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Heat Integration for the Air-Conditioning Application using Waste Heat Recovery in the Cast Iron Industry

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The energy demand in the cast iron industry has been increasing for the past decades. Besides this, there is also high-energy demand for air conditioning, especially in the hot climate of the United Arab Emirates (UAE). Process integration tools can identify and measures the potential of energy saving via Heat Integration. The current paper presented a case study for industrial buildings' cooling demand via absorption chiller utilizing waste heat from a cast iron industry located in the Emirates Industrial Area, Sharjah, UAE. The Heat Integration approach has been applied via Pinch Analysis and Problem Table Algorithm to identify the minimum hot and cold utilities. Hot streams consist of four high-temperature furnaces exit gases. The heat exchanger network has been designed to fulfill the energy requirement using ProSim Simulis Pinch software (version 2.0). The minimum hot and cold utilities were predicted at 8,793 W and 1,600 W. The Pinch Point was found at 30 °C with more than 80 % of energy recovery. Moreover, the current study can achieve the lowest fuel consumption with fewer emissions, reduced utility consumption, less cost, and superior performance. The paper also includes several recommendations for the improvement of the cast iron industry's overall efficiency.

1. Introduction

Energy demand is increasing day by day, mainly due to high population density. The rising in population leads to a rise in energy consumption and therefore increase in energy demands. Moreover, emissions from developing countries are rising rapidly and contributing to environmental issues, such as climate change, dirty air and produce high amounts of carbon dioxide and other greenhouse gases, which will lead to global warming and affect human health around the world. The iron and steel industries are comprehensively treated as material, energy, and emission-intensive industries (Sun et al., 2019). Many technologies, in addition to policies, have been introduced to achieve sustainable steel making. The idea of waste heat recovery is considered as a potential factor to achieve sustainable steel making in industries (Sun et al., 2018). Heat is the major source of energy in power plants, industries and other factories (Zhang et al., 2020). Researchers are putting more effort into generating and developing new techniques to recover the heat and reuse it again for sustainability. Industrial waste heat is defined as the heat rejected to the environment from the industrial processes, where the energy produced is mostly heat and electricity (Papapetrou et al., 2018). The steel and iron industries are energy-intensive, emission-intensive, and material-intensive (Sun et al., 2019). The production of steel and iron is mainly produced via two main routes: the electric arc furnace (EAF) route and the blast furnace–basic oxygen furnace (BF–BOF) route (Price et al., 2002). Integrated heat recovery achieves more significant savings by integrating a vast network or heat exchangers across various processes. The integrated heat recovery links the output of one process heat to the input of another process that requires heat, which may save higher amount of energy by appropriate matching of hot and cold streams. There are several ways to recover industrial waste heat (Jouhara et al., 2018). One of the least expensive and the simplest form of recovering the waste heat is to use

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a heat exchanger and recover the heat back to the process. Moreover, the waste heat can also be converted into electricity which permits the exploiting the exegetic potential of the waste heat (Jouhara et al., 2018). Waste heat recovery for the steel industry has many benefits: reducing water loss, decreasing overall production cost and decreasing energy cost.

