Heat Exchanger Network Analysis of The Power Plant Industry Using Aspen Energy Analyzer Software

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Abstract. Heat recovery is considered as the key to improve energy efficiency in the process design. An appropriate heat exchanger network (HEN) design is an effective tool to maximize heat recovery from the process streams and to minimize energy consumption. The objectives of this study were arranging optimum HEN based on the annual cost in the power industry. HEN in the Paiton Steam Power Plant, East Java, Indonesia, was designed using spreadsheet and Aspen Energy Analyzer with Peng-Robinson equation. Pinch analysis was conducted by comparing T_{min} (10°C - 19°C) to obtain Maximum Energy Recovery (MER) and Heat Exchanger Area (HEA). The HEN design was optimized using grid diagram. Simulation in this study succeeded to reduce the annual cost the most effectively at ΔT_{min} 16°C. This design optimized the process integration and contributed to the capital, operation, and total annual cost reduction of 14.3%. The maximum energy recovery was 286,706 kW and HEA 138.790 m^2. This result is a solution for Steam Power Plant as an effort for enhancing energy efficiency and the company competitiveness.

Keywords: Aspen Energy Analyzer, Heat Exchanger Network, Maximum Energy Recovery, Power Plant Industry

INTRODUCTION

Along with the increasing need for electrical energy, it takes electricity providers who can provide a reliable, stable, and efficient electricity supply. Energy efficiency is a major element in sustainable development (Muharja et al. 2021, 2020a). Energy efficiency indicates the system's ability to utilize energy sources to perform work and indirectly contribute to reduce fuel usage and greenhouse gas emissions (Muharja et al.

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2019, 2020b). In addition, the higher the energy efficiency, the higher the competitiveness of the company (Fleiter et al. 2012). The difference between Heat Exchanger Network (HEN) efficiency in existing conditions or initial conditions and retrofit design or final conditions occurs due to the reduced heat load of external energy in the form of heating or cooling (El-darwish and Gomaa 2020, Mrayed et al. 2021).

HEN is the minimum possible usage of external energy as well as the maximum utilization of internal heat. An appropriate analysis of HEN is needed when there are changes to the design (Klemeš et al. 2020). HEN design and optimization have been studied over the years extensively, so significant progress has been made (Kang and Liu, 2019, Wang et al. 2021a). Heat recovery has been considered as a key measure to improve energy efficiency in process engineering systems. The retrofitting of the HEN design is an effective way to utilize heat from the process stream and minimize energy consumption. In industrial HEN retrofit applications, different types of heat exchangers have different temperature ranges and costs. Considering these aspects of the retrofit design process will make it more practical (Wang et al. 2020). HEN systems can optimize existing heat exchangers, equipped with pinch technology as a method of analysis of HEN system design (Mrayed et al. 2021, Ogbonnaya et al. 2021, Seader et al. 2016).

Pinch analysis can be used to solve the problem of energy utilization in the industry. Stream populations are used to set heating and cooling targets (Akpomiemie and Smith, 2018, Taher Al-Mayyahi et al. 2019). Pinch Analysis-based methods are intensively used for thermal integration, extending the use of mathematical programming. The most advanced innovation of pinch analysis can be found in the previous report (Wang et al. 2021a). One useful tool is the Advanced Grid Diagram which further develops the Retrofit Thermodynamic Diagram, which can illustrate the thermodynamic feasibility of the HEN design plan. The determination of the grid diagram with the factors of temperature, heat capacity, and flow rate will determine a better HEN design based on thermodynamics (Wang et al. 2021b). Based on the literature review, there has not been much research on the HEN optimization in the power generation industry. In case in Indonesia, Paiton Power Plant as the largest power station in Indonesia with a capacity of 2x400 MW is interesting power plant to study.

From the backgrounds, this work aims to obtain the optimal value of the HEN design based on the annual cost value obtained in the power plant industry. Process Flow Diagram of the Power Plant is described in Fig. 1. Briefly, the power plant utilizes the heat from coal burn process that supplied into the boiler (Q-230). The steam generated from Q-230 is transferred into the turbine (N-310). From N-310, the electrical power was generated from the generator (X-330) then transmitted by the transformator (X-340).

This study also aims to reconstruct the existing HEN design for a more efficient simulation process. To get the best value, it is necessary to do several stages of calculation and modeling. Therefore, a HEN is required at each plant to determine the heat and cold flow as well as maximize heat recovery. This method can significantly reduce the need for external utilities. HEN also identifies the energy utilities (external) needed to meet the remaining energy needs of the stream.

