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Heat Exchanger Network Synthesis on Gas Separation Plant No.2 (GSP2) in Thailand

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Energy conservation is one of the most common concerns in gas separation plants. It plays a key role in energy and operating cost saving of their high-energy consuming processes. Although many research works on heat exchanger network (HEN) synthesis has been extensively studied for more than 40 years, most of them have limitations on computational time and feasibility due to their mathematical difficulties. Thus, they are impractical for large problems as industrial cases. In this work, a strategy for HEN synthesis was presented and applied to the industrial case of gas separation plant no.2 (GSP2) in Thailand consisting of twelve hot and eleven cold process streams. The strategy for HEN synthesis is a combination of Pinch Technology, the well-known thermodynamics-based approach, and mathematical programming based on the stage-wise superstructure model. HEN was synthesized in two parts; above and below pinch, corresponding to the optimal pinch temperature as well as the heat recovery approach temperature (HRAT) predicted by Pinch Analysis in order to assure near-optimal design. The HEN was then improved by a mathematical model applying relaxation technique based on a concept of loop and path toward better design with less complexity. According to the industrial case of GSP2, the proposed strategy for HEN synthesis is effective where a good solution can be obtained with reasonable computational time.

1. Introduction

The world has been facing an energy crisis for a few decades. The rising cost of energy has a significant impact on industry, especially gas separation plant (GSP). According to its high-energy consuming, energy conservation is one of the most common concerns to save an operating cost. Heat exchanger network (HEN) synthesis, heat integration between hot and cold process streams, has been widely applied for that purpose. Research works on HEN synthesis have been done for more than 40 years by many researchers (Klemeš and Kravanja, 2013); Linnhoff and Hindmarsh (1983) introduced the thermodynamics based technique to predict an optimal heat recovery approach temperature (HRAT) for inventing good HEN design. Yee and Grossmann (1990) developed the mixed integer nonlinear programming (MINLP) formulation of stage-wise superstructure considering all trade-offs simultaneously. Barbaro and Bagajewicz (2005) presented a rigorous mixed integer linear programming (MILP) formulation for HEN synthesis relying on transportation/transshipment concepts. Since mathematical formulations for HEN synthesis contain nonlinear equations, most of them are impractical for large problems as industrial cases due to large computational time and lack of feasibility. To overcome this limitation, heuristics, thermodynamic methods and optimization should be used in a combination to narrow solution space and numerical complexity (Anantharaman et al., 2013). This research work developed the three-step approach for HEN synthesis and applied to the industrial case of gas separation plant no.2 (GSP2) in Thailand. The strategy is a combination of thermodynamic principles based on Pinch Technology concept (Linnhoff and Vredeveld, 1984) and mathematical optimization based on stage-wise superstructure model (Yee and Grossmann, 1990).

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2. Methodology

There are three steps to synthesize HEN as shown in Figure 1. In the first step, an optimal HRAT was predicted and then used to synthesize HEN to assure near-optimal design in the second step. After that the HEN was improved toward better design with less complexity in the last step.

2.1 Targeting by Pinch Analysis

Pinch Analysis predicted the optimal HRAT as well as Pinch location providing the best value of objective function based on vertical heat transfer area and minimum number of process heat exchangers. In this study, Grassroots Potential Program (Siemanond and Kosol, 2012) was used as an automated tool for this step. The program was implemented on Microsoft Excel incorporating with Visual Basic for Applications (VBA).

2.2 HEN synthesis by stage-wise model with pinch temperature

The stage-wise model with pinch temperature is the MINLP stage-wise model (Yee and Grossmann, 1990) where pinch temperatures of hot and cold process streams are located in the model as shown in Figure 2. The model synthesized a HEN by using the pinch temperatures from previous step to restrict utility load. The HEN was designed in 2 parts; above and below Pinch. This simplifies the model to be optimized only number of heat exchangers and their area.

2.3 HEN improvement by stage-wise model with topology control

According to the heuristic rule of the Euler's general network theorem observed by Hohmann (1971) expressed in a simple relationship, as shown in the following equation where U_{min} is minimum number of units and N is number of process streams and utilities.

$$U_{min} = N - 1 \tag{1}$$

The number of heat exchangers in the previous step is often large because of the existence of pinch in the HEN; as a result, the designed HEN is complex and unfavorable for construction. In this step, the relaxation technique was introduced to improve the HEN from previous step and reduce its complexity, achieving a better value of objective function. The Pinch Point was removed to allow cross-pinch heat transfer, and the problem was then re-optimized with the control of matching from the previous step. The number of heat exchangers should be reduced with some shift of HRAT.

