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Pinch Analysis Application for Fouled Crude Distillation and Condensate Fractionation Units of a Refinery

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Preheat trains of each Crude Distillation Unit (CDU) and Condensate Fractionation Unit (CFU) of a refinery in Malaysia were experiencing severe fouling. This led to lower heat recoveries of the pump arounds and higher fuel gas consumptions in the furnace and the reboiler of the units. Consequently, potential energy recovery options and possible fouling mitigation strategies needed to be explored. Adding few new heat exchangers to increase heat recovery in the below pinch region has been found to potentially reduce the fuel gas consumption by about 7 – 10 %, depending on crude scenarios. Further analysis of the preheat trains showed that heat exchangers at the higher temperature end of the network (above Pinch region) experiencing more severe fouling than the others. These heat exchangers were then recommended to be cleaned more frequently or to be modified to become less susceptible to fouling. This approach of adding new heat exchangers in the below pinch region and doing more frequent cleaning in the above pinch region could be seen as a practical application of the Plus/Minus principle of Pinch Analysis. More detailed process engineering calculations needed in the next phase of this project for actual implementations and detailed economic evaluation.

1. Introduction

The concept of heat integration has been around for more than four decades and it has been extended far beyond the traditional scope of process industries. This includes supply chain problem, resource planning, carbon-constrained energy sector planning, and carbon and footprint-constrained energy planning (Klemeš and Kravanja, 2013). Basic introduction and user guide on Pinch Analysis has been thoroughly demonstrated via case studies by numerous researchers. The work of Kemp (2007) is one of the best resources to start with.

For designing crude preheat train with multiple types of crude, Siemanond and Kosol (2011) have utilized the stage model of Zamora and Grossmann (1996). Based on the optimization of this Mixed Integer Non-Linear Programming (MINLP) model, they obtained several designs from which the one with the highest Net Present Value (NPV) was selected. For retrofitting heat exchanger network, existing equipment and plot space have to be considered thoroughly (Rossiter, 2015). One of the simplest approaches, yet a robust one, involves systematic steps such as obtaining data, generating utility targets, identifying major inefficiencies in the existing heat exchanger network, defining and evaluating options, and finally selecting the best or combination of options (Rossiter, 2015). To come up with the options to retrofit, Asante and Zhu (1997) have provided some guidelines that can be followed. They are relocating or re-piping of heat exchangers, adding new ones, or creating stream splits within the network. As one of the sources of inefficiencies, cross-pinch matches are known to have negative impacts on both hot and cold utilities. Knowing this issue, Li et al. (2019) retrofitted cross-pinch matches in an industrial CDU system to minimize penalties caused by these cross-Pinch matches. Wang et. al. (2020) has considered various heat exchanger types when retrofitting heat exchanger networks, depending on their typical temperature ranges, pressures, and sizes. Li and Li (2019) made a comparison of latest graphical tools for targeting and retrofit of Heat Exchanger Network (HEN) where they suggested what method to apply in which scenario. However, these graphical methods are obviously very tedious for larger scales. In another extension, Wang et.al. (2021) explored the use of Particle Swarm Optimization (PSO) algorithm to optimize operating conditions such as temperatures and duties of existing HEN or HEN designed from graphical approaches.

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Langer et. al. (2019) proposed a stepwise approach in retrofitting existing HEN by decoupling design and flexibility analysis. Multiple designs can be done by any existing design methodologies, while the flexibility analysis can then be performed on each design. Quantity and quality of the designs and the identifications of variations in the operations determine the success of this approach. This approach provides a tool for designers to have a quick evaluation on design alternatives.

On the other hand, for heat exchanger networks experiencing severe fouling, some of the options to increase heat recoveries include replacing exchangers with units featuring higher velocity (to reduce the growth of fouling rates) and to decrease wall temperature through the reduction of the temperature at which the hot stream enters the unit. The latter can be achieved by introducing matches that use hot stream at a position earlier in the train (Yeap et al., 2006). Previously, Wilson et al. (2002) argued that the use of fouling models and the use of temperature field plot can bring better insights on the operation of systems experiencing severe fouling such as the preheat train of crude distillation units.

By considering both Pinch Analysis method and development of fouling models of heat exchangers, Vasilyev and Boldyryev (2018) built dynamic preheat train models to assist in designing and revamping an existing heat exchanger network. Their dynamic models were run for a two-year case study period for both base case and retrofit designs. This rigorous modelling together with the applied Pinch Analysis when retrofitting the preheat train network provided strong strategies and recommendations for optimal operations of the network.