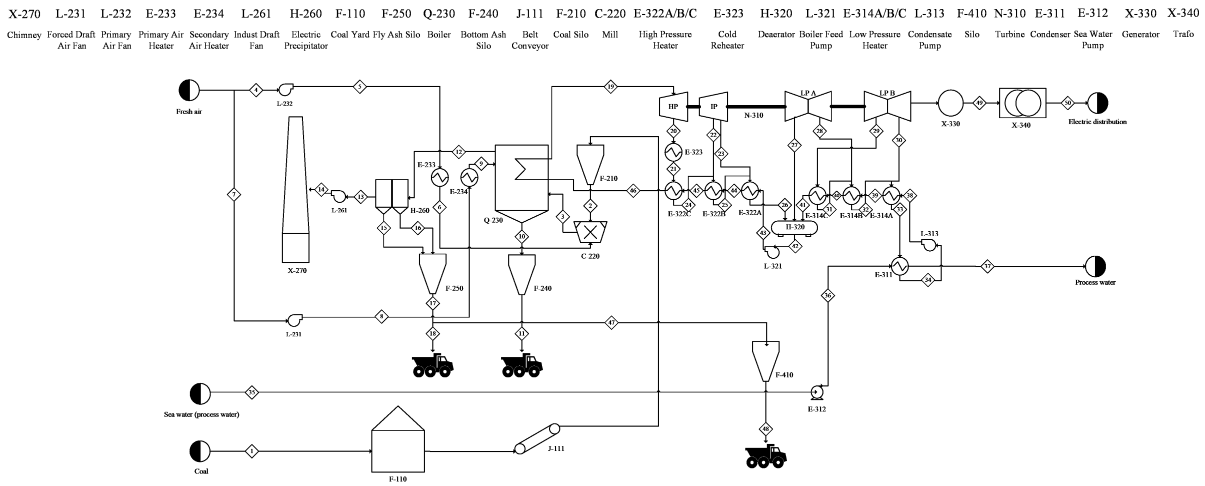


Fig. 1: Overall Process Flow Diagram of Paiton Power Plant.

METHOD

Modelling and Simulation

The modeling and simulation were built based on Fig 2. The modeling and simulation used to create this HEN design program is a set of desktops (computers) with windows 10 operating systems, Microsoft Excel (spreadsheets), and Aspen Energy Analyzer. Aspen Energy Analyzer's fluid package used for the calculation of the thermodynamic and equilibrium properties was based on the Peng-Robinson equation of state that which has been widely used for VLE calculations for pure, binary, or multicomponent components.

Design of Heat Exchanger Network

Data Compilation

The design of HEN begins with the necessary data collection from Paiton Power Plant so it can determine the appropriate HEN design. Calculation of temperature change of the stream (ΔT) value on each stream must be done. Heat transfer characteristics of HEN and external utility requirements were analyzed by determining the heat flow load (H) in the network. The heat flow load is the result of the mass flow rate (m), specific heat capacity (Cp), and temperature changes. Based on Eq. (1) as follows.

$$H = mC_p\Delta T \qquad (1)$$

Cascade Diagram Analysis

Pinch analysis can be used for standard HEN analysis. In this study, the pinch value was used to determine the pinch temperature. The pinch analysis process was done by comparing the value of ΔT_{min} (10°C - 19°C). HEN calculations were performed to obtain pinch value data and minimum utility values of heating and cooling. Temperature values that are sequenced and ΔH_i are used for the calculation of cascade diagrams. The next step in the analysis of pinch methodology was involving the formulation of the stream population, the formation of cascade diagrams, composite curves for hot and cold streams, and grand composite curves (Njoku et al. 2019). The temperature intervals (T*) were required to create feasible temperature driving forces from supply temperature and target temperature by adding $\Delta T_{min}/2$ for cold streams and subtracting $\Delta T_{min}/2$ for hot streams using Eq. (2) and (3) as follows:

$$T^*_{cold} = T_{cold} + \frac{1}{2}\Delta T_{min} \quad (2)$$

$$T^*_{hot} = T_{hot} - \frac{1}{2}\Delta T_{min} \quad (3)$$

The interval temperature will be used to determine the temperature of the system. So, the temperature sequence was obtained from the smallest to the largest. Cascade diagram's calculations are performed to determine the minimum heat utility value ($Q_{H\ min}$), the minimum cold utility ($Q_{C\ min}$), and the pinch temperature value (T_{pinch}). The energy between an interval is calculated by summing the initial energy with the value ΔHi sequentially. The initial energy is assumed to be equal to zero (H = 0) for the initial calculation of the cascade diagram. If in the initial energy calculation between an interval and the smallest energy value of zero, then the calculation of cascade diagram is completed and obtained pinch temperature. The calculation of the cascade diagram generates the values of $Q_{H\ min}$ (heat utility), $Q_{C\ min}$ (cold utility), and pinch temperature value (T_{pinch}) as a result of the calculation of Maximum Energy Recovery (MER) and Heat Exchanger Area (HEA) targets.

Grid Diagram Analysis

HEN design can be improved using grid diagram analysis. Here are the steps to be able to generate a grid diagram: (1) The horizontal line was drawn to represent each stream contained in the system. The line was drawn from the left (top of the pinch temperature) to the right (bottom of the pinch temperature) with the appropriate order of components, (2) a vertical line (dotted) was drawn from top to bottom which represents the pinch temperature, (3) the connection between the hot and cold streams began the pinch line, (4) the grid diagram was divided into 2 (two) zones, below the pinch temperature (right side of the pinch line) and above the pinch temperature (left side of the pinch line), (5) in the installation process between hot and cold streams are connected by points that represent the Heat Exchanger (HE) based on energy analysis, and (6) the grid diagram design is acceptable if all target temperatures have been reached.

