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Heat Exchanger Network Improvement on Gas Separation Plant No.6 (GSP6) in Thailand

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One of the most common concerns of gas separation plants throughout the world is high energy and utility consumption. This research was undertaken to address this problem at PTT Public Company Limited in Thailand and focused on improving the heat exchanger network (HEN) of its Gas Separation Plant No. 6 (GSP6). One way of decreasing utility consumption is the application of a technique that can find an optimum HEN. This technique is the pinch design method (PDM) with a stage-wise model mathematical programming using Mixed-Integer Linear Programming (MILP). First, HEN improvement potential is found from hot and cold composite curves of the existing HEN of GSP6 with heat recovery approach temperature (HRAT) or ΔT_{min} at 7.95°C. Then mathematical programming by General Algebraic System (GAMS) is used to develop a stage-wise model proposed by Yee et al. (1990). Here, the PDM is proposed to determine above and below pinch sections to generate the HEN at different ΔT_{min} at 3°C and 5°C. Furthermore, the relaxation technique using GAMS is used to improve the results of the stage-wise model that would generate maximum net present value (NPV). The study concludes by providing a HEN design with reduced utility usage and complexity, resulting in a more profitable HEN.

1. Introduction

The most widely accepted methodology for reducing energy or utility usage in industrial projects is the pinch design method (PDM). It can be used for heat exchanger network (HEN) and utility optimization, such as the low-temperature process design. HEN integration can be divided into two categories: 1) grass-roots design and 2) retrofit design. For industrial projects, the retrofit design is more commonly used than the grass-roots design. The PDM is based on the minimum approach temperature (ΔT_{min}) that determines the energy saving and total investment cost and consists of two major steps: 1) calculation of the minimum energy requirement (targeting step), and 2) design of the HEN (designing step). The first step determines the pinch point location by computing the hot and cold composite curves, which provide the energy savings target. The second step involves the PDM that uses ΔT_{min} for retrofitting the existing network using the stage-wise model proposed by Yee et al. (1990). To complete the PDM, the relaxation technique is included to improve the results of the second step. The objective function of the relaxation step is based on Euler's General Network Theorem, observed by Hohmann (1971). As the relaxation technique has the effect of decreasing the number of heat exchangers, it minimizes the cost of investing in new heat exchangers. The retrofit design procedure of this work uses the composite curves technique in the targeting step to determine the optimum minimum temperature difference (ΔT_{min}) that would result in lower utility consumption, and mathematical programming in the designing step using General Algebraic System (GAMS) along with the stage-wise model to generate a profitable retrofit design that would yield positive net present value (NPV).

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2. Methodology

2.1 Targeting step by composite curves

In this step, pinch point location is determined by computing the hot and cold composite curves to arrive at the optimum ΔT_{min} or heat recovery approach temperature (HRAT) that yields possible energy savings and to identify where retrofitting is needed.

2.2 HEN retrofit step by n-stage model

After obtaining the composite curves, different ΔT_{min} at 3 ºC and 5 ºC are used. Each HEN is developed based on n-stage model by GAMS, as shown in Figure 1. It is applied to design HEN both above and below the pinch sections. The PDM algorithm at each section is based on Smith (1995), as shown in Figures 2.

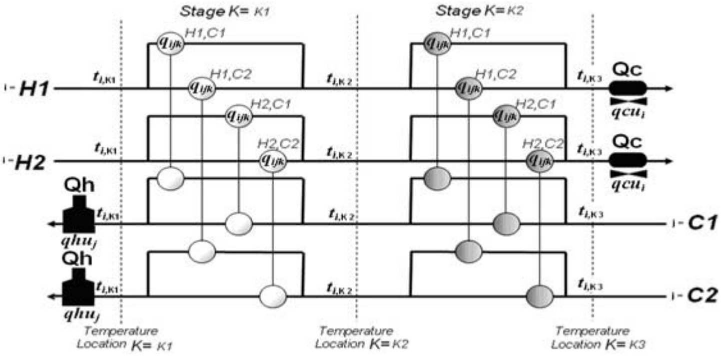


Figure 1: N-stage model.

