasses (GHG) emitting industrial sector, accounts for around 5% of global anthropogenic GHG emissions. The cement producers are required to reduce carbon dioxide emissions for as minimum 15 % by 2050, which represents the direct reduction up to 913 Mt of CO_2 (Boldyryev et al., 2016). For minimisation of CO_2 emissions and its impact on environment, it is necessary to adopt more energy efficient technologies (Klemeš et al., 2014). The existing process of cement plant is indicating a huge gap for energy efficiency. The minimal temperature approach between both hot and cold side is 380 °C which indicates poor level of heat recovery. Pinch Technology is one way to improve the existing process of industries to increase their profitability through reduction in energy, water and raw materials consumption, reduction in GHG emissions, and waste generation. The Pinch Technology usage allows in finding the balance between energy and costs as well as the correct the position of utilities and heat exchangers (Auta et al., 2012). In this paper, researchers use the Pinch Technology for increasing the energy efficiency of cement industry (Boldyryev and Varbanov, 2014).

Pinch Technology is based on the basic principles of first and second law of thermodynamics. It is easy to use, as it does not require any knowledge of complex mathematical formulation. Pinch Technology involves understanding of the concepts of Pinch Point, Composite Curves (CC), Grand Composite Curves (GCC) and HEN (Heat Exchanger Network) design. The design of Heat Exchanger Network is an important aspect of energy conservation, which leads to reduction in GHG emissions, and usage of external utilities in a plant. In this process, HEN is designed for a given minimum temperature difference (ΔTmin) resulting into Maximum Energy Recovery (MER) and minimum number of heat exchangers used (Manizadeh et al., 2018).

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The first step in the design of HEN is to find the Pinch Temperature from the extracted process (both hot and cold) streams to reach the requirement of minimum external utilities through the Problem Table Algorithm / temperature interval method using minimum temperature difference. Next step is to design Heat Exchanger Network that satisfies these targets, and later it can be optimized in targeting levels by comparing energy cost and the capital cost of the network, so that the total cost is minimised (Bokan and Pople, 2015). The principles involved in Pinch Technology are simplified by introducing the commercial software like Aspen Energy Analyser, which is developed by Aspen Technologies Ltd. This software combines Pinch Technology and mathematical programming in the design of Heat Exchanger Networks. This work uses the available process stream data of a cement industry to design the Heat Exchanger Network with the help of Aspen Energy Analyser in order to explore the energy and cost saving opportunities available to the plant.

2. Methodology

The adopted methodology for this study is based on the study done by Boldyryev et al., 2016 and Verma and Kumar, 2017. The synthesis of optimal flow sheets for Pinch Analysis initially developed by Linnhoff et al., 1998 and later other researchers followed the same for further development. In this work the Aspen Energy Analyser software developed by Aspen Technologies Ltd. was used for constructing of Composite Curve and design of Heat Exchanger Network. There are four key steps of Pinch Analysis in the design of Heat Exchanger Network for both new and existing processes: data extraction; targeting; HEN design and optimization.

2.1 Data Extraction

The stream data for cement industry is shown in below Table 1 the data extracted contains source temperature, target temperature, heat capacity flow rate (mass flow rate x specific heat capacity) of each stream and utility data and the cost data, which is helpful in determining the energy cost and capital investment. Calculation of heat duty for each stream is done by using Aspen Energy Analyser. The extracted data contains seven hot streams and nine cold streams.

Table 1: Stream Table [Verma and Kumar, 2017]

Stream Type	Source Temperature (Ts, °C)	Target Temperature (Tt, °C)	Heat Capacity Flowrate (kJ/°C.h)
H1	270	55	21.814
H2	1,000	280	66.946
H3	280	110	19.085
H4	280	90	1.193
H5	1,400	100	24.51
H6	290	100	114.839
H7	270	105	14.053
C1	30	100	68.008
C2	280	810	35.033
C3	810	1,400	34.625
C4	30	90	5.147
C5	90	150	2.86
C6	30	150	62.305
C7	30	290	128.564
C8	30	90	24.51
C9	30	90	5.343

2.2 Computer Simulation

The basic information needed to carry out Pinch Analysis with the help of Aspen Energy Analyser are inlet and out let temperatures of process and utility streams and heat capacity flow rate. The calculation of enthalpy of each stream is done by Aspen Energy Analyser. The Process Streams tab in Aspen Energy Analyser allows us to provide information about the process streams in the HEN. The Utility Streams tab allows us to provide the utilities used in the HEN to cool or heat the process streams (Bokan and Pople, 2015). In this study, we specified hot utility as a very high temperature steam and cooling utility as cooling water. The individual stream associated with default local heat transfer coefficient, which is calculated by Aspen energy Analyser.