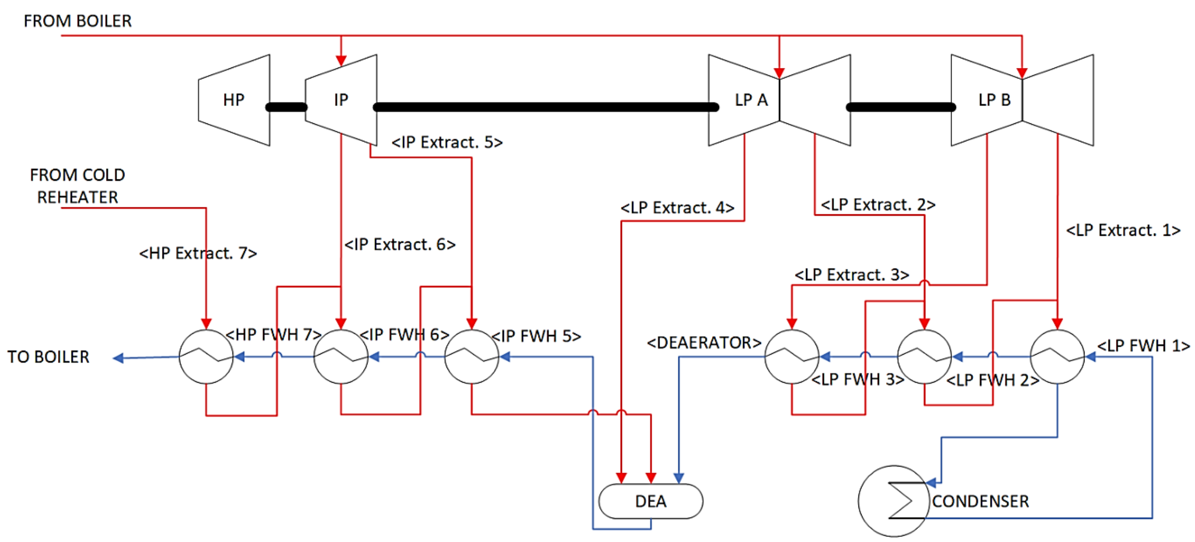


Fig. 2: Process Flow Diagram of Steam Power Generation.

Table 1. Stream data in Paiton Power Plant Unit 1-2.

No	Component	Stream Number	Type	Tin (℃)	Tout (℃)	M (kg/s)	Cp (kJ/kg℃)	Q (kW)
1	LP FWH 1	38	Cold	42.51	82.26	264.05	4.17	43,810.75
2	LP FWH 2	39	Cold	82.26	106.07	264.05	4.19	26,368.11
3	LP FWH 3	40	Cold	106.07	125.91	264.05	4.23	22,097.31
4	Deaerator	41	Cold	125.91	150.90	327.41	4.25	34,765.64
5	IP FWH 5	43	Cold	150.90	164.41	327.41	4.25	18,808.14
6	IP FWH 6	44	Cold	164.41	204.00	327.41	4.29	55,569.47
7	HP FWH 7	45	Cold	204.00	250.06	327.41	4.43	66,747.13
8	LP Extraction 1	30	Hot	85.06	48.11	16.86	2.03	-1,262.92
9	LP Extraction 2	28	Hot	124.99	87.66	10.82	2.06	-831.17
10	LP Extraction 3	29	Hot	185.79	111.67	9.36	2.05	-1,421.46
11	LP Extraction 4	27	Hot	243.05	150.90	5.93	2.05	-1,120.75
12	IP Extraction 5	23	Hot	304.99	156.50	6.55	2.10	-2,043.10
13	IP Extraction 6	22	Hot	422.76	170.01	19.66	2.18	-10,818.76
14	HP Extraction 7	21	Hot	349.52	209.60	31.22	2.50	-10,903.28

The entire process was simulated using the Aspen Energy Analyzer. The following type of stream, supply temperature (T_{in}), target temperature (T_{out}), mass flow (M), specific heat (C_P) is listed in the problem table data as shown in Table 1.

Scenario Description

The steps that need to be taken in carrying out this research are shown in Fig. 3.

RESULTS AND DISCUSSION

Pinch analysis includes composite curves, shifted composite curves, and grand composite curves are supported by stream population algorithms as well as grid diagrams (Walmsley et al. 2018). The composite curve is obtained by plotting the temperature and enthalpy flow process to identify utility targets and pinch temperatures. Grand composite curves are obtained by plotting the clean heat flow of a process at different temperatures as well as assisting in identifying the needs of external heating and cooling utilities.

Utilization of wasted heat energy would save the use of raw materials. The work that can be done is integrating processes for efficient energy use (Muharja et al. 2023, 2018). Maximum Energy Recovery (MER) was obtained with pinch technology analysis. Pinch technology analysis can also give an idea of the pressure conditions, temperature, and amount of energy used or wasted (Goodarzvand-Chegini and GhasemiKafrudi, 2017). Boilers produce steam that is delivered to the High Pressure (HP) turbine. Next the output of the turbine, steam is sent back to the boiler for reheating, and then the steam is sent to the Intermediate Pressure (IP) turbine, then the IP output of the turbine will be sent to the Low Pressure (LP) turbine. Next, the LP turbine output will be applied to the condenser in the form of a shell and tube heat exchanger. An air coolant flows through the condenser tube while steam condenses on the side of the shell. Heat is transferred from steam extraction from HP and IP to raise their temperature (Żymełka et al. 2018).