Heat Integration is an essential step for improving energy performance (Inayat et al., 2011). This process reuses the surplus heat in another process through a heat exchanger, aiming to recover the thermal energy waste for sustainable goals (Kapustenko et al., 2020). Pinch Analysis is simply a methodological approach to decrease the energy consumption of processes and applied via thermodynamic principles and using the data of streams of materials that have inlet and outlet temperature and heat capacity. The heat duty of the stream [J/kg or GJ/t] is the heating or cooling heat requirement. Furthermore, by integrating these streams' heat capacity flow rate between the inlet and outlet temperature, hot and cold curves can be generated. After applying each individual stream minimum temperature difference is (dTmin) is identified. This Analysis is used in steel industries to enhance integrated heat recovery. It is also utilized to evaluate the potential energy savings by applying integrated heat recovery across all the primary steel supply chain processes. The Problem Table Algorithm can be used as an alternative to Pinch technology. The Grand Composite Curve is a graph used in Pinch technology for multiple utilities consumption Analysis. Problem Table Algorithm Analysis generates a table and identify the temperature range and the consumption, from a set of potential options, considering thermodynamically limitations. Heat exchanger network synthesis (HENs), through thermodynamic and computational methods, has been used widely in process engineering for Heat Integration and recovery (Furman and Sahinidis, 2002). A heat recovery approach in cast iron foundries create opportunities for production of electricity for varied internal purposes (Lazzarin and Noro, 2016). Heat recovery can be easily done from air compressors, induction furnaces, and induction coils. A model for waste heat recovery developed by Yang et al. (2020) to identify the optimum operating conditions for circulating water. Walmsley et al. (2015) explored Pinch Analysis as a method for lowering carbon footprint emissions for industries with plants such as steel plants and investigate greenhouse gases as a result of industrial processes. The applications of renewable methods and the possibility of improving heat efficiency indicate that a 20 % energy saving can be achieved through Heat Integration. This would have a huge effect on reducing the carbon emission in New Zealand.

The Iron industry is one the most significant industrial consumer of heat energy. A large amount of heat energy is being used in the many heat-intensive processes, such as iron ore extraction. Several methods have been established to ensure the recovery of heat from such a process, but not efficient as they focus on the recovery of heat from a single process in the entire chain. This is mainly due to the physical separation of most processes, making it harder to implement heat exchangers to transfer heat from hot flow processes to cold flow processes efficiently. Better heat recovery methods are needed in this industry to ensure proper heat recovery on a larger scale. Pinch Analysis offers a way out to designers looking to solve the challenge of heat exchange in existing systems where separation of processes is a challenge and making it challenging to implement heat exchangers. This case study aims to apply the Heat Integration approach for heat recovery in the cast iron industry. In addition, design the heat exchangers networks based on the industry data for water heating and air conditioning applications within the industrial buildings.

2. Methodology

The hot and cold stream data have been collected from the one cost and iron industry located in Emirates Industrial Area, Sharjah, UAE (Najim Al Khaleej Steel Fabrication & Metal Casting LLC.). There are four furnaces considered as hot streams (H1-H4). The outlet temperatures of the furnaces were measured using thermocouples. There are three cold streams (C1-C3) taken into account (two for water heaters and one for cooling via adsorption chiller). Figure 1 showed hot and cold streams and inlet temperature and the desired outlet temperature, which can be attained via a heat recovery system. The outlet temperatures of the furnaces are taken based on the average of several readings. The target outlet temperature of hot streams set to 25 °C. On the other hand, the inlet temperature for all three cold streams is set to be 25 °C.

Both Pinch Analysis and Problem Table Algorithm (PTA) are applied for heat recovery calculations. PTA is an alternative for Pinch Analysis, but instead of using curve construction, the method uses mathematical calculations. Capable of giving a more accurate/precise answer. Additionally, it is used to find the Pinch Point for heat recovery and the hot and cold utilities. The benefit of this algorithm is to minimize the required utilities for heating or cooling applications. An energy balance developed within each segment of the temperature interval connecting the hot segment to the cold ones. Because there is a temperature difference set for the heat transfer, the actual interval temperatures have to be adjusted accordingly to do the energy balance properly. A Cascade diagram has been produced to identify the Pinch Point temperature. Simulis Pinch software applied for Pinch Analysis calculations using the streams data such as inlet and outlet temperatures and CP values. The software calculated the heat duty, cold and hot utilities, Pinch temperature and maximum energy recovery.

Finally, a Grand Composite Curve and heat exchangers network has been developed to achieve the objectives of the current study. The stream data has been given in Table 1.