The Pinch Design Method (PDM) was used to obtain a Heat Exchanger Networks. The next procedure was creating a problem table, Composite Curve, Grand Composite Curve and the cascade diagram to obtain pinch temperature, minimum hot and cold utilities at minimum approach temperature. The following assumptions were considered for the design of a counter current and shell and tube Heat Exchanger Network: constant heat capacities and no phase changes, respectively (Dagde and Piagbo, 2012). The purpose of design HEN is to match the process-to-process streams with less usage of cold and hot utilities. The design of HEN is an arrangement of several heat exchangers, which reduces the external utilities in the plant. The optimum design of HEN is required to maximise the heat recovery with minimal total cost design. Therefore, it is very essential to synthesize an optimum HEN with the minimum operating and capital costs (Owat and Skolpap, 2019).

3. Results and Discussion

The results obtained on various steps are summarised in below sections.

3.1 Minimum Temperature Approach

In order to generate minimum energy targets, the ΔTmin (minimum approach temperature) value was specified for the problem. Minimum Temperature Approach or ΔTmin is the minimum temperature difference allowed between hot and cold streams in the heat exchanger. It is an important design parameter for the development of energy efficient Heat Exchanger Network, as its value affects capital and operating costs of the plant (AbuBakar et al., 2015) As minimum value of ΔTmin results in lower value of operating cost but higher value of equipment cost, while with lower value of ΔTmin the area required for heat exchanger would be more, thereby increasing the capital cost. While higher value of minimum approach temperature leads to a decrease in capital cost and increase in operating costs, as there is a rise in overall heat recovery. Therefore, an optimized value of ΔTmin is required to get a minimum value of both. But, for integration of different types of plants - like Oil refineries, Chemical plants, Petrochemical industries and many others, different ΔTmin values are optimum for each plant. According to the values based on Linnhoff March's application experience, the value of ΔTmin for chemical industries is between 10 - 20 °C. The optimum value of ΔTmin was automatically obtained by using the range-targeting feature in Aspen Energy Analyser. The range targets plot is shown in Figure 1. The software tool simulates the capital and operating cost at the different values of ΔTmin and generates a graph of total cost vs ΔTmin (Nagamalleswara Rao, 2016). This graph gives the information corresponding to the optimization of the minimum approach temperature, which is calculated by minimising the total annual cost. It means finding the best compromise between utility requirements, heat exchange area and unit shell number. The value with the least total cost is then chosen as the optimum minimum approach temperature for this case study. From the range targets plot, a value of 11 °C was determined as the optimal value for case study. This is within the range value of 10 - 20 °C for chemical industry given in literature (Kemp, 2007).

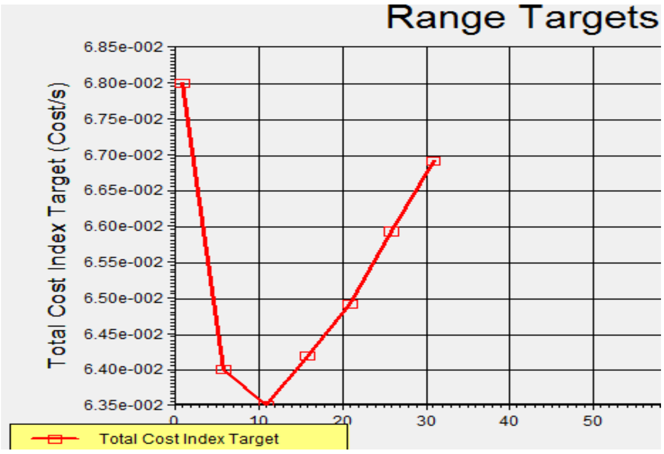


Figure 1: Range target plot to determine the optimal ΔTmin value

3.2 Pinch Analysis energy target results

The next step is the determination of energy targets based on Composite Curves and minimum approach temperature, ΔTmin. After deciding the optimal value of ΔTmin, the hot and cold Composite Curves are combined and represented in a temperature-enthalpy graph, in the form of the combined Composite Curve. The Composite Curve (CC) provides the overall energy targets (minimum hot and cold utility demand) and pinch temperature, but graphical representation is not suitable for identifying appropriate utility levels and loads. The Grand Composite Curve (GCC) shows the interaction between the process and the utility stream. Therefore, a GCC was constructed from Problem Table Algorithm (PTA) method by using a simulation tool. To visualize the correspondence between CC and GCC, these are placed next to each other in Figure 2.