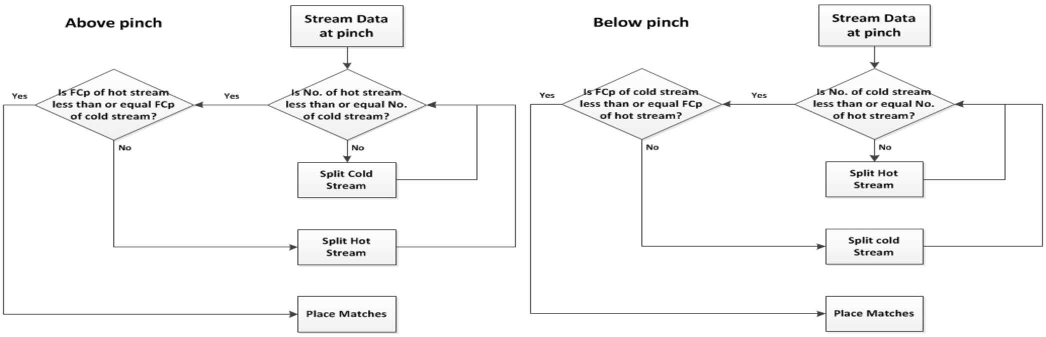


Figure 2: Algorithm of above and below pinch design.

2.3 Relaxation step

After obtaining the HEN retrofit design from the second step, the relaxation technique is introduced to finalize the pinch designed HEN. The goal of this step is to reduce the number of heat exchangers with minimizing the investment cost of new heat exchanger. In theoretical, it involves with the concept of loop and path. In practical, loop and path cannot be used directly to optimization program so that they are adapted to an objective function. The constraint of this step is fixing the position of heat exchanger matching from the second step and the objective function is to minimize the number of heat exchangers and energy usage between relaxation step and before relaxation step, as shown below. Moreover, the pinch point from the second step is not considered for relaxing.

$$\text{objective function} = \mathrm{M}in(\sum \Delta Z + \sum \Delta Z_{CU} + \sum \Delta Z_{HU} + \sum \Delta Q_H + \sum \Delta Q_C) \qquad (1)$$

The results of this step follow Euler's General Network Theorem, observed by Hohmann (1971), to determine the minimum number of units as a summation of the number of process streams and utilities minus one component, expressed in the simple relationship.

$$U_{min} = N - 1 \qquad (2)$$

where U_{min} is the minimum number of units and N is the number of process streams and utilities.

3. Case study

The case study is HEN retrofit of base case GSP6, as shown in Figure 3. The HEN consists of 14 hot and 14 cold process streams (H1-14, and C1-14) with 8 process exchangers (E1-8), 7 hot utilities, and 13 cold utilities. The HRAT of base case is equal to 7.95 ºC and base case design consumes 250,020 kW of hot utility and 280,242.6 kW of cold utility. The area of process-process heat exchanger at base case is 26,936.37 m^2. The total number of heat exchangers is 28. The retrofit design has a project life of 20 years (350 working days per year) and an annual interest rate of 10 %. In this case study, area calculation does not include utility heat exchanger. Retrofitting HEN includes new heat exchanger addition, area addition, area reduction, and new shell addition to existing process-process heat exchangers. The maximum area addition and area reduction of existing process-process heat exchangers in retrofitting HEN are 10 % and 40 % of existing area, respectively. The maximum area per shell is 5,000 m^2 and the maximum number of shells per heat exchanger is 4.

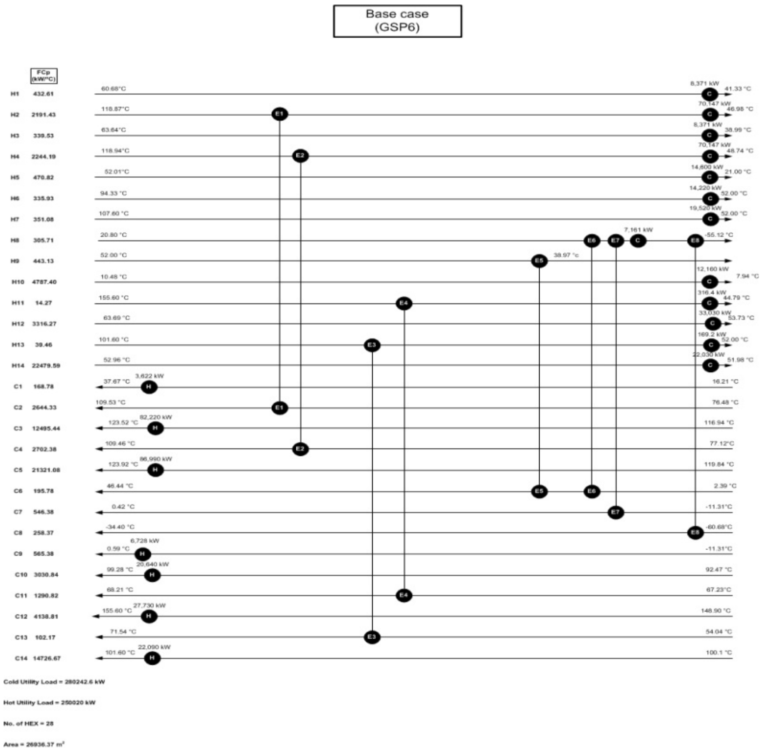


Figure 3: Grid diagram of the base case GSP6.

