

Heat Exchanger Network Optimization in A Natural Gas Dehydration Unit

Adhi Kurniawan, Juwari, and Renanto Handogo

Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya

e-mail: renanto@chem-eng.its.ac.id

Abstract—A dehydration unit using triethylene glycol absorption is a common process in natural gas processing. In its regeneration section, the regenerated lean glycol needs to be cooled before entering the glycol absorber, while the rich glycol is to be preheated before entering the regenerator. This is a good candidate for heat exchanger network (HEN) optimization. In this work, the HEN was revisited using pinch analysis (PA) and mathematical programming (MP) using superstructure. The optimized networks were evaluated using simplified total annual cost (TAC). The PA method using small ΔT_{min} (minimum temperature approach) led to the configuration of three exchangers, a heater and a cooler, with minimized utilities. At larger ΔT_{min} , the configuration became into two exchangers, two heaters, and a cooler. The minimum calculated TAC is \$60,351/year at $\Delta T_{min} = 12.5^{\circ}\text{C}$. Furthermore, it was revealed that one heater and one exchanger were too small. Therefore, they were omitted, and the heat load were redistributed to the network. The calculated TAC became \$59,224/year. The superstructure approach resulted in two exchangers, a heater, and a cooler; with a calculated minimum TAC of \$57,597/year. The two approaches have resulted in very similar minimized TAC.

Keywords—Pinch Analysis, Superstructure Approach, Total Annual Cost.

I. INTRODUCTION

DEHYDRATION is one of the important processes in a natural gas processing unit. It reduces the water vapor content in the gas stream to avoid operational problems such as internal pipe corrosion, water condensation, and gas hydrate formation. Absorption using triethylene glycol (TEG) solution is one of the available methods of dehydrating natural gas. A lean glycol solution is contacted countercurrently with a wet gas stream in a TEG Absorber column. The rich glycol comes out from the bottom of the column. It is then routed to the regeneration unit, in which the rich glycol is preheated before entering a reboiled stripper. The reboiler is typically operated at 200°C (maximum 204°C) and near atmospheric pressure approximately at 105 kPa [1]. After regenerated, the glycol can be reused in the absorber column again. To improve the absorption process, the lean glycol needs to be cooled to absorber operating temperature which is typically operated at $16\text{--}38^{\circ}\text{C}$ [2]. This provides an opportunity to recover the heat between the two glycol streams, i.e. hot lean glycol and cold rich glycol.

There are several publications related to the design optimization of TEG dehydration and regeneration system focusing on improving the TEG purity and gas moisture while minimizing the energy requirement. Only few of them focuses on revisiting the heat recovery options to optimize the overall technical and economic performance. Affandy et al

(2017) studied the optimization of TEG dehydration system by replacing the trayed absorber column into a packed absorber, and varying the area of heat exchangers in the regeneration system [3]. They used a sequential optimization approach to determine the lowest Total Annual Cost (TAC). Figure 1 indicates that the heating (including reboiler) and cooling cost constitutes around 84% of the energy cost [4]. Therefore, an improvement in the heat recovery is expected to reduce the energy cost. This study focuses on the smaller system of the glycol regeneration system, i.e. its heat recovery system that exchange the heat between the hot lean and cold rich glycol. It is intended to apply the available methods of heat exchanger network (HEN) design and optimization to the TEG regeneration system. It is expected that if the regeneration system has optimized heat recovery system, then consequently the overall regeneration performance will be improved.

The design and optimization of heat exchanger network (HEN) has been one of the most interesting subject in chemical engineering. Due to the extensive research in this field of study, the recent development will be described only in short. The state of the art of the heat integration, both using pinch analysis and mathematical programming, has been elaborated by Klemeš and Kravanja (2013) [5].

In this study, the heat exchanger network within the TEG regeneration system will be developed using two methods, i.e. (a) pinch analysis, and (b) mathematical programming using superstructure approach. The grid diagram will be constructed based on the results from each method. The energy cost and the annualized capital cost will be calculated and be used to determine the Total Annual Cost (TAC). The minimum temperature approach will be the variable to minimize the calculated TAC.