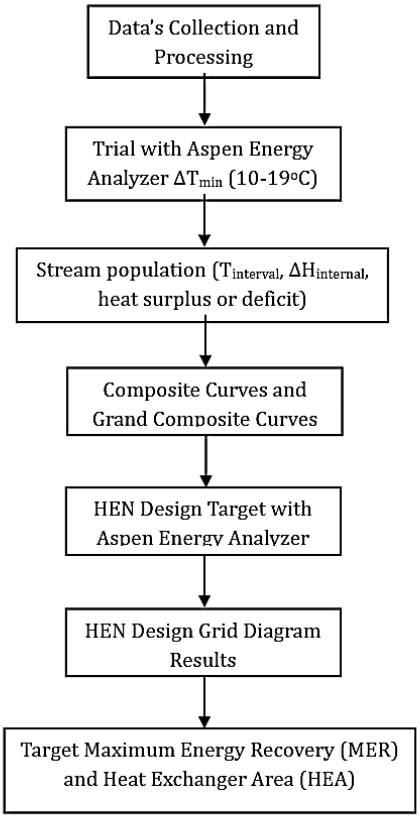


Fig. 3: Research methodology.

Aspen Energy Analyzer is a heat integration software that combines traditional pinch analysis with mathematical programming for HEN design and optimization along with minimum Total Annual Cost (TAC) on a process. The software designed HEN using pinch methods or mathematical programming with an automatic recommendation of design features involving linear programming models and two-step Mixed Integer Linear Programming (MILP). As depicted in Fig. 4, the software optimizes the design of HEN considering the degree of freedom, the feasibility of heat exchanger network, temperature specifications aimed at minimizing TAC, and the placement of the area of HE which indicates a correlation between energy, area, and unit in a HEN design (Lai et al. 2019). Paiton Power Plant Unit 1-2 has 14 components as found in Table 1. The research was conducted on the entire HE. The basic data required for pinch analysis includes supply temperature (T_{in}), target temperature (T_{out}), mass flowrate (M), and heat capacity constant (C_P).

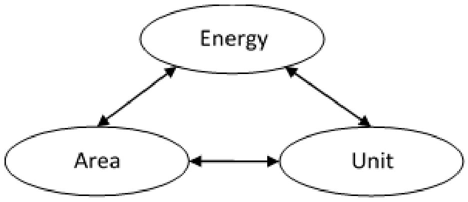


Fig. 4: The trade-off between energy consumption, heat exchanger area needs, and number of units.

The heat capacity value (CP) was derived from Equation 1. Based on the analysis in Table 2, the optimum ΔT_{min} value was obtained at a temperature of 16°C as shown in Fig. 5 which compares annual cost with ΔT_{min}. Further analysis was done after the value of ΔT_{min} was found. Annual cost value was obtained by trial the ΔT_{min} through Aspen Energy Analyzer. Calculation of Total Annual Cost (TAC) to obtain optimal ΔT_{min} values as well as showed the importance of super targeting as the optimal TAC achieved involving multiple utilities is important in the use of multi utility (Karimi et al. 2019). This finding is in agreement with another work which shows that TAC plays an important role in determining ΔT_{min} (Zamora et al. 2020). The case study conducted by Hassan et al. (2019) showed that TAC is one of the important parameters to decide the ΔT_{min}. A higher value at higher ΔT_{min} resulting in the number and demand for utility units can increase due to the limited amount of heat exchanged in heat exchanger unit, so that it increases the annual cost. Meanwhile, a relatively low ΔT_{min}

can increase the annual cost because achieving lower ΔT_{min} requires a heat exchanger with higher equipment specifications and maintenance cost.

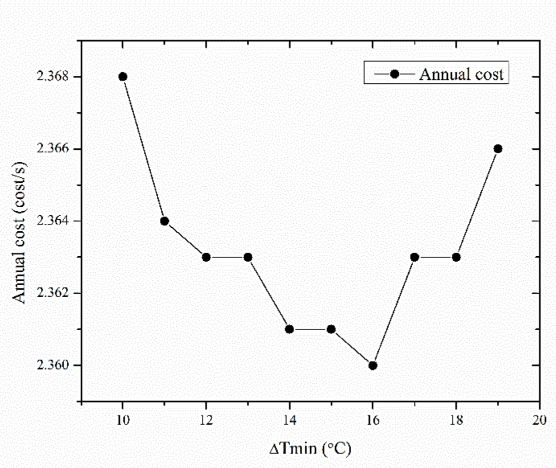


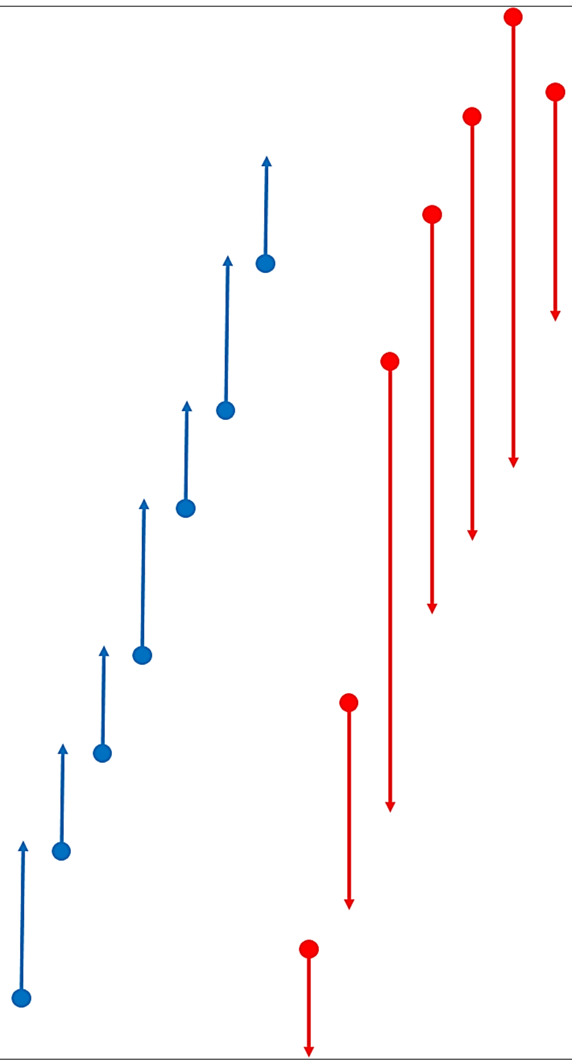
Fig. 5: Mean ΔT_{min} results vs annual cost.