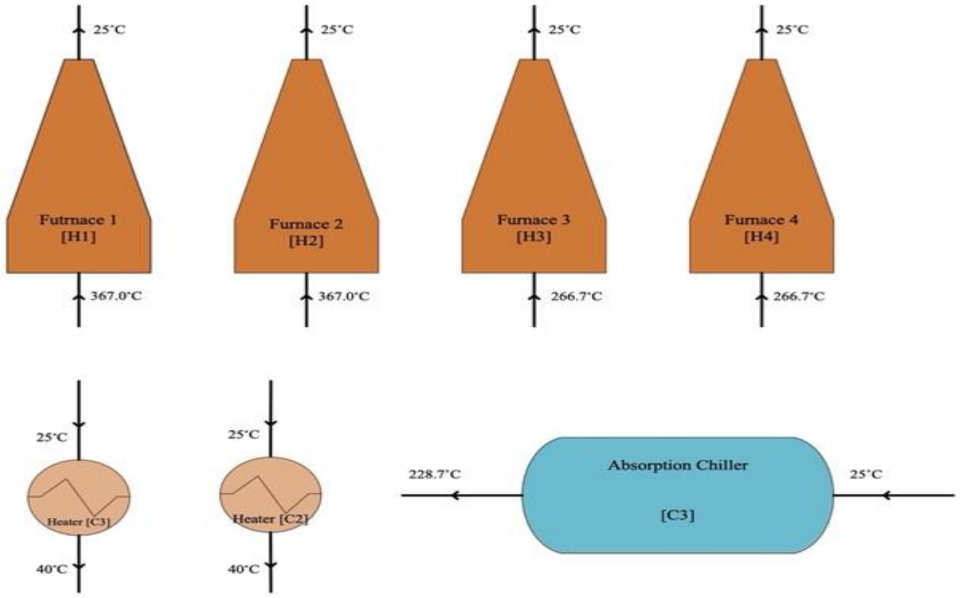

Figure 1: Hot and cold streams for Heat Integration calculations

Table 1: Hot and cold streams data

No.	Hot Streams	T (in) °C	T(out) °C	dT °C	dTmin °C	CP
1	H1	367	25	342	10	37.4
2	H2	367	25	342	10	42.3
3	H3	266.7	25	241.7	10	37.4
4	H4	266.7	25	241.7	10	42.9
5	C1	25	228.7	203.7	10	209
6	C2	25	40	15	10	376.2
7	C3	25	40	15	10	376.2

3. Results and discussion

PTA performed via heat balances according to the data collected from the industry. The stream population was drawn, and the heat duty interval was calculated. Figure 2 shows the cascade of heat balance which was performed from high-temperature interval to lower temperature interval. The heat accumulated the highest negative value and was the minimum hot utility, which equals 8,793.4 W. Afterwards, and the heat cascade was adjusted to find the Pinch Point and cold utility. The Pinch Point was located at a temperature of 30 °C, and the minimum cold utility was obtained at 1,600 W. Furthermore, Pinch Analysis utilizes graphs to find hot and cold utilities and heat recovered as well shown in Figure 3. It has been observed that before applying Heat Integration, the cold utility was 46,665.9 W to cool the furnaces, but it was found 1,600 W after Heat Integration. Similarly, the hot utility was 53,859.3 W initially and obtained 8,793.4 W after Heat Integration. Hence, the heat recovered by Pinch Analysis and PTA is 45,066 W, and the auxiliary required cold utility was reduced by 96.57 %, which helps to reduce the energy cost. However, the hot utility was decreased by 83.67 %.

The Grand Composite Curve showed in Figure 4 as temperature vs. Enthalpy diagram used to determine the various utility mix that can be used. In other words, it is plotting the available excess heat to each temperature interval represented in a curve. This curve was developed by the heat cascade shown in Figure 2. The green shaded area shows the heat recovered. Moreover, after using the two-heat recovery Analysis, which was graphical and mathematical, the Grand Composite Curve was plotted, which can help identify the possible utility level to be introduced. The graph line intersects with the y-axis, and the temperature value represents the Pinch

Point, i.e., 30 °C. The results obtained from (PTA and Pinch Analysis) were used to design the Heat Exchangers Network (HEN) to attain energy targets using Simulis Pinch software. This software proposes various HEN solutions to meet the natural constraints of the industrial sites. Moreover, HEN utilizes heat transfer between hot and cold streams to decrease heating and cooling utilities. Using HEN based on the Pinch Point helps reduce the number of exchangers, decreasing the area to fulfill maximum energy recovery.