Considering the above-mentioned literature, an investigation to increase the heat recovery of a crude preheat train in an existing refinery unit in Malaysia was conducted. The unit has been experiencing heavy fouling situations. The amount of heat recovered via process-to-process heat exchangers has reduced significantly during the operation. The inlet temperatures to the furnace and to the column of this unit have not achieved their design values. The main contribution of this work is to apply Pinch Analysis method in industrial situations experiencing heavy fouling to obtain simple yet practical solutions that can be implemented in sequence. A stepwise strategy for revamping activities was then proposed. Due to the project time constraints, dynamic model of the crude preheat train to account for fouling management strategies, as conducted by Vasilyev and Boldyryev (2018) could not be developed. This item could be proposed for further study.

2. Methodology

The project scope consists of a Crude Distillation Unit (CDU) and Condensate Fractionation Unit (CFU) of a refinery in Malaysia. Two different crude cases (light and heavy) were considered. Both cases operated differently to maximize yields and required different hot utilities. In these columns, fuel gas was used as the main heat sources for their furnaces. In this work, both heat recovery options and fouling mitigation technologies were evaluated and proposed to the plant.

The work methodology started by obtaining design data of heat exchangers from their respective datasheet. Operating conditions were obtained from data historian, which were then used to simulate current operating basis (i.e., light and heavy cases). Once the calculated column temperature profiles, product yields, product cuts were agreed, the corresponding mass and energy balances around the preheat trains were used to make the Composite Curve (CC). In this work, ΔT_{min} of 20 °C has been selected as a guide to obtain the thermodynamic target of hot and cold utilities. This value is typically used in the refineries and petrochemicals (Linnhoff March, 1998). It is also found to be slightly higher than the minimum ΔT_{LMTD} of all heat exchangers in the design case. Hence, this selection is practically on the conservative side. A lower ΔT_{min} could be used, which obviously leads to a lower utility target, which in turn leads to an impractical target for our energy improvement programs. Insights from the CC was put together with the heat exchangers in a Grid Diagram (GD) for a visual help in identifying heat recovery opportunities. All identified opportunities were then re-simulated back in the same process simulation files. If the proposed improvements were profitable and technically feasible, the associated modification costs were then estimated and quick economic return calculations were performed (e.g., payback period). Cost estimation was done using Aspen Capital Cost Estimator v12 (cost basis of 2019, Malaysia). Finally, an improvement roadmap was developed and proposed.

Regarding fouling mitigation technologies, discussions with several vendors were performed to cover a wide range of technologies on offer at present. Subsequently, both qualitative and semi-quantitative evaluations were conducted to compare these technologies. Then, a preferred technology was proposed for potential implementation.

3. Results and discussions

Due to frequent fouling that occurred in the CDU and CFU heat exchangers, current operating conditions (i.e., temperatures) do not reflect the design requirement. Inlet temperatures to the furnace of CDU and to the CFU column are much lower compared to the design. Unrecovered energies are destroyed in the cold utilities (i.e., cooling water and air cooler) while the hot utilities (i.e., furnaces) are doing extra heating. Figure 1 shows the Composite Curves (with the ΔT_{min} of 20 °C) for light and heavy cases. As expected, both curves look very similar with each other. However, the required amounts of hot utilities and the respective pinch points are slightly different. From the figures, current hot utility consumptions for light and heavy cases are 41 % and 47 % higher than the targets obtained from Pinch Analysis. It is important to note that these numbers originate from fouled conditions where the recovered heats are lower than those of design. The resulting inlet temperatures to the columns are lower, as explained above.