Table 2 shows data of the shifted temperature (T_{in}* and T_{out}*) with ΔT_{min} processing. The calculation of heat flow (hot stream) is the initial temperature minus ½ΔT_{Min}. Cold stream is calculated by adding ½ΔT_{min} at the initial temperature. The next steps was analyzed based on literature from Smith (2005) as shown in Fig. 5 with the stream population to determine the energy needed for each stream.

Fig. 6 shows the stream population between the relationship of cold flow and heat flow which was used to describe the cascade diagram as shown in Fig. 7. Cascade diagrams were used to analyze hot and cold utilities as well as to determine pinch values. Pinch temperature was obtained when the value of H (enthalpy) of the initial energy assumed to be equal to zero (H=0) is reduced by the ΔHi to get the smallest energy. Furthermore, the smallest energy was placed in the initial calculation until the result of H (enthalpy) is equal to 0 (zero). The intervals temperature was obtained from Eq. (2) to obtain the existing temperature population..

Table 2. Shifted Temperature (Tin* and Tout*) Calculation for ΔT_{min} 16 °C.

No	Component	Tin (°C)	Tout (°C)	Tin* (°C)	Tout* (°C)
1	LP FWH 1	42.51	82.26	50.51	90.26
2	LP FWH 2	82.26	106.07	90.26	114.07
3	LP FWH 3	106.07	125.91	114.07	133.91
4	Deaerator	125.91	150.90	133.91	158.90
5	IP FWH 5	150.90	164.41	158.90	172.41
6	IP FWH 6	164.41	204.00	172.41	212.00
7	HP FWH 7	204.00	250.06	212.00	258.06
8	LP Extraction 1	85.06	48.11	77.06	40.11
9	LP Extraction 2	124.99	87.66	116.99	79.66
10	LP Extraction 3	185.79	111.67	177.79	103.67
11	LP Extraction 4	243.05	150.90	235.05	142.90
12	IP Extraction 5	304.99	156.50	296.99	148.50
13	IP Extraction 6	422.76	170.01	414.76	162.01
14	HP Extraction 7	349.52	209.60	341.52	201.60



Interval Temperature	ΔT Internal	∑Cp C - ∑Cp H	ΔH Internal	Surplus/ Deficit
414.76				
	73.24	-42.80	-3134.98	Surplus
341.52				
	44.53	-120.73	-5376.08	Surplus
296.99				
	38.93	-134.49	-5235.64	Surplus
258.06				
	23.01	-134.49	-3094.58	Surplus
235.05				
	23.05	1302.48	30022.25	Deficit
212.00				
	10.4	1256.97	13072.52	Deficit
201.60				
	23.81	1334.90	31783.93	Deficit
177.79				
	5.38	1315.72	7078.58	Deficit
172.41				
	10.4	1304.26	13564.31	Deficit
162.01				
	3.11	1347.07	4189.37	Deficit
158.90				
	10.4	1346.08	13999.26	Deficit
148.50				
	5.6	1359.84	7615.12	Deficit
142.90				
	8.99	1372.00	12334.32	Deficit
133.91				
	16.92	1094.60	18520.59	Deficit
116.99				
	2.92	1072.33	3131.21	Deficit
114.07				
	10.4	1066.00	11086.35	Deficit
103.67				
	13.41	1085.17	14552.17	Deficit
90.26				
	10.6	1079.89	11446.85	Deficit
79.66				
	2.6	1102.16	2865.61	Deficit
77.06				
	26.55	1073.26	28495.03	Deficit
50.51				
	10.4	-34.18	-355.46	Surplus
40.11				

Fig. 6: Stream population.

The analysis in Fig. 6 aims to determine the pinch value and determine the exchange energy of each stream. The value of $Q_{H\ min}$ was 206,916.2 kJ h^{-1} and $Q_{C\ min}$ was 355.5 kJ h^{-1} as found in Fig. 6. The pinch for heat flow was obtained by adding a pinch temperature of ½ΔT_{Min} and obtaining a yield of 58.51°C. The pinch value for cold flow was obtained by reducing the pinch temperature by ½ΔT_{Min} and obtaining a yield of 42.51°C (Di Pretoro and Manenti, 2020). Fig. 7 also describes the heat surplus deficit table. Pinch values on hot and cold streams are shown in Fig. 7.