In this case study, assumption of the HEN retrofit consists of: 1) topology of heat exchanger is 1-1 shell and tube heat exchanger, 2) specific heat capacity is assumed to be constant, and 3) utility costs are assumed to be constant for any temperature. Moreover, the retrofit design does not include relocation of heat exchanger so that relocation cost is equal to zero. The fixed cost for splitting stream is $20,000 per split. The investment cost equations for heat exchanger modification, assuming 1-1 shell and tube heat exchanger with carbon-steel and medium pressure, are shown below. The investment cost equations are based on the heat exchanger correlation of Peters et al. (2004).

$$\text{Heat exchanger cost (\$)} = 4{,}838.5 + [68.5\times\text{Area (m}^2)] \tag{3}$$

$$\text{Area addition cost (\$)} = 2{,}419.25 + [68.5\times\text{Area}_{\text{added}}\text{ (m}^2)] \tag{4}$$

$$\text{Area reduction cost (\$)} = 2{,}419.25 + [0.5\times\text{Area}_{\text{reduced}}\text{ (m}^2)] \tag{5}$$

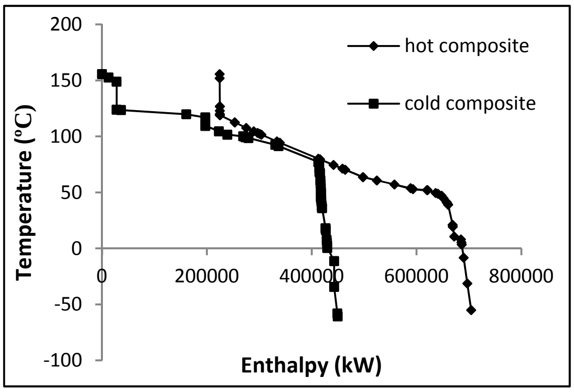
$$\text{New shell addition (\$)} = 4838.5 + [68.5\times\text{Area}_{\text{shell}}\text{ (m}^2)] \tag{6}$$

The costs for hot utility and cold utility are 0.024 $/kW and 0.026 $/kW, respectively. Moreover, these utility costs are used in the real process. Furthermore, utility costs are assumed to be constant along the temperature level. For calculation overall heat transfer coefficient, each heat transfer coefficient inside the heat exchanger is used the real value obtained from the process, expressed in the simple relationship.

$$U = \frac{1}{\frac{1}{h_1} + \frac{1}{h_2}} \tag{7}$$

4. Results and Discussion

Based on the HRAT of base case equal to 7.95 °C, the studied HRAT is varied due to the small magnitude of HRAT at base case so that they are shifted to HRAT at 3 °C and 5 °C for retrofit design of HEN.



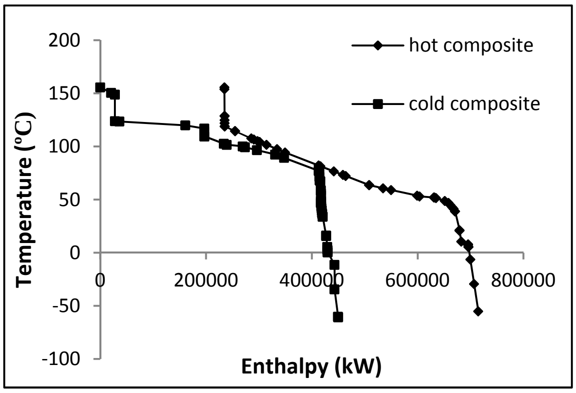
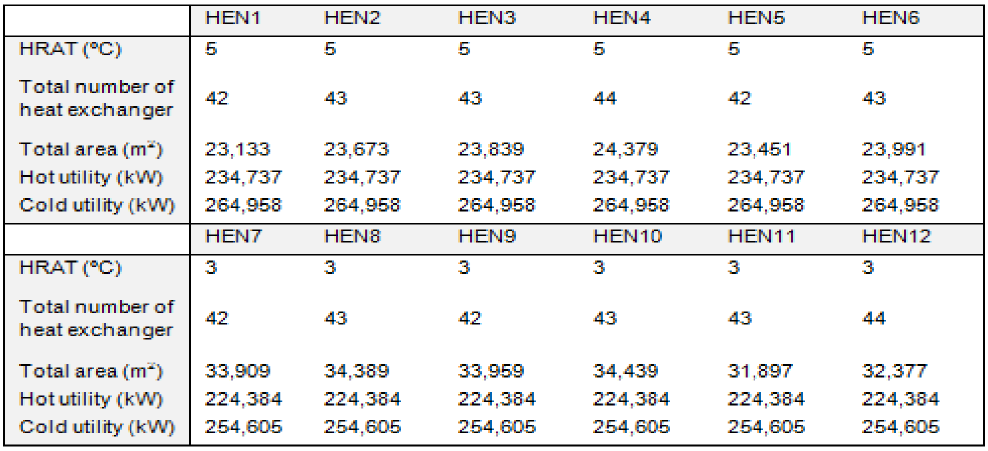