II. METHOD

A. Flow Diagram

Figure 2 depicts the flow diagram of TEG Dehydration system used in this study. The basic process data is tabulated in Table 1.

B. Pinch Analysis

The design of the heat exchanger network using Pinch analysis is using the following approach. It starts with the determination of minimum external utility requirements using shifted temperature (Problem Table Algorithm) [6]. Another way to define the minimum utility requirements is using the Grid Diagram Table [7]. The grid diagram for each ΔT_{min} is developed by pinch design method, i.e. divide the

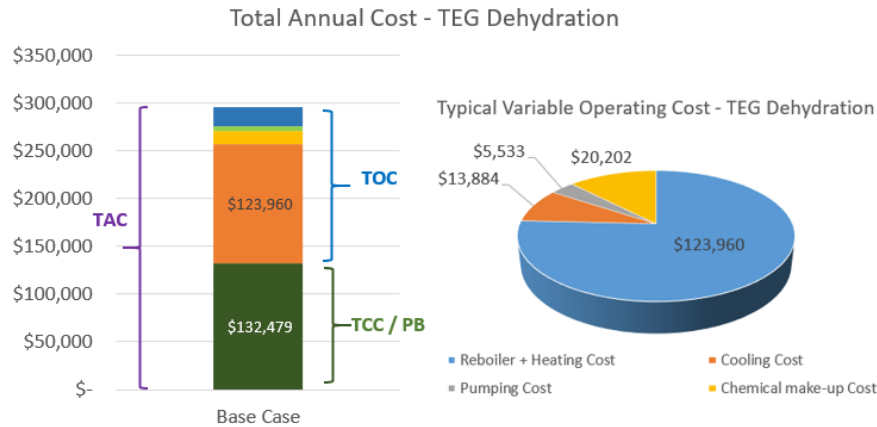


Figure 1. Total annual cost for typical TEG dehydration with conventional regeneration.

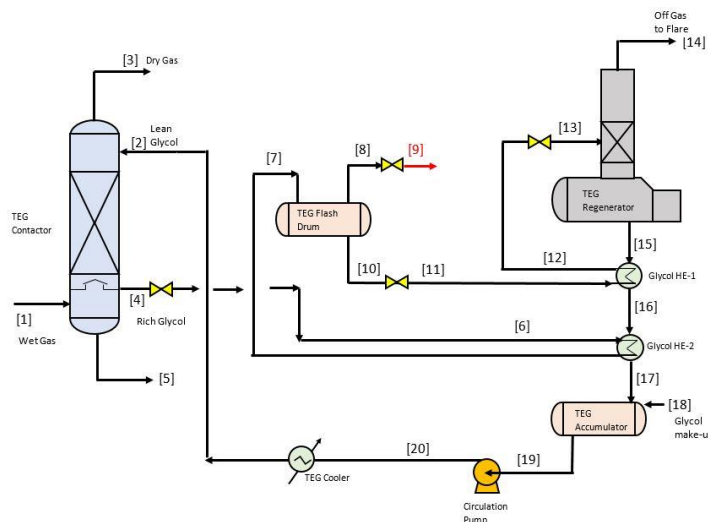


Figure 2. Process flow diagram for TEG dehydration with conventional regeneration.

Table 1.
 Basic Process Data in The TEG Dehydration System Used in this Study

No	Stream Name	T _s (°C)	T _t (°C)	Q (kW)	CP (kW/°C)
1	Lean TEG	189.0	45.0	612.00	4.25
2	Rich TEG 1	32.41	104.2	263.47	3.67
3	Rich TEG 2	99.9	170.0	321.76	4.59

network into two separate subnetworks, start at the pinch, examine the heat capacity inequality for each matches to ensure temperature feasibility, and use tick-off heuristic which guides the design to use minimum number of units [6]. The area of heat exchangers, heater, and cooler are calculated using the approach explained in the next subsection. After the initial network is defined, examine if there is any heat exchanger loop, or utility path. This provides possibility for further optimization to minimize the total annual cost by relaxing the temperature ΔT_{min} constraint [6]. The total annual cost for the design heat exchanger network is determined using the same approach explained in next subsection.