The composite curve in Fig. 8 was derived from the relationship between the hot and cold flow. The heat flow on the curve is depicted with a red line, while the cold flow is indicated by the blue line. The composite curve between cold and hot streams indicates the nearest point approach known as the pinch point (Njoku et al. 2019). The composite curve's data shows the Maximal Energy Recovery (MER) value. At ΔT_{min} 16°C, MER value of 1,032,142,104 kJ h^{-1} from the highest reduction in hot flow enthalpy with the lowest cold flow enthalpy.

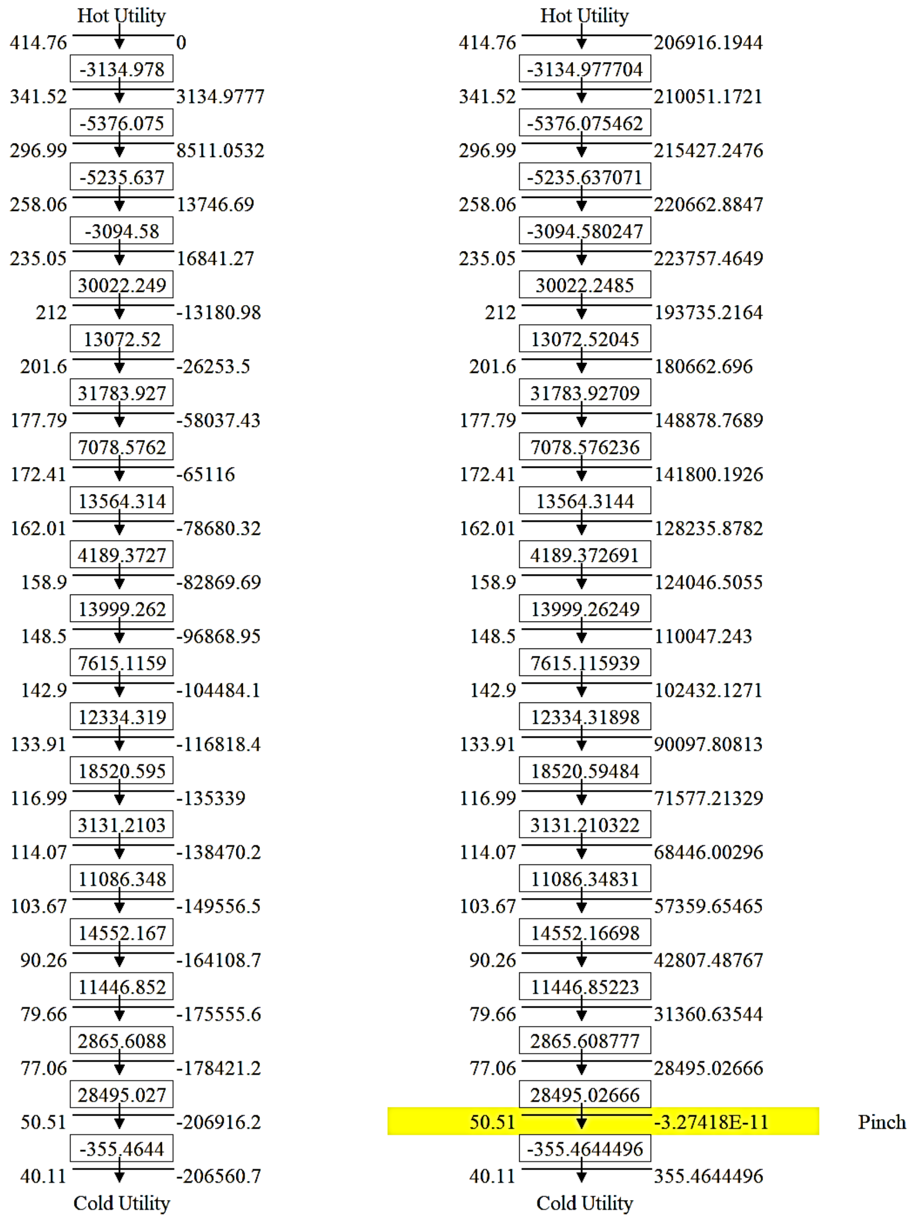


Fig. 7: Cascade diagram.

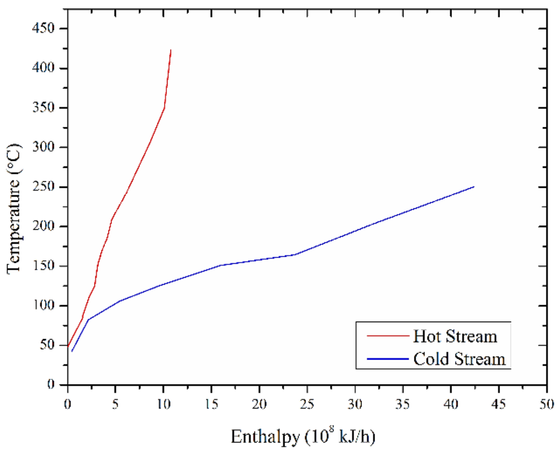


Fig. 8: Composite curve.