Figure 4: Composite curve at HRAT = 3ºC.

Figure 5: Composite curve at HRAT = 5ºC.

In accordance with the above results, HEN retrofit designs are generated by GAMS using the n-stage model. Retrofit designs are divided into two categories: HRAT at 3 °C and 5 °C. Each HEN is separately designed at above and below pinch sections, keeping the old process-process heat exchanger as much as possible. Both HEN designs at HRAT at 3 °C and 5 °C consist of three and two alternative designs at above and below pinch sections so that the total alternative designs for each HRAT are similarly equal to 6. Therefore, there are 12 combinations of HEN designs: HEN1-12, as shown in Table 1.

Table 1: Summary of HEN retrofit designs before relaxation.



	HEN1	HEN2	HEN3	HEN4	HEN5	HEN6
HRAT (°C)	5	5	5	5	5	5
Total number of heat exchanger	42	43	43	44	42	43
Total area (m^2)	23,133	23,673	23,839	24,379	23,451	23,991
Hot utility (kW)	234,737	234,737	234,737	234,737	234,737	234,737
Cold utility (kW)	264,958	264,958	264,958	264,958	264,958	264,958
	HEN7	HEN8	HEN9	HEN10	HEN11	HEN12
HRAT (°C)	3	3	3	3	3	3
Total number of heat exchanger	42	43	42	43	43	44
Total area (m^2)	33,909	34,389	33,959	34,439	31,897	32,377
Hot utility (kW)	224,384	224,384	224,384	224,384	224,384	224,384
Cold utility (kW)	254,605	254,605	254,605	254,605	254,605	254,605

In accordance with Euler's General Network Theorem, the minimum number of units of base case with HRAT at 7.95 °C is 29, meaning the number of exchangers after retrofitting must be equal or greater than 29. Although in every retrofit design the total number of heat exchangers is more than the minimum number of heat exchangers, the HENs are very complex and less practical to industrial revamp. To deal with the problem, this study introduces the relaxation technique which minimizes the number of heat exchangers. However, although the relaxation technique decreases the complexity of HEN retrofit design and the total area, it may increase utilities usage and HRAT a bit. The results of HEN retrofit design after relaxation are shown in Table 2.

Table 2: Summary of HEN retrofit designs after relaxation.

	HEN1	HEN2	HEN3	HEN4	HEN5	HEN6
New HRAT (°C)	6.01	6.01	5.95	5.95	6.01	6.01
Old HRAT (°C)	5	5	5	5	5	5
Total number of heat exchanger	30	30	30	30	30	30
Total area (m²)	21,924	21,572	22,406	22,240	22,180	22,620
Hot utility (kW)	239,946	239,946	239,670	239,670	239,946	239,946
Cold utility (kW)	270,166	270,166	269,890	269,890	270,166	270,166
NPV ($)	880,754	904,918	868,970	880,386	863,266	813,128
Payback period (y)	4	4	4	4	4	4
IRR (%)	28.05	29.21	26.52	26.99	27.26	25.21
	HEN7	HEN8	HEN9	HEN10	HEN11	HEN12
New HRAT (°C)	6.01	6.01	6.61	6.16	6.66	6.21
Old HRAT (°C)	3	3	3	3	3	3
Total number of heat exchanger	30	30	30	30	30	30
Total area (m²)	21,542	22,426	20,372	22,015	19,865	21,520
Hot utility (kW)	239,946	239,946	243,056	240,745	243,332	241,020
Cold utility (kW)	270,166	270,166	273,276	270,965	273,552	271,241
NPV ($)	886,925	806,420	486,142	714,972	500,016	727,670
Payback period (y)	4	4	5	5	5	4
IRR (%)	28.34	24.96	21.57	23.89	23.1	25.27

From Table 2, it is seen that the optimal design is HEN2 with a new HRAT at 6.01 °C, a total number of 30 heat exchangers, a maximum NPV of 904,917.86 $, a payback period of 4 years, and an IRR of 29.21 %.