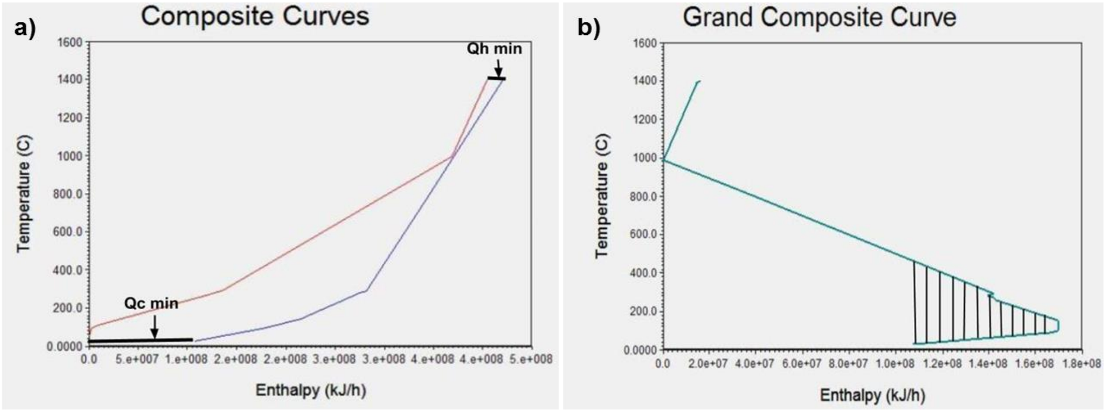


Figure 2: a) Composite Curves (CC), b) Grand Composite Curve (GCC)

In Figure 2a, the upper curve represents the hot Composite Curve while the lower curve represents the Cold Composite Curve and the overlapping region between the hot and the cold Composite Curves represents process-to-process heat exchange. The minimum distance between the curves shows minimum approach temperature (ΔTmin) and this point is known as Pinch Point. The area above the Pinch is heat sink, as there is an overshoot of Cold Composite Curve, which required hot utilities, and the part below the pinch is heat source, as there is a surplus of heat, which needs to be rejected by using cold utilities.

From Figure 2b, it was observed that the overall energy targets and scope of process-to-process heat exchange. In Figure 2b, the point where duty is zero is called Pinch Point. The pocket in GCC represents process-to-process heat exchange and from the graph it can be noticed that process-to-process heat exchange is maximum below the Pinch.

Table 2: Targets demand based on Case Study Data

Target Summary					
Energy Target (kJ/h)		Area Target (m^2)		Pinch Temp (°C)	
Heating (kJ/h)	$1.594*10^{7}$	Counter Current (m^2)	6,858.8	Hot (°C)	Cold (°C)
Cooling (kJ/h)	$1.075*10^{8}$	1-2 Shell & Tube (m^2)	7,786.6	1,000	989
Total Minimum	17	Capital (Cost)	$2.123*10^{6}$		
Minimum for MER	18	Operating (cost)	$4.574*10^{2}$		
Shell	23	Total Annual (cost)	$6.350*10^{2}$		

The energy targets as shown in the above Table 2 are calculated with the help of Composite Curves. It can be observed from the table that the energy target for the process of heating and cooling are $1.594*10^{7}$ kJ/h and $1.075*10^{8}$ kJ/h, while the area target is $7.786*10^{3}$ m^2 for the shell and tube heat exchanger. The hot and cold pinch temperatures are 1000 °C and 989 °C, whereas the pinch temperature is 994.5 °C. The heat exchanger cost index targets shown in the table are based on the Aspen Energy Analyser default values of cost and economic parameters for calculation, as the cost and operations information were not well known from the case study data. The existing cement industry uses $8.341*10^{7}$ kJ/h (23,169 kW) of hot utility whereas minimum hot utility demand, determined by Pinch Analysis, is $1.594*10^{7}$ kJ/h (4,428 kW). The process uses $1.750*10^{8}$ kJ/h

(48,611 kW) of external cold utility compared to minimum cold utility demand 1.075*10^8 kJ/h (29,861 kW). The heat recovery is increased from 63,750 kW to 82,500 kW. It is reminded that in the existing process unit only 63,750 kW of thermal energy is recovered. The existing process unit 18,750 kW is far from the MER design and can be recovered.