C. Superstructure Approach

The design of the heat exchanger network using simplified superstructure as depicted in the Figure 3 [8]. Mathematical equations used in the superstructure approach are as follows.

Minimize the objective function:

$$\frac{7296}{3} \times \left[(A_{H1,C1})^{0.65} + (A_{H1,C2})^{0.65} + (A_{HU,C2})^{0.65} + (A_{H1,CU})^{0.65} \right] + (Q_{HU} \times C_{HU}) + (Q_{CU} \times C_{CU}) \tag{1}$$

Subject to

Mass balances for splitters:

$$F_{1,1} + F_{2,1} = F_{hot,in} \tag{2}$$

$$F_{1,3} + F_{1,4} - F_{1,2} = 0 \tag{3}$$

$$F_{2,3} + F_{2,4} - F_{2,2} = 0 \tag{4}$$

Mass balances for mixers:

$$F_{1,1} + F_{2,3} - F_{1,2} = 0 \tag{5}$$

$$F_{2,1} + F_{1,3} - F_{2,2} = 0 \tag{6}$$

$$F_{1,4} + F_{2,4} - F_{hot,out} = 0 \tag{7}$$

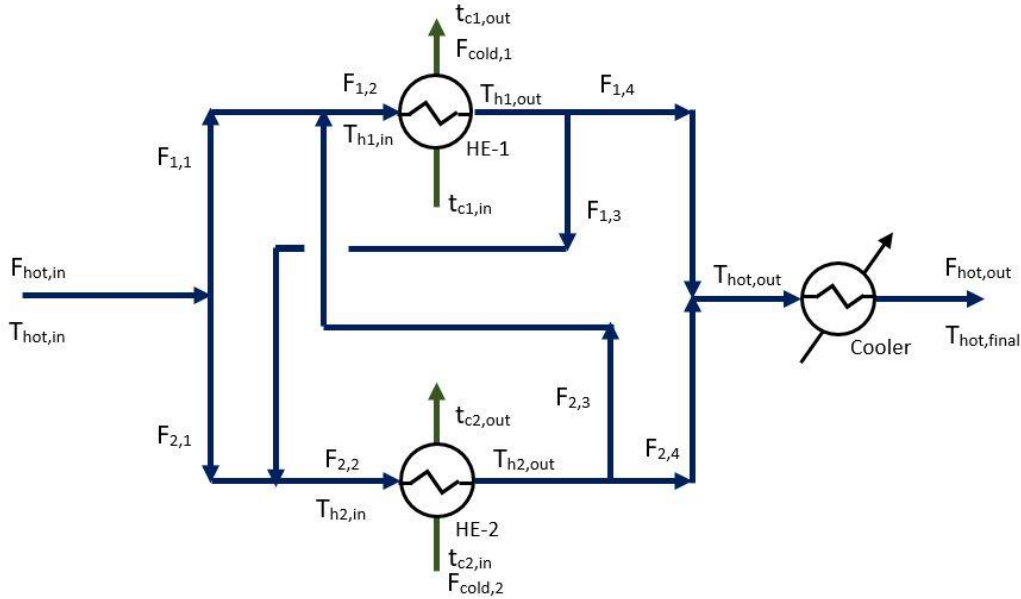


Figure 3. Superstructure model for heat exchanger network.

ΔT_{min}	12.5	°C	Interval			1	2	3	4	PINCH	5	6
Stream Name	Heat Flow (kW)	FCp (kW/°C)	Supply Temp (°C)	Target Temp (°C)	Shifted Temp (°C)	182.8	176.3	116.1	110.5	106.2	38.75	38.66
H1	612.00	4.25	45.0	104.2	Hot	→						
C1	263.47	3.67	32.41	104.2	Cold	←						
C2	321.76	4.59	99.9	170.0	Cold	←						
$\Sigma FCp,hot - \Sigma FCp,cold$						4.25	-0.34	-0.34	-4.01		0.58	-3.67
ΔT						6.5	60.2	5.6	4.3		67.4	0.09
ΔH_{net}						27.63	-20.47	-1.90	-17.24		39.09	-0.33
$\Sigma \Delta H_{net}$											-11.99	38.76

Figure 4. A Grid Diagram Table for the heat exchanger network using $\Delta T_{min} = 12.5^\circ C$.