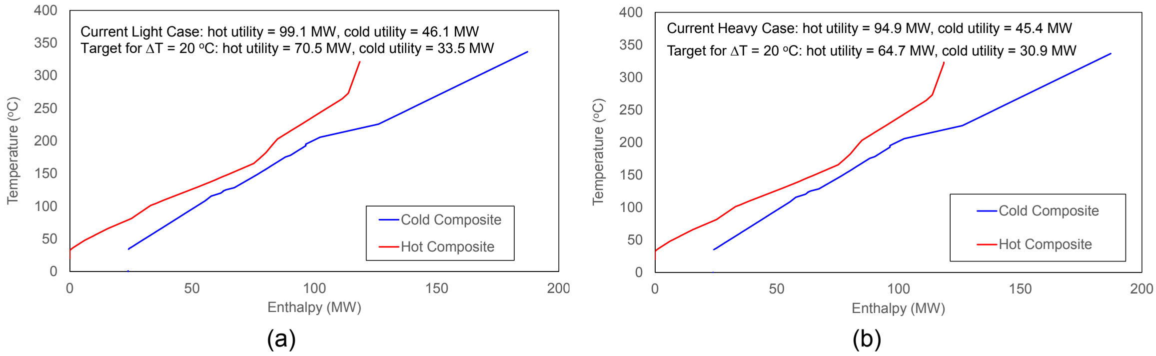

Figure 1: Composite Curve for current (a) light and (b) heavy cases

Based on this targeting result, furnaces' duties need to be reduced via increasing their inlet temperatures. This is done by recovering the heat currently wasted in the cold utilities. This recovery is achieved by cleaning heavily fouled heat exchangers, modifying existing heat exchangers, enlarging existing heat exchangers, and adding new heat exchangers (one at a time, whenever possible), which are going to be elaborated below.

Figure 2 shows the Grid Diagram (GD) of the existing configuration of the preheat train. For clarity, heat exchangers located in the CDU train are on the top part of the figure, while those in the CFU is on the below part. This kind of arrangement makes it easier to visualize whether heat from one unit is utilized in the same unit or in the other. Its subsequent practical complications, if any, can be easily captured. In this Figure 2, the vertical line is the Pinch line with the associated hot and cold Pinch temperatures on top and below it. Each horizontal line represents a process stream. The arrow indicates the direction of the stream, either increasing in temperature (from left to right or cold stream) or the other way around. Blue and red circles denote cold and hot utilities. White circles are process-to-process heat exchangers. Duties shown are all calculated duties from the measured flowrate, and inlet and outlet temperature.

As seen in Figure 2, there are eleven heat exchangers with red broken lines around it identified in the plant as having severe fouling. Green circles (in Figure 2) are heat exchangers that experience significant duty reductions compared to the design. This is a sign of a heavily fouled heat exchanger. Combining this two information, four (4) out of eleven identified fouled heat exchangers are experiencing large duty reductions. These four heat exchangers are shown as green and with read dotted lines, i.e., E-1105, E-1104, E-1108, and E-1171. The remaining seven (7), even though experiencing heavy fouling, can still maintain the design duty assigned to them. This is primarily due to higher ΔT_{LMTD}, especially with those at the higher temperature end of the streams. Their corresponding upstream heat exchangers are fouled, reducing the overall heat transfer coefficients, and the crude only receives lower amount of heat. As a result, its outlet temperature is lower. This then creates a higher ΔT_{LMTD} in the subsequent heat exchangers. Looking at this diagram, it makes perfect sense to increase their cleaning frequencies.

From Figure 2 as well, heat exchangers with blue lines are the proposed additional heat exchangers. They are determined simply by minimizing the amount of heat currently removed in the cold utilities. Some of these energies are recovered by either increasing surface area of existing heat exchangers or adding a new heat exchanger. For example, Option 1 recovers heat from the overhead CFU column to the feed of CFU. Options 2 until 5 recovers heat within CDU. Option 8 recovers heat from diesel rundown to replace the use of steam in E-1154/55 of the CFU unit. This last option involves heat exchange between the two units (CDU and CFU) and it is practically very far away from each other. Option 6 and 7 are to increase the surface area of existing heat exchangers, E-1101 and E-1103 which is a typical strategy in most cases (Asante and Zhu, 1997). This enlargement is to recover huge amount of energy currently being discharged to the cold utilities (e.g., air cooler and cooling water). When these options were simulated back in process simulation software, a total energy reduction of about 7 % to 10 % could be achieved, depending on the type of crudes. These energy reductions were then translated into the amount of fuel gas saved in the furnaces of the columns. This approach of adding new heat exchangers in the below pinch region and cleaning more frequently those in the above region can be considered as a typical example of utilizing the Plus/Minus principle in both regions (Kemp, 2011).