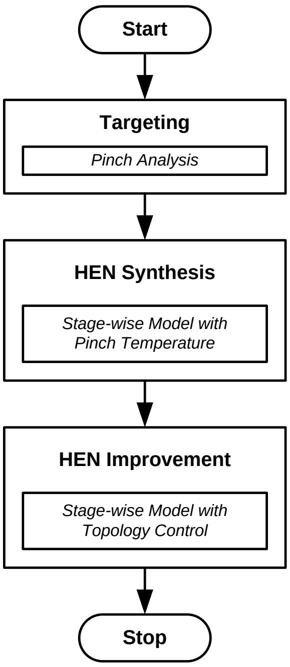

Figure 1: The proposed three-step strategy for HEN synthesis

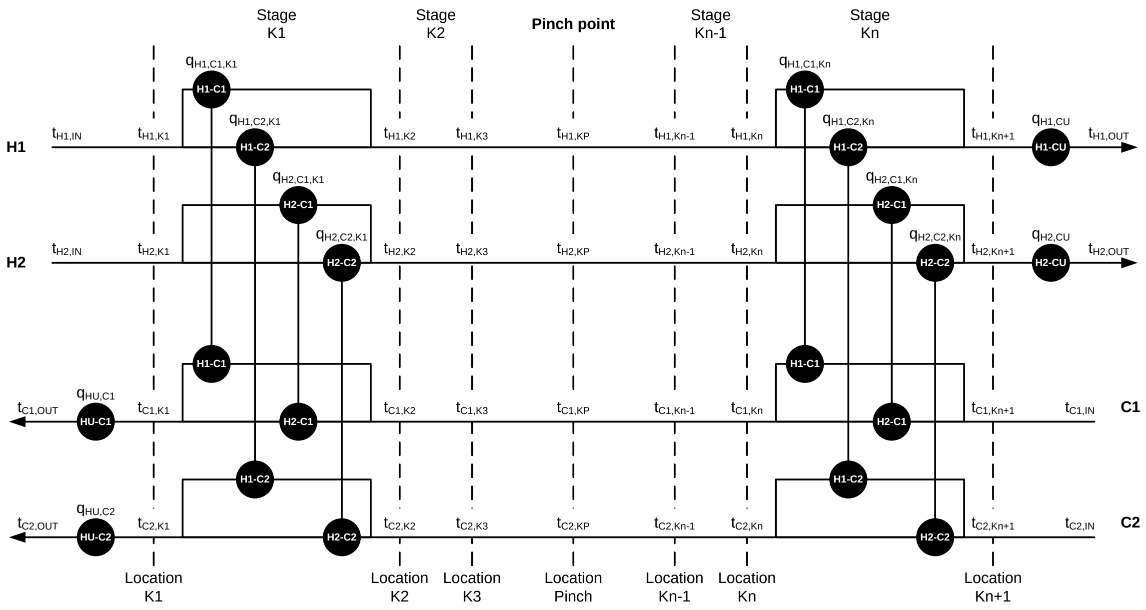

Figure 2: Stage-wise model with Pinch temperature

3. Case Study

The case study is the industrial case of GSP2 in Thailand consisting of twelve hot and eleven cold process streams, one cooling and one heating utility. The data for HEN synthesis are shown in Table 1, 2, and 3. The objective function of all steps is to minimize net present cost (NPC). The mathematical models were implemented in the General Algebraic Modeling System (GAMS) 24.2.1 and solved with the MINLP solver DICOPT using CONOPT 3 and CPLEX 12.6 as nonlinear programming (NLP) solver and MILP solver, respectively. The default options were used for all solvers. The CPU times are reported corresponding to runs performed in Notebook PC Model SVS15135CHB with Intel(R) Core(TM) i5-3230M CPU @ 2.60 GHz processor and 4.00 GB of ram memory. The results shown in this paper are the screened results where the heat exchangers with no heat duty have been removed.