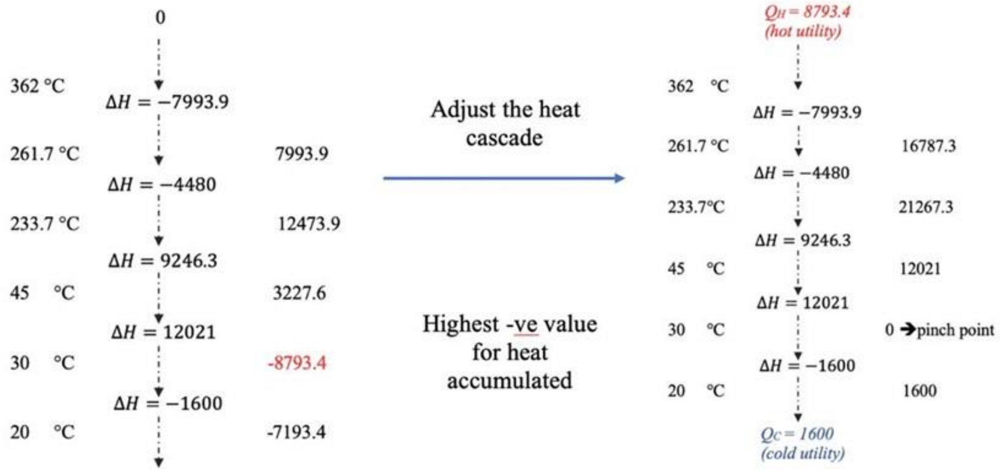

Figure 2: Cascade diagram using Problem Table Algorithm

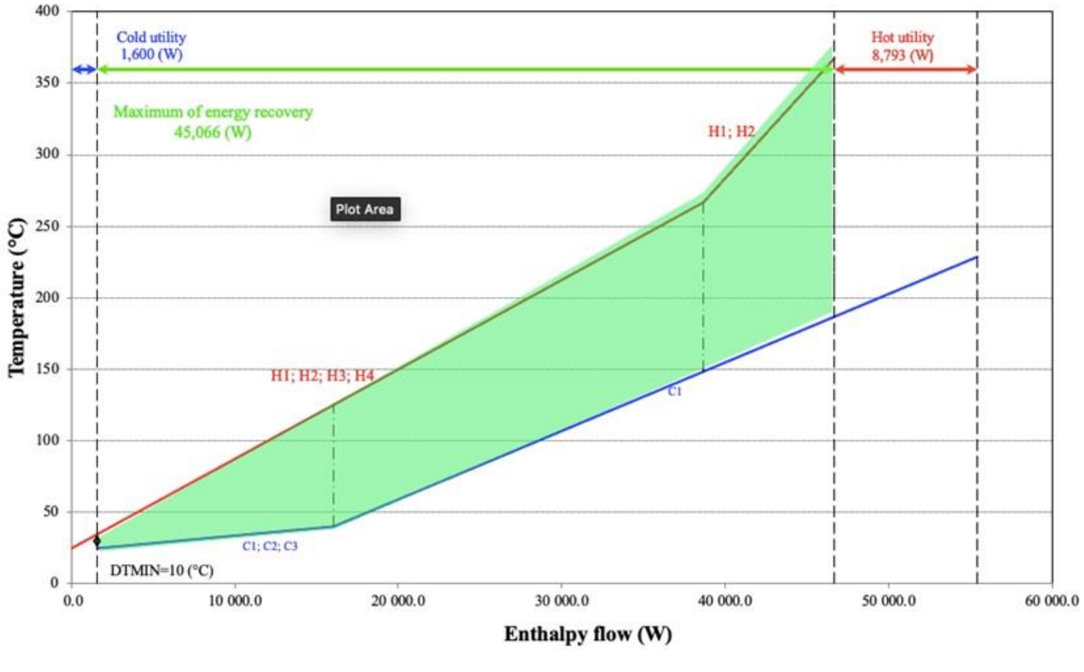

Figure 3: Pinch Analysis for minimum hot and cold utilities

Figure 5 illustrates the final HEN of the designed streams according to the data collected. The hot streams were represented on the left side of the temperature axis, whereas the cold streams on the right side. The Pinch Point is displayed at the bottom of the temperature axis, where all heat exchangers were designed above it. There are two important rules considered for HEN designing; first of all, the section above Pinch is match stream with CP (cold) larger than or equal to CP (hot), and secondly, for the section below, the Pinch is to match stream with CP (hot) larger than or equal to CP (cold). The CP rule for the above and below Pinch Point should be followed and an attempt should be made to minimize the number of heat exchangers for the current application. The orange lines that appeared on the diagram above stand for exchanging heat between two streams where the white nodes are the connection of the heat exchangers with a total of five heat exchangers. Most of the hot streams transfer heat with C1 since it has high heat duty compared to C2 and C3. The cold utilities in Figure 5 are indicated as blue shaded nodes and the hot utilities are indicated as red shaded nodes. The heat duty exchanged was found based on the exchanger characteristics given by the software such as UA factor and Log Mean Temperature Difference (LMTD). The possible number of heat exchangers predicted by software are 32. The final number of heat exchangers was found to be 5.