Table 2.
 Summary Results of Heat Exchanger Networks Derived from Pinch Analysis

Case	min temp approach	Q_{cmin} (kW)	Q_{hmin} (kW)	Q_{rec} (kW)	Number of HE units	Number of Heaters	Number of Coolers	Total Area (m ²)	Capital Cost (\$)	Annualized Capital Cost (\$/yr)	Energy Cost (\$/yr)	Total Annual Cost (\$/yr)
1	10.0	28.14	1.36	583.0	3	1	1	79.7	175,200	58,400	2,604	61,004
2	12.5	38.76	11.99	573.2	3	1	1	68.3	161,036	53,679	6,672	60,351
3	15.0	49.39	22.62	578.4	2	2	1	60	152,298	50,766	10,735	61,501
4	17.5	60.01	33.24	567.8	2	2	1	53.8	145,586	48,529	14,793	63,322
5	20.0	70.64	43.85	557.1	2	2	1	49.1	139,929	46,643	18,863	65,506

Energy balances for mixers:

$$F_{1,1} \cdot T_{Hot,in} + F_{2,3} \cdot T_{h2,out} - F_{1,2} \cdot T_{h1,in} = 0 \quad (7)$$

$$F_{2,1} \cdot T_{Hot,in} + F_{1,3} \cdot T_{h1,out} - F_{2,2} \cdot T_{h2,in} = 0 \quad (8)$$

$$F_{2,4} \cdot T_{h2,out} + F_{1,4} \cdot T_{h1,out} - F_{hot,out} \cdot T_{hot,out} = 0 \quad (9)$$

Energy balances for heat exchangers, heater, and cooler:

$$F_{1,2} \cdot (T_{h1,in} - T_{h1,out}) = F_{cold,1} \cdot (t_{c1,out} - t_{c1,in}) \quad (10)$$

$$F_{2,2} \cdot (T_{h2,in} - T_{h2,out}) = F_{cold,2} \cdot (t_{c2,out} - t_{c2,in}) \quad (11)$$

$$Q_{HU} - F_{cold,2} \cdot (t_{c2,f} - t_{c2,out}) = 0 \quad (12)$$

$$Q_{CU} - (F_{1,4} + F_{2,4}) \cdot (T_{Hot,out} - T_{Hot,final}) = 0 \quad (13)$$

Feasibility constraints:

$$T_{H1,out} - t_{c1,in} \geq \Delta T_{min} \quad (14)$$

$$T_{H1,in} - t_{c1,out} \geq \Delta T_{min} \quad (15)$$

$$T_{H2,out} - t_{c2,in} \geq \Delta T_{min} \quad (16)$$

$$T_{H2,in} - t_{c2,out} \geq \Delta T_{min} \quad (17)$$

Non-negativity constraints

$$F_{1,1}, F_{1,2}, F_{1,3}, F_{1,4}, F_{2,1}, F_{2,2}, F_{2,3}, F_{2,4} \geq 0 \quad (18)$$

The areas in the objective function are calculated using the following approximation based on heat exchanger sizing by Luyben (2011) [9].

Heat exchanger, HE-1:

$$A_{H1,C1} = \frac{Q_{H1,C1}}{0.57 \times LMTD_{H1,C1}} \quad (19)$$

Heat exchanger, HE-2:

$$A_{H1,C2} = \frac{Q_{H1,C2}}{0.57 \times LMTD_{H1,C2}} \quad (20)$$

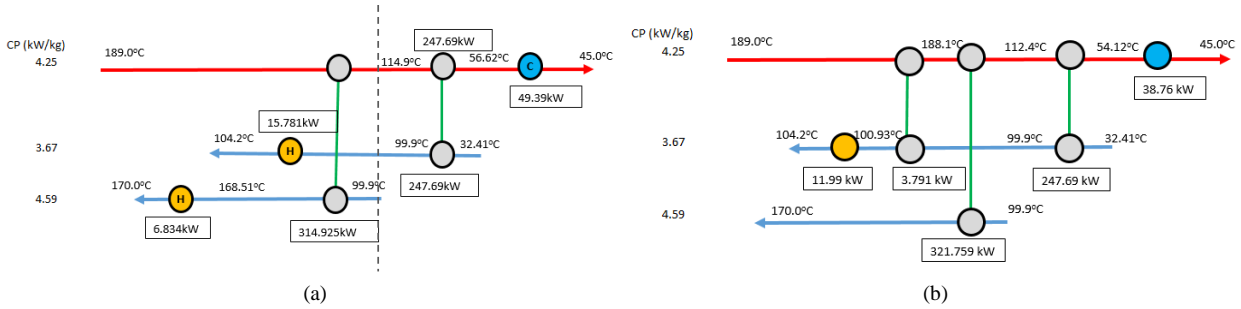


Figure 5. Grid diagram heat exchanger network based on minimum utility from pinch analysis with ΔT_{min} of (a) 12.5°C and (b) 15°C.

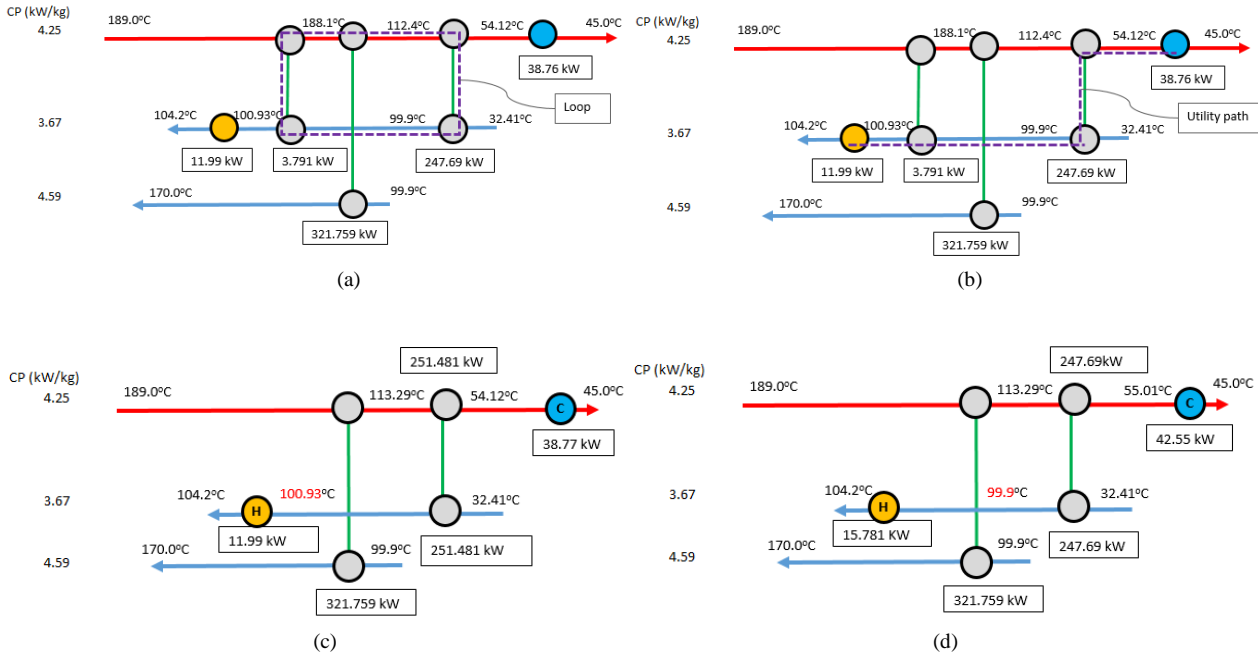


Figure 6. Grid diagram heat exchanger network – optimization through (a) removing loop – Case 2A; (b) review utility path – Case 2B; (c) result Case 2A; and (d) result Case 2B.