Table 1: Stream data

Stream	FCp (kW/°C)	T_{in} (°C)	T_{out} (°C)	h (kW/m^2-°C)
H1	98.19	-14.74	-37.78	1.35
H2	794.90	9.24	6.17	8.48
H3	4,421.41	53.20	51.27	0.80
H4	145.99	83.28	52.00	0.80
H5	321.20	58.48	52.00	0.80
H6	8.18	171.10	91.42	9.50
H7	90.03	-39.21	-48.21	0.80
H8	276.10	33.00	-40.00	11.05
H9	89.18	50.00	26.82	2.36
H10	6.54	95.65	26.11	1.96
H11	24.13	72.47	26.11	2.35
H12	15.55	49.29	26.11	0.62
C1	13.78	15.10	85.50	11.05
C2	271.91	67.64	80.90	0.10
C3	1,171.93	164.30	170.10	1.96
C4	723.88	99.67	106.70	0.33
C5	196.32	82.85	86.17	0.34
C6	3,255.13	-39.59	-38.59	0.62
C7	13.77	-20.22	22.78	0.33
C8	7.05	-50.00	5.00	2.36
C9	147.80	-53.33	21.67	0.80
C10	81.82	-42.33	26.67	0.80
C11	172.61	21.67	44.85	0.80

Table 2: Utility data

Utility	T_{in} (°C)	T_{out} (°C)	h (kW/m^2 °C)
HU1	250.00	180.00	0.337
CU1	-55.00	-54.00	0.62

Table 3: Cost data

Cost Data		
CU1	$/kW d	0.066
HU1	$/kW d	0.033
Heat exchanger cost	$	4,838.50 + 68.5A
Splitting cost	$/split	20,000
Project life time	y	20
Interest rate	%	10
Yearly operating days	d/y	350
EMAT (exchanger minimum approach temperature)	°C	3

4. Result and discussion

The result of targeting step is shown in Table 4 and Figure 3. The optimal HRAT was 4.9 °C corresponding to the best NPC of $ 5,228,430 and the hot and cold pinch temperatures of 72.54 °C and 67.64 °C. Note that NPC in the first step was calculated based on vertical heat transfer and minimum number of heat exchangers.

The Hot and Cold Pinch temperatures were then used for HEN synthesis in the second step getting the result as shown in Table 5 and Figure 4. The computational time is reasonable (13,294 s or 3 h 41 m 34 s). The utility load is identical because the HRAT was fixed at the same value. The number of heat exchangers is larger than the minimum number of units about one unit predicted by targeting step. The area of heat exchangers is slightly more than the predicted one because of non-vertical heat transfer in the actual network. This ensures the reliability of the predicted HRAT.

The designed HEN was then improved in the last step, as the result shown in Table 6 and Figure 5. It required very short computational time because the topology, involving binary variables, was controlled in the optimization reducing the problem size. With a penalty of heat exchanger area, utility load and number of heat exchangers were decreased giving the better NPC. According to the previous step, two of heat exchangers were disappeared (E12 and E16); as a result, the total number of heat exchangers is more than the minimum number of heat exchangers of HEN without pinch based on Euler's general network theorem (24 units) about one unit. It can be noticed that there is no splitting in the HEN because of the expensive splitting cost.

Table 4: Summary report of targeting step

Pinch Analysis results		
Optimal HRAT	°C	4.9
Hot pinch temperature	°C	72.54
Cold pinch temperature	°C	67.64
Optimal cooling utility load	kW	17,441
Optimal heating utility load	kW	14,019
Optimal number of heat exchangers	Units	26
Optimal total vertical area	m^2	4,294.6
Payback period	y	0.43
NPC (Objective function)	$	5,228,430

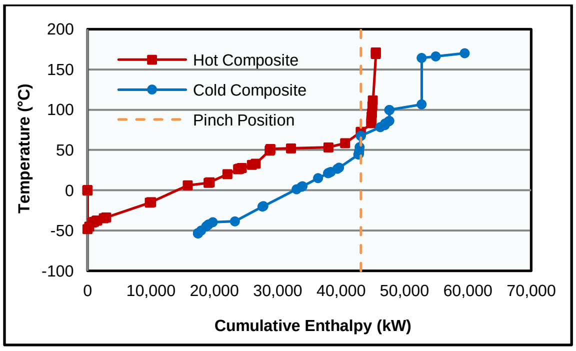

Figure 3: Composite Curves at optimal HRAT

Table 5: Summary report of HEN synthesis step

Stage-wise model with pinch temperature results		
Number of cycle	cycles	2
Total CPU time	s	13,294
Average CPU time per cycle	s/cycle	6,647
HRAT	°C	4.9
Total cooling utility load	kW	17,441
Total heating utility load	kW	14,019
Total number of heat exchangers	Units	27
Total area of heat exchangers	m^2	6,275.6
Total splitting	splits	0
Total number of splits	splits	0
Payback period	y	0.58
NPC (Objective function)	$	5,368,967