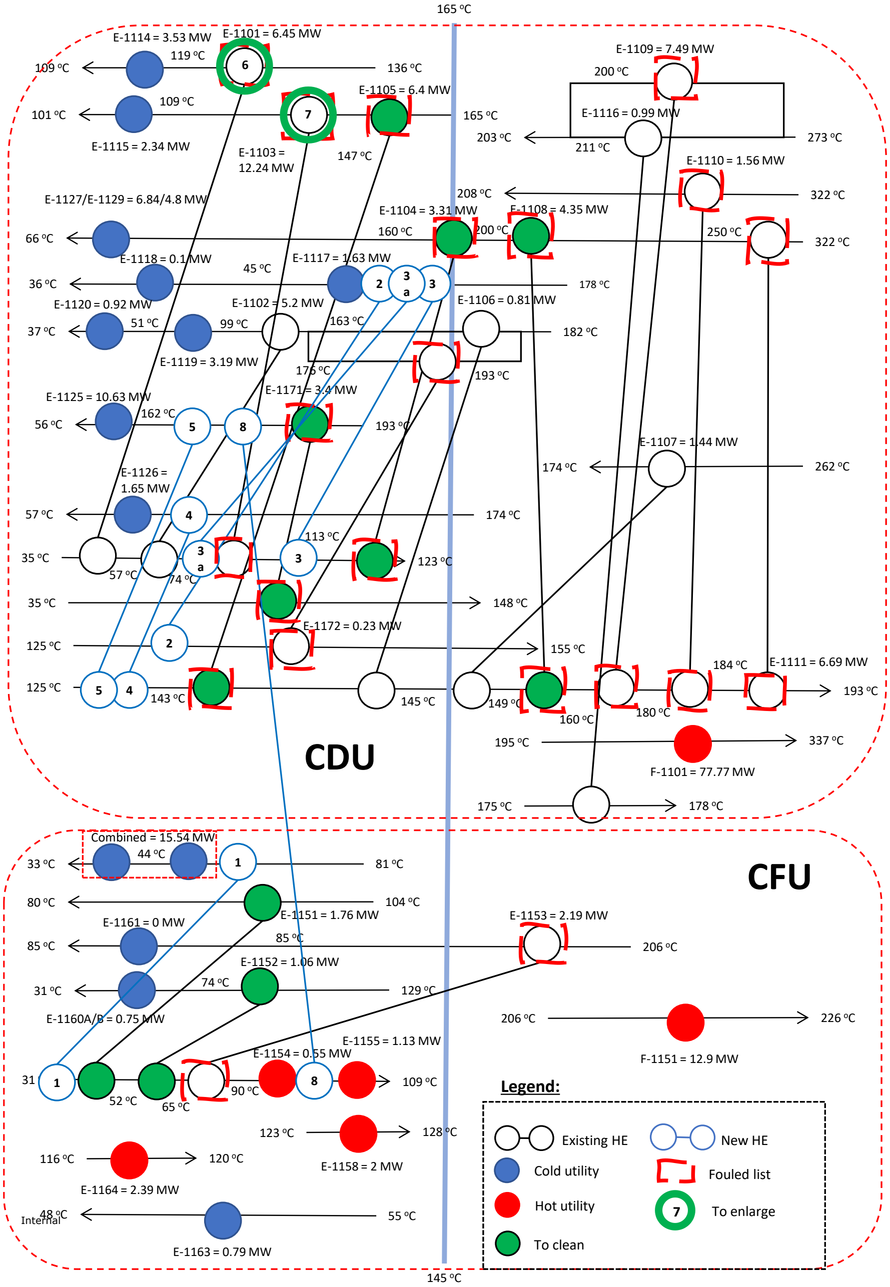

Figure 2: Grid diagram of the preheat trains of CDU (upper) and CFU (lower)

An important insight was observed while evaluating heat recovery options. All options identified during this study try to recover heat below the pinch (see Figure 2). These options come from the fact that all energy is removed in the cold utilities, and recovering them from the cold utilities by shifting it a little bit more upstream is a logical approach. However, recovering more heat in the below pinch region will cause the outlet temperature of the crude to increase. As a result, the ΔT_{LMTD} of downstream heat exchangers get smaller towards the pinch point. As the heat exchanger is limited by the existing UA (overall heat transfer coefficient [U] multiplied with heat transfer area [A]) calculated from the base-case, the duty of the subsequent heat exchangers reduces. The same amount of recovered energy in each option is not reflected by the same amount of duty reduction in the furnaces. On the other hand, if the heat recovery was performed in the region above pinch, the downstream ΔT_{LMTD} will still reduce, but there is no pinch point as the bottleneck and hot utility may still be reduced. In the current analysis, it is more practical to have more frequent cleaning for the heat exchangers located above the

Pinch (hotter end of the train) and/or modify them into a less susceptible ones against fouling rather than adding more exchangers into it.

Economic benefits for some options are performed and a graphical evaluation of these options are summarized in Figure 3. This figure provides a quick guideline on which option to consider first and its possible further modifications. It covers not only the individual option, but also some combinations of these options. The capital investment was estimated using Aspen Capital Cost Estimation (at +/- 50 % accuracy) with the cost basis of 2019 in Malaysia. The region in the lower left of the figure is the most profitable one with lowest indices of both Capital Expenditure (CAPEX) and Pay Back Period (PBP). For comparability reason, the indices are calculated as the ratio of each option to the minimum value of each criterion, e.g., CAPEX of Option 1 over the minimum CAPEX, which is Option 3. The size of the bubble is to make a clear separation between the options. Option 1+3+8 is shown to be the best option where the fuel gas saving has been estimated to be around 0.68 – 0.96 M€/y with CO_2 equivalent reduction of 7.2 – 10.3 kt/y, for both crude oil cases. This option shows the highest amount of heat recovery, which in turns, reduces the fuel gas consumption in the furnaces of the columns.