Heater:

$$A_{HU,C2} = \frac{Q_{HU,C2}}{0.57 \times LMTD_{HU,C2}} \quad (21)$$

Cooler:

$$A_{H1,CU} = \frac{Q_{H1,CU}}{0.57 \times LMTD_{H1,CU}} \quad (22)$$

The log-mean temperature difference (LMTD) is calculated using the Chen approximation to avoid numerical calculation problem (division by zero) [10].

$$LMTD = \left[\Delta T_1 \times \Delta T_2 \times \left(\frac{\Delta T_1 + \Delta T_2}{2} \right) \right]^{\frac{1}{3}} \quad (23)$$

where

$$\Delta T_1 = T_{h,in} - t_{c,out} \quad (24)$$

$$\Delta T_2 = T_{h,out} - t_{c,in} \quad (25)$$

D. Total Annual Cost Calculation

The Total Annual Cost for each HEN configuration was calculated using the method from Luyben (2011) [9]. The TAC is the sum of annualized total capital cost (TCC) and the annual total operating cost (TOC). In this study, the TCC was annualized by dividing it using small payback (PB) period of 3 (three) years. Whereas, the TOC was limited to the energy cost, i.e. external hot and cold utility costs.

$$TAC = TOC + \frac{TCC}{PB} \quad (26)$$

$$TOC = (Q_{HU} \times C_{HU}) + (Q_{CU} \times C_{CU}) \quad (27)$$

$$TCC = 7296 \times A^{0.65} \quad (28)$$

E. Mathematical Programming

The mathematical programming of the superstructure heat exchanger network using General Algebraic Modeling System (GAMS) was adapted from the program listing written by Andrei (2010) [11].

III. RESULTS AND DISCUSSION

The design of heat exchanger network with pinch analysis approach was carried out using minimum temperature approach ranging from 10-20°C. The minimum external utilities requirements, both cold and hot utilities, were determined using Problem Table Algorithm (PTA). Figure 4 shows the Grid Diagram Table (GDT) of the HEN using $\Delta T_{min} = 12.5^\circ\text{C}$ for example [7].

The calculated minimum utilities requirements for the other ΔT_{min} were tabulated in Table 2. It shows that at small minimum temperature approach (<15°C), the pinch analysis (PA) led to the configuration of 3 (three) heat exchangers, one heater, and one cooler. At larger minimum temperature

Table 3.
 Summary Results of Heat Exchanger Networks Optimized from Case 2

Case	min temp approach	Q _{cmin} (kW)	Q _{hmin} (kW)	Q _{rec} (kW)	Number of HE units	Number of Heaters	Number of Coolers	Total Area (m ²)	Capital Cost (\$)	Annualized Capital Cost (\$/yr)	Energy Cost (\$/yr)	Total Annual Cost (\$/yr)
2A	12.4	38.76	11.99	573.2	2	1	1	66.6	157,652	52,511	6,673	59,224
2B	13.4	42.55	15.78	569.4	2	1	1	65.1	156,062	52,021	8,121	60,141

Table 4.
 Summary Results of Heat Exchanger Networks Derived from Superstructure Approach

Case	min temp approach	Q _{cmin} (kW)	Q _{hmin} (kW)	Q _{rec} (kW)	Number of HE units	Number of Heaters	Number of Coolers	Total Area (m ²)	Capital Cost (\$)	Annualized Capital Cost (\$/yr)	Energy Cost (\$/yr)	Total Annual Cost (\$/yr)
S-2	12.5	42.25	14.48	570.7	2	1	1	60.0	149,919	49,973	7,624	57,597

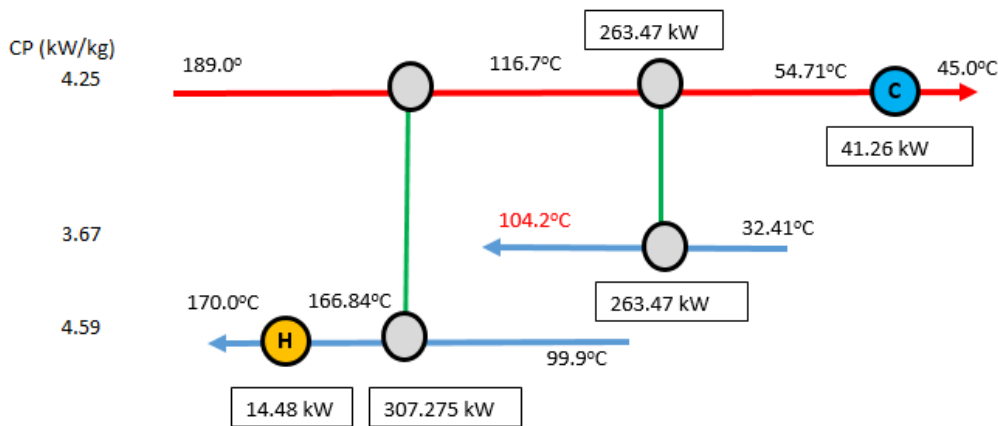


Figure 7. Grid diagram heat exchanger network based on superstructure approach.