The grand composite curve in Fig. 8 was obtained by the result of plotting between temperature and H (enthalpy) on the cascade diagram. The Grand composite curve is designed to determine hot and cold utility targets and illustrates the difference between heat flow and cold flow. Based on Fig. 8 and Fig. 9, the differences before and after the flow pinch analysis can be observed. The effect of differences in temperature between cold flow and heat flow is influenced by the distance between streams, energy needs, lost energy, and increasingly smaller effectiveness. Heat recovery value in Fig. 7 was obtained from the curve slice, while the remaining slices on each curve constitute the minimum energy requirement. Based on Fig. 8, it is shown that the curve shift diagram that touches the pinch temperature was 50.51°C. The highest point on the grand composite curve was 1,076,570,839.7 kW, which indicates heating duty and the lowest point that shows cooling duty was 44,428,736.16 kW. The result of HEN's target design with Aspen Energy Analyzer obtained an area for heat exchanger in the amount of 138,789.48 m^2 for counter current and 146,043.6 m^2 for shell and tube as shown in Fig. 10.

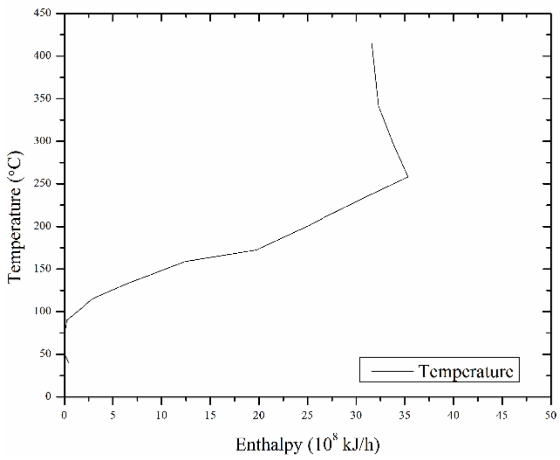


Fig. 9: Grand composite curve.

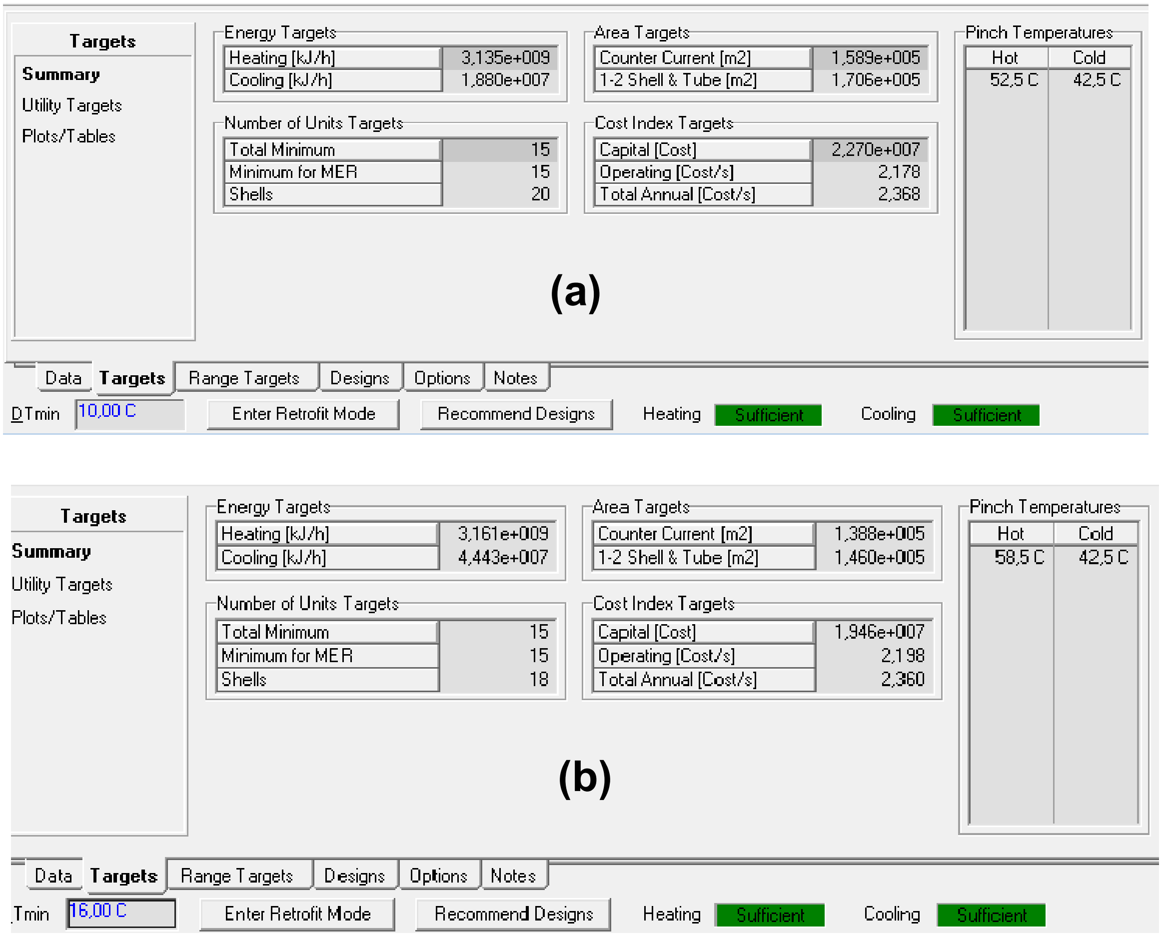


Fig. 10: The comparison of target HEN results before (a) and after re-design (b).