3.3 Heat Exchanger Network analysis

The process streams and utility streams data were used to design a Heat Exchanger Network. The Heat Exchanger Network design obtained is represented using a grid diagram and is shown in Figure 3. All the heating and cooling requirements of the process were combined together the result is shown in the Grid Diagram. The direction of flow of the stream was taken in to consideration for placing heat exchangers on the grid diagram. The process streams are shown as horizontal lines, with hot streams flow from left to right, while cold streams flow from right to left. This is very important parameter when placing heat exchangers before or after another heat exchanger on the streams. Simply the grid diagram is an overview of all the heating/cooling requirements of the process. The local heat transfer coefficient associated with the individual stream (HTC) is the default values calculated by Aspen energy Analyser. Flow rate, effective heat capacity flow rate and minimum approach temperature are the parameters used in Aspen energy Analyser. Grid diagram contains process streams, utility streams and heat exchangers. In the grid diagram, thick blue colour line represents cold stream, thick red colour line represents hot stream, grey circle shows that the process to process heat exchanger, blue colour circle represents cooler and red colour circle represents heater.

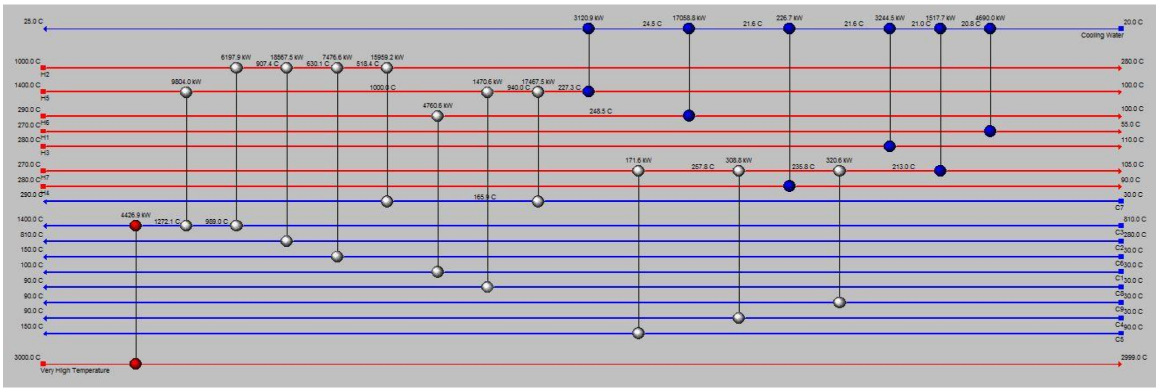
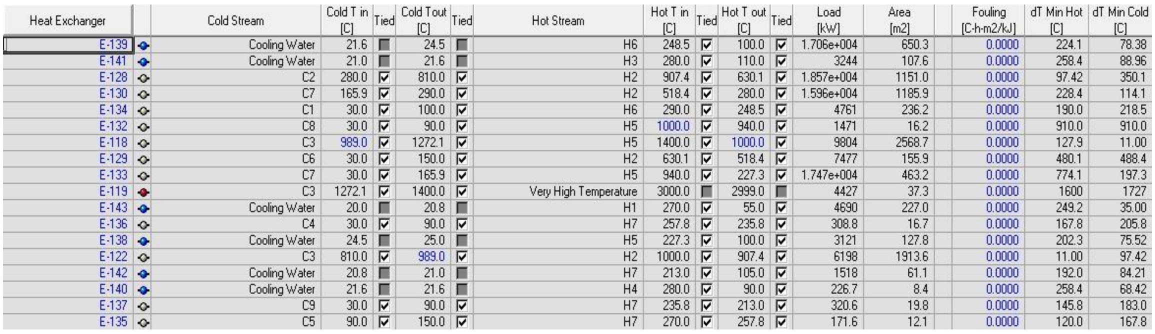


Figure 3: Grid diagram of Heat Exchanger Network

The process has seven hot streams and nine cold streams. The current HEN has eleven heat exchangers between process streams, one heater for heating by very high temperature stream and six coolers for cooling by cooling water. A summary of existing heat exchanger duty, area and temperature profile generated by Aspen Energy Analyser are given in Figure 4 for process-to-process stream, coolers and heater. The grid diagram shows that the current HEN is operated efficiently and recovers maximum energy from process streams with less usage of external utilities. However there is a possibility to improve it further. After base case design synthesis, the design was optimized to minimise the total annualized cost by using Aspen Energy Analyser. From results, authors observed that the optimized design also has simple structure and low operating cost.