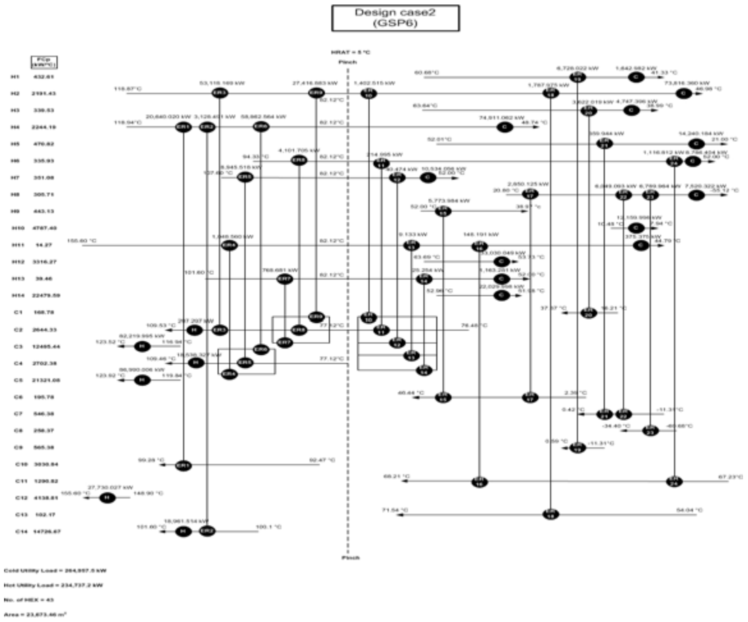


Figure 6: HEN retrofit design case 2 before relaxation

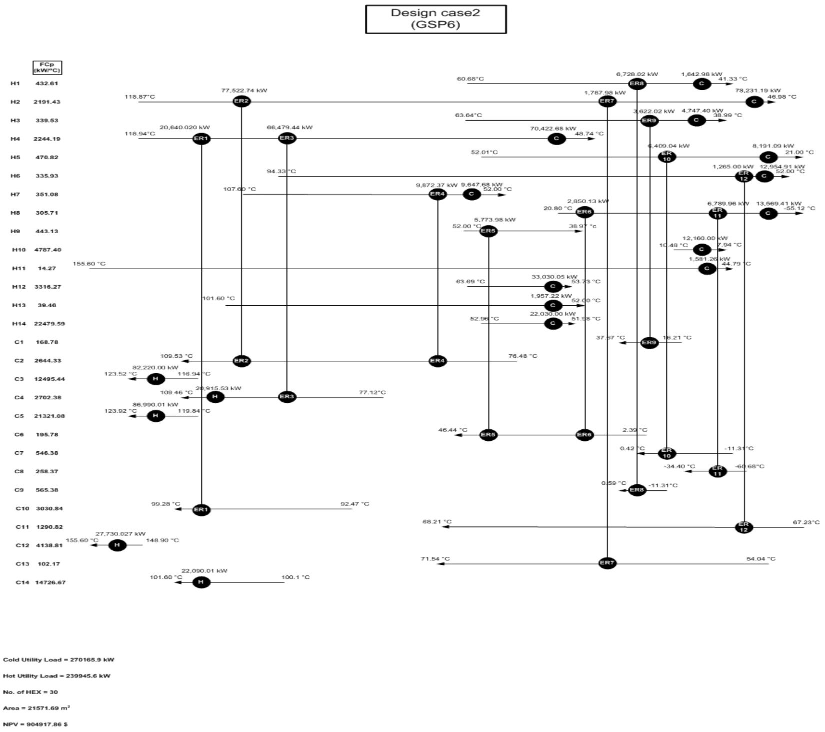


Figure 7: HEN retrofit design case 2 after relaxation.

5. Conclusion

From this study, it can be concluded that the retrofit design with relaxation shown in Figure 7 is the best design, giving the maximum NPV and IRR. Using the structure from the second step as shown in Figure 6, the relaxation technique reduced the total number of heat exchangers from 43 to 30, which although not much higher than the minimum number of heat exchangers, nevertheless followed Euler's General Network Theorem. Using the results from three existing process-process heat exchangers of eight heat exchangers, our study proves that the relaxation technique can reduce the complexity of HEN. Finally, this study provides a profitable HEN design to reduce utility usage of GSP6.

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