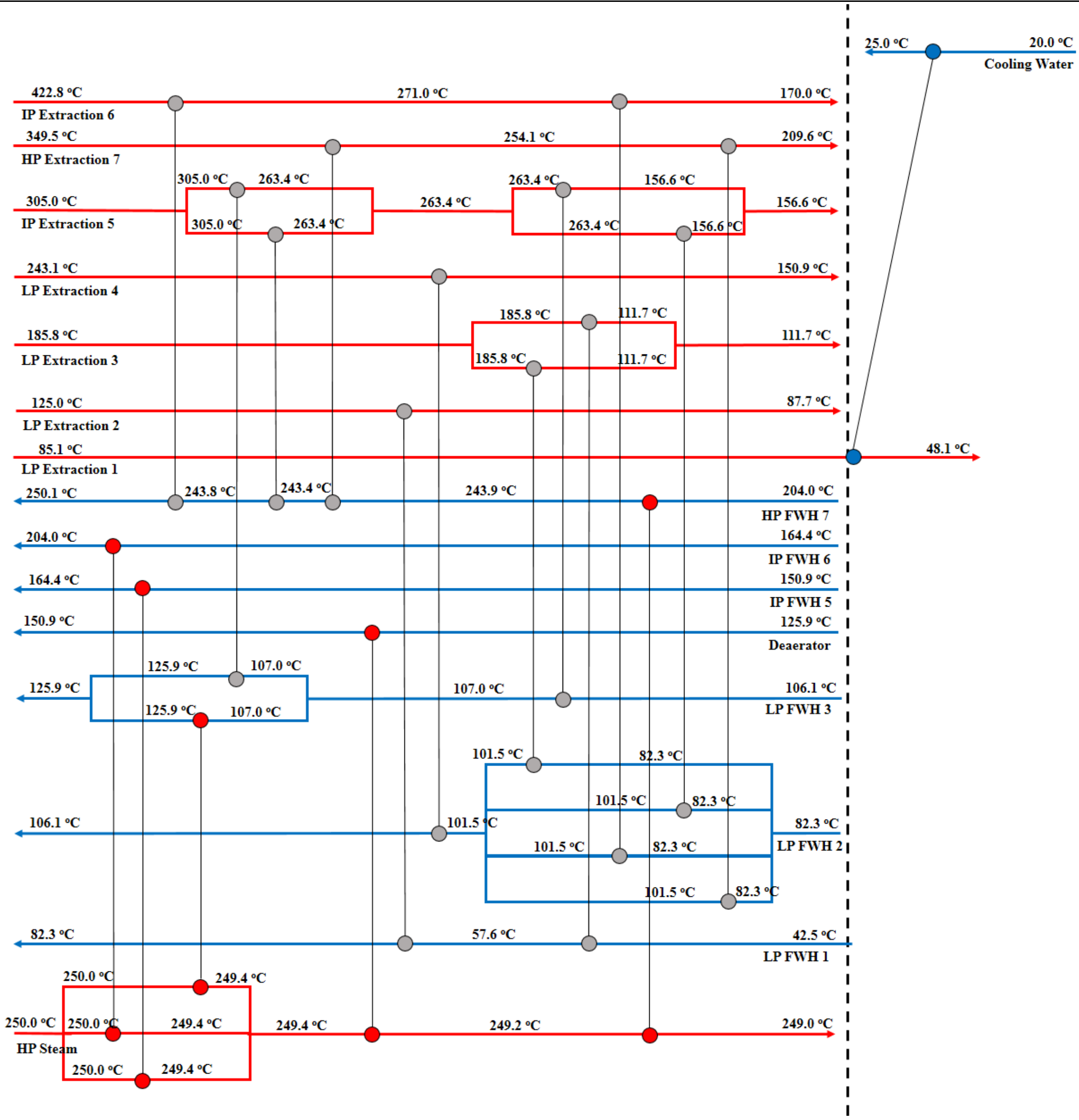


Fig. 11: Grid diagram.

HEN is designed to optimize energy transfer by combining heat and cold flow which requires additional energy (either heating or cooling). The grid diagram corresponds to pinch analysis as shown in Fig. 11. There is no additional heat under the pinch utility, no additional coolant above the pinch utility, as well as no heat transfer that crosses the pinch value. If there is a displacement at the pinch value, then the grid diagram should be set back to add heat on of the pinch value as well as add cold at the bottom of the pinch value. Grid diagrams on the result use split or flow separation because the flow which less suitable if integrated so that separation is required by not breaking the design data. Based on the results of the grid diagram design that has been obtained, a modification of the design of the new flow diagram is discovered. This new design gave a positive impact to the process which contributes to the cost reduction of capital, operating, and a total annual of about 14.3%. The Maximum Energy Recovery (MER) value obtained by calculation in this article was 286,706.14 kW and Heat Exchanger Area

(HEA) is 138,789.48 m^2 for counter current and 146,043.6 m^2 for shell and tube.

CONCLUSIONS

Optimization of heat exchanger network design of Power Plants was carried out to achieve the minimum capital, operating, and total annual cost reduction of about 14.3%. Pinch analysis using Aspen Energy Analyzer was able to reconstruct the arrangement of Heat Exchanger Network (HEN). This study shows that pinch analysis with ΔT_{min} 16°C can be applied to the power plant industry because it can reduce Total Annual Cost (TAC) and maximize MER in the operating process.

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