approach ($>15^{\circ}\text{C}$), the PA method resulted in HEN configuration of 2 (two) heat exchangers, two heaters, and one cooler. Table 2 also indicates that the Case 2 ($\Delta T_{\min} = 12.5^{\circ}\text{C}$) has the lowest TAC. This configuration will be used in the subsequent optimization.

The minimum number of heat exchangers, heater, and cooler were determined using construction of grid diagram with procedure from Smith (2005) [6]. The constructed grid diagram for HEN with $\Delta T_{\min} = 12.5^{\circ}\text{C}$ is shown in Figure 5(a). It has 3 exchangers, 1 cooler, and 1 heater. The related grid diagram for HEN with $\Delta T_{\min} = 15^{\circ}\text{C}$ is depicted in Figure 5(b). It has different structure compared to the one in Figure 5(a); that it consists of 2 exchangers, 2 heaters, and 1 cooler.

Examining the grid diagram for HEN in Figure 5(b), it can be noticed that there are two possibilities of further optimization, i.e. via HE loop and utility path evaluation. The grid diagrams after optimization are depicted in the Figure 6.

The grid diagram in Figure 6(c) was developed by reassigning the 3.791kW load to the heat exchanger with 247.69kW, such that it has now 251.481kW load. The external utilities remain the same as the Figure 6(a). The utility path in Figure 6(b) was examined. The heat load 3.791kW was then redistributed to both heater and cooler. The utility load has become 15.781kW and 42.55kW for heater and cooler, respectively. The grid diagram is depicted in Figure 6(d). The related TAC for both optimized networks are tabulated in Table 3. It can be seen that the Case 2A has slightly lower TAC compared to Case 2B. The superstructure

approach resulted in different HEN configuration of 2 exchangers, 1 heater, and 1 cooler; as depicted in the Figure 7. The $\Delta T_{\min} = 12.5^{\circ}\text{C}$ is used in the network determination. The HEN calculation results along with the calculated TAC is tabulated in Table 4. It can be seen that the TAC from the superstructure approach is lower (\$57,597/year) compared to the optimized cases, i.e. Case 2A and 2B.

IV. CONCLUSION

In this work, the HEN within the TEG regeneration system was revisited using pinch analysis (PA) and mathematical programming (MP) using simple superstructure. The optimized networks were evaluated using simplified total annual cost (TAC). The PA method using small ΔT_{\min} (minimum temperature approach) led to the configuration of three exchangers, a heater and a cooler, with minimized utilities. At larger ΔT_{\min} , the configuration became into two exchangers, two heaters, and a cooler. The calculated TAC are found to be minimum (\$60,351 /year) at $\Delta T_{\min} = 12.5^{\circ}\text{C}$. Furthermore, it was revealed that one heater and one exchanger were two small. Therefore, they were omitted, and the heat load were redistributed to the network. There are two approaches used in the calculation, i.e. through omission of exchanger in a loop, and in a utility path. The calculated TAC became \$59,224/year. The superstructure approach resulted in two exchangers, a heater, and a cooler; with a calculated minimum TAC of \$57,597/year. The two approaches have

resulted in very similar minimized TAC (+/- 3% difference).

ACKNOWLEDGEMENT

The authors thank Deputi Bidang Penguatan Riset dan Pengembangan, Kementerian Riset dan Teknologi / Badan Riset dan Inovasi Nasional for providing the financial support of this study through Penelitian Dasar Unggulan Perguruan Tinggi, Direktorat Riset dan Pengabdian kepada Masyarakat Institut Teknologi Sepuluh Nopember (ITS) Nomor: 1153/PKS/ITS/2020.

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