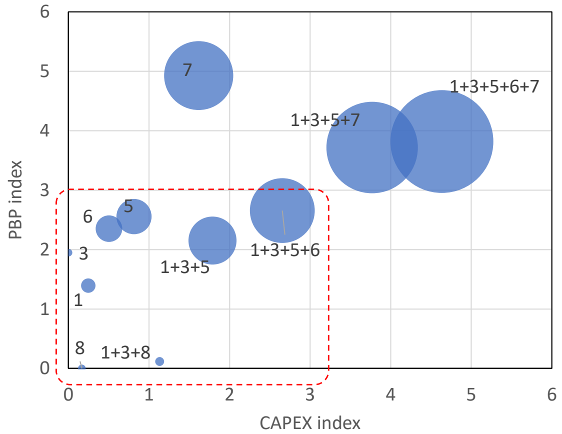

Figure 3: Stepwise implementation strategies for the revamping activities

Separately, four fouling mitigation technologies have been evaluated, e.g., tube inserts, helical baffle, ultrasonic, and their combinations. One technology provider has been found to be the most suitable one to pursue further. Due to limited space, this evaluation is not described in more detail here. Depending on each situation, most companies can obtain between 10 % to 40 % improvement, while others can even reach 100 % of improvement. To properly quantify this improvement, a base case was evaluated where an exponential regression model was developed to match the reduction of duties. Then, 10 % and 40 % improvements are evaluated against this base case. Figure 4 shows the base case of a fouled heat exchanger and its expected improvements. The blue dots are the calculated duties of this heat exchanger, based on its measured flowrate, known composition, and its inlet and outlet temperature. The red line is a regressed exponential model based on the dots, while the green and dark blue represent the 10 % and the 40 % improvements.

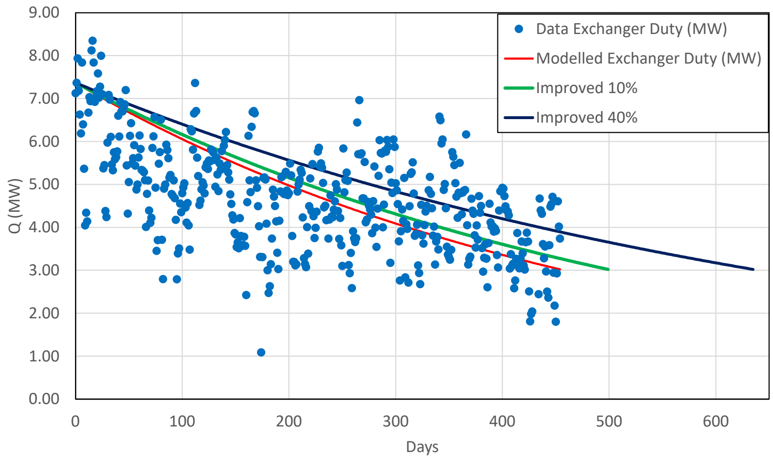

Figure 4: Performance of a heat exchanger and its estimated improved performance by 10 % and 40 %

4. Conclusions and recommendations

Pinch Analysis and fouling mitigations evaluations have been conducted on two units (i.e., CDU and CFU) of a refinery plant in Malaysia. Targets from Pinch Analysis reveals that about 41-47 % of energy reductions can be theoretically obtained. Simulation of these options into the process flowsheet shows that about 7-10 % of energy reductions can be achieved practically. An important insight obtained from this study is that the amount of energy saved in the furnace or reboiler is lower than the energy recovered from the below pinch region. Increasing heat recoveries in this below the Pinch region reduces the available ΔT_{LMTD} of downstream exchangers as they go towards the pinch point. Based on the current analysis, it seems more sensible to increase the cleaning frequencies of heat exchangers located at the higher temperature end of the network (above the Pinch) and add few new heat exchangers in the below pinch region. From the concept of Plus/Minus principle, this approach can be considered as maximizing heat recoveries on both below and above pinch regions. Based on the best option identified, total fuel gas saving has been estimated to be about 0.68 – 0.96 M €/y and CO_2 equivalent emission reduction of about 7.2 – 10.3 kt/y, for both crude oil cases. Practical details concerning the implementations including site and physical constraints will be part of future engineering work.

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