Heat Exchanger		Cold Stream	Cold T in [C]	Tied	Cold Tout [C]	Tied	Hot Stream	Hot T in [C]	Tied	Hot T out [C]	Tied	Load [kW]	Area [m2]		Fouling [C-h-m2/kJ]	dT Min Hot [C]	dT Min Cold [C]
E-139	🔵	Cooling Water	21.6	■	24.5	■	H6	248.5	☑	100.0	☑	1.706e+004	650.3		0.0000	224.1	78.38
E-141	🔵	Cooling Water	21.0	■	21.6	■	H3	280.0	☑	110.0	☑	3244	107.6		0.0000	258.4	88.96
E-128	⚪	C2	280.0	☑	810.0	☑	H2	907.4	☑	630.1	☑	1.857e+004	1151.0		0.0000	97.42	350.1
E-130	⚪	C7	165.9	☑	290.0	☑	H2	518.4	☑	280.0	☑	1.596e+004	1185.9		0.0000	228.4	114.1
E-134	⚪	C1	30.0	☑	100.0	☑	H6	290.0	☑	248.5	☑	4761	236.2		0.0000	190.0	218.5
E-132	⚪	C8	30.0	☑	90.0	☑	H5	1000.0	☑	940.0	☑	1471	16.2		0.0000	910.0	910.0
E-118	⚪	C3	989.0	☑	1272.1	☑	H5	1400.0	☑	1000.0	☑	9804	2568.7		0.0000	127.9	11.00
E-129	⚪	C6	30.0	☑	150.0	☑	H2	630.1	☑	518.4	☑	7477	155.9		0.0000	480.1	488.4
E-133	⚪	C7	30.0	☑	165.9	☑	H5	940.0	☑	227.3	☑	1.747e+004	463.2		0.0000	774.1	197.3
E-119	🔴	C3	1272.1	☑	1400.0	☑	Very High Temperature	3000.0	■	2999.0	■	4427	37.3		0.0000	1600	1727
E-143	🔵	Cooling Water	20.0	■	20.8	■	H1	270.0	☑	55.0	☑	4690	227.0		0.0000	249.2	35.00
E-136	⚪	C4	30.0	☑	90.0	☑	H7	257.8	☑	235.8	☑	308.8	16.7		0.0000	167.8	205.8
E-138	🔵	Cooling Water	24.5	■	25.0	■	H5	227.3	☑	100.0	☑	3121	127.8		0.0000	202.3	75.52
E-122	⚪	C3	810.0	☑	989.0	☑	H2	1000.0	☑	907.4	☑	6198	1913.6		0.0000	11.00	97.42
E-142	🔵	Cooling Water	20.8	■	21.0	■	H7	213.0	☑	105.0	☑	1518	61.1		0.0000	192.0	84.21
E-140	🔵	Cooling Water	21.6	■	21.6	■	H4	280.0	☑	90.0	☑	226.7	8.4		0.0000	258.4	68.42
E-137	⚪	C9	30.0	☑	90.0	☑	H7	235.8	☑	213.0	☑	320.6	19.8		0.0000	145.8	183.0
E-135	⚪	C5	90.0	☑	150.0	☑	H7	270.0	☑	257.8	☑	171.6	12.1		0.0000	120.0	167.8

Figure 4: Heat exchangers parameters of base case design.

4. Conclusions

This research has highlighted the importance of Pinch Technology in improving the performance of cement manufacturing process. This paper provides results that show a Heat Exchanger Network with maximum heat recovery among process streams, thereby reducing the external utility consumption. In this study, researchers considered one type of hot and cold utility to design HEN. After keeping the ΔTmin 11 °C, the hot and cold pinch are achieved at 1,000 °C and 989 °C. The result shows that the heat available in the process is 4,428 kW while the heat demand in the process is 29,861 kW, which indicates that more heat is to be supplied from the process than heat to be removed from the system. The results show that the external hot utility demand of the plant is far less than the cold utility demand of the plant. From the extracted data HEN is designed for the base case. The network with a ΔTmin of 11 °C is the most optimal where the largest energy savings are obtained with the appropriate use of utilities i.e., 80.89 % for hot utilities and 38.57 % for cold utilities is saved as compared to the current plant configuration. The excess heat recovery is increased by 22.73 % and use of this excess heat provides a way to reduce the use of primary energy and to contribute to global CO_2 reduction. It has been observed that Pinch Technology as an Energy Integration technique saves more energy and utilities cost than the traditional energy technique, and this means saving of utility and capital cost. In future studies, stream splitting and heat loss should also be considered. This work allows making a retrofit of existing cement industry and general recommendation for further analysis of heat recovery and utility systems. The results of this paper will be used for Total Site analysis of cement plant and selection of heat transfer equipment. It is also recommended that further research could be conducted in using Pinch Technology to other industries.

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