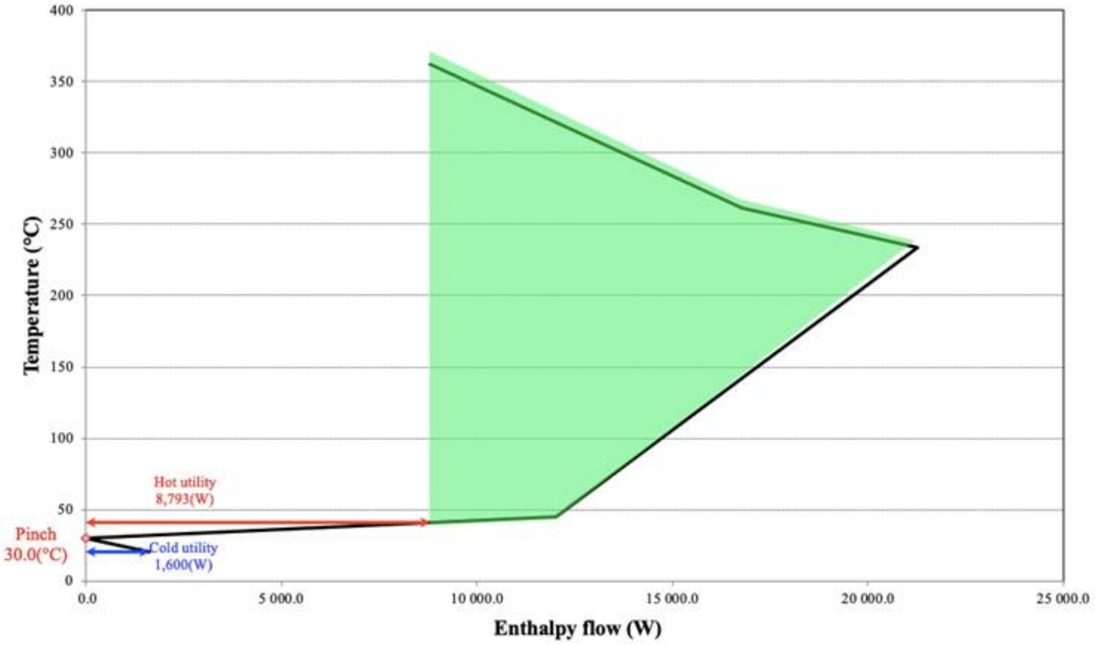

Figure 4: Grand Composite Curve for heat recovery

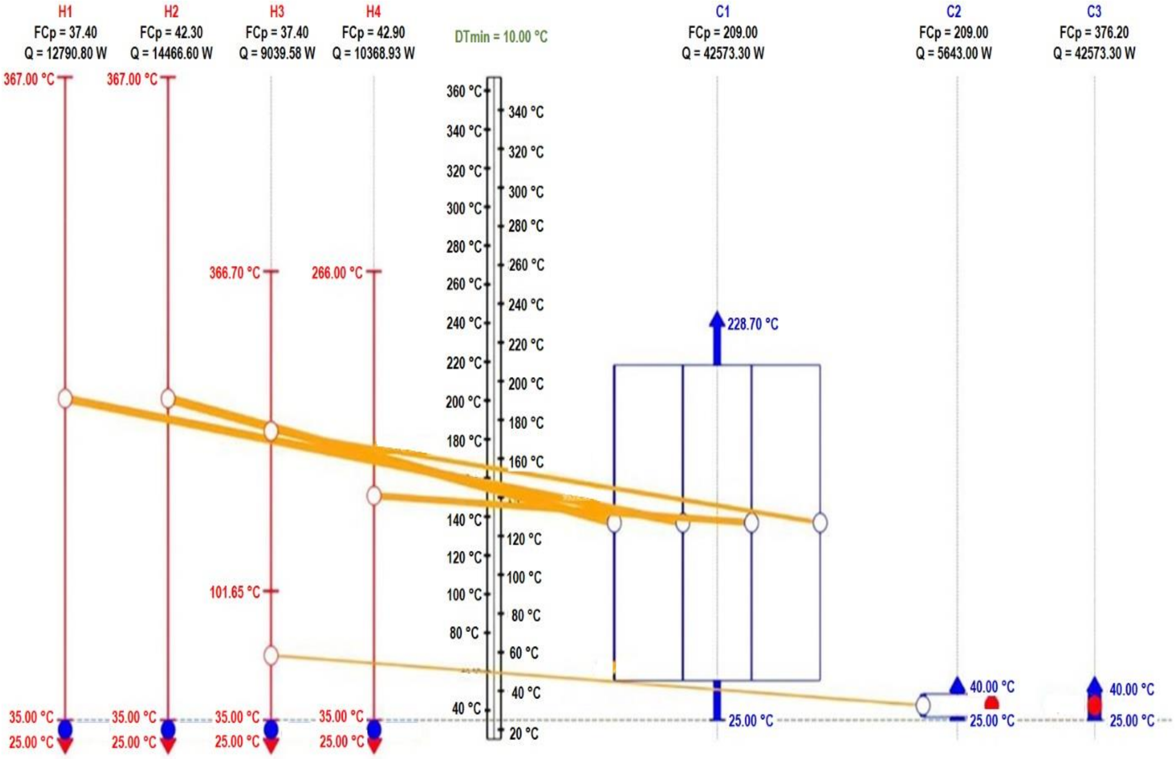

Figure 5: Heat exchanger network based on hot and cold streams

4. Conclusions

Since the energy demand in all steel industries is increasing daily, heat energy recovery systems were introduced many years ago. For reaching energy and climate targets, industrial waste heat has been recognized as a considerable heat resource. This system utilizes waste heat produced by the cast iron industries by a heat exchanger that transfers heat through hot and cold streams. The energy produced via waste heat recovery is used for other applications such as heaters and absorption chillers for air conditioning. After accumulating the data from Najim Al Khaleej Steel Fabrication & Metal Casting LLC Sharjah, UAE, heat recovery Analysis was done based on Pinch Analysis and problem table algorithm. The Pinch Point was obtained at 30 °C. In contrast, the minimum hot utility value was 8,793.4 W. The minimum cold utility was 1,600 W. Furthermore, the heat recovered was calculated as 45,066 W. Additionally, the Grand Composite method was adopted to identify the possible energy targets. Finally, a heat exchangers network has been designed using Simulis Pinch software (version 2.0), which predicted a minimum of five heat exchangers to fulfill the Heat Integration requirement. It is recommended to perform an economic Analysis in a future study for more accurate Analysis for energy-efficient and cost-effective processes.

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