Table 6: Summary report of HEN improvement step

Stage-wise model with topology control results		
Number of cycle	Cycles	2
Total CPU time	s	2
Average CPU time per cycle	s/cycle	1
HRAT	°C	4.4
Total cooling utility load	kW	17,350
Total heating utility load	kW	13,928
Total number of heat exchangers	Units	25
Total area of heat exchangers	m^2	6,551.8
Total splitting	splits	0
Total number of splits	splits	0
Payback period	y	0.58
NPC (Objective function)	$	5,351,506

5. Conclusion

The strategy for HEN synthesis was presented in this paper. The method consists of three steps; targeting, HEN synthesis and HEN improvement. From this study, it can be concluded that the heuristics from Pinch Analysis can help mathematical optimization to generate the good HEN solution for large-sized problem with reasonable computational time requirement. The study also proves that the relaxation technique can help reduce the complexity of HEN. Therefore, the proposed strategy is the effective method for HEN synthesis, even for industrial problems. For future work, non-isothermal mixing should be taken into account in the HEN improvement step to get more possibility of better solutions.

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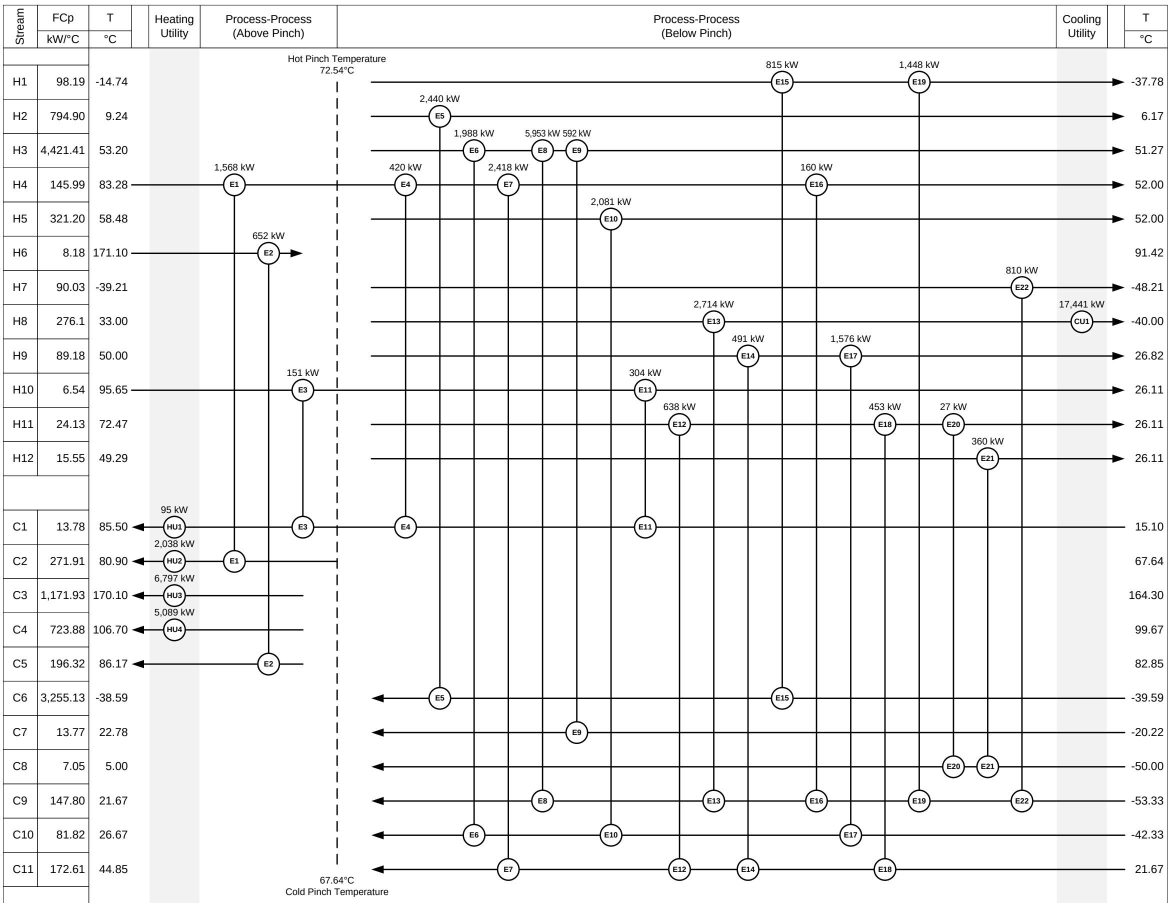
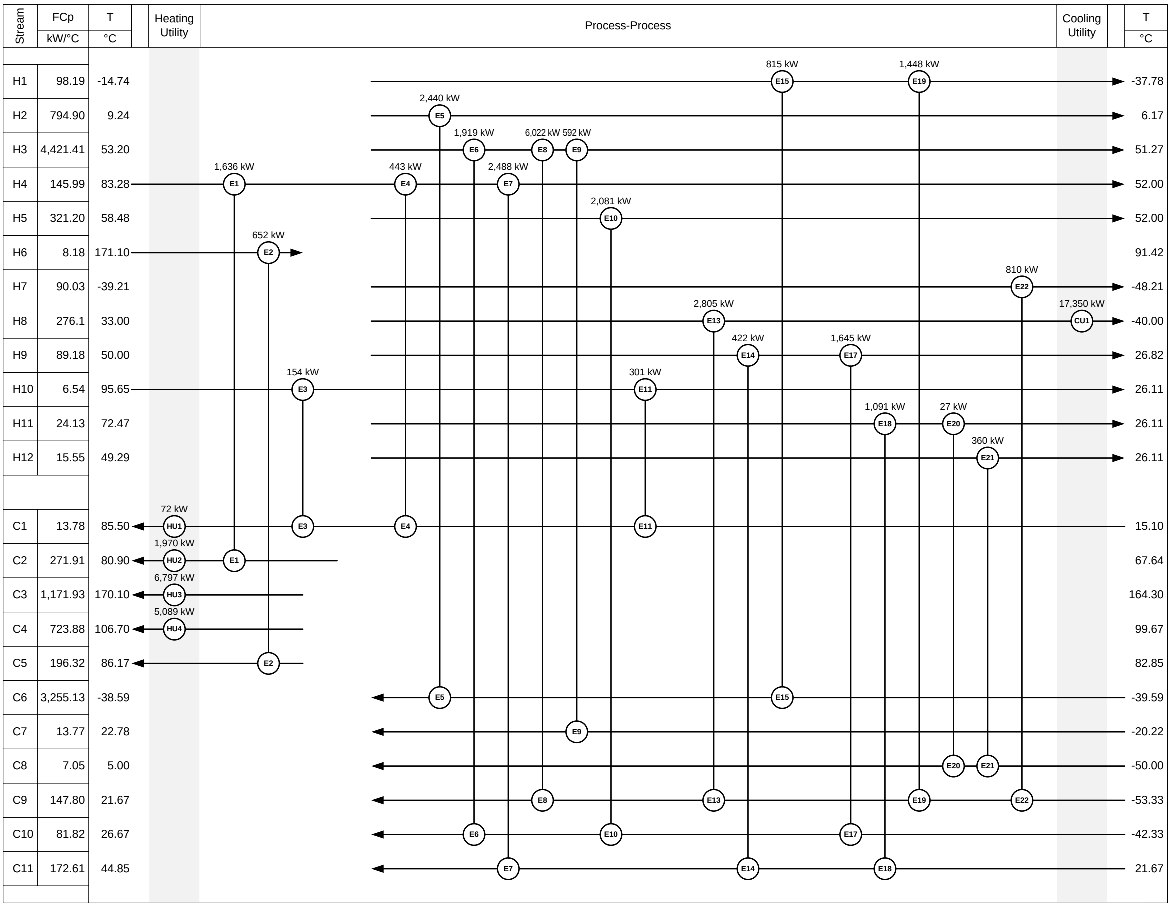


Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2
E1	2,484.8	E5	90.5	E9	54.1	E13	65.3	E17	38.6	E21	12.0	HU2	195.1
E2	59.6	E6	133.7	E10	79.9	E14	38.2	E18	64.0	E22	301.2	HU3	599.1
E3	9.3	E7	257.2	E11	8.7	E15	94.4	E19	232.8	CU1	782.7	HU4	280.5
E4	38.6	E8	310.4	E12	37.2	E16	4.4	E20	1.0	HU1	2.2		

Figure 4: Grid diagram of GSP2 case study from HEN synthesis step



Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2	Heat Exchanger	Area m^2
E1	2,746.9	E5	90.5	E9	54.1	E14	38.4	E19	232.8	CU1	780.8	HU4	280.5
E2	59.6	E6	130.2	E10	81.0	E15	94.4	E20	1.0	HU1	1.7		
E3	12.2	E7	272.2	E11	8.7	E17	40.3	E21	12.0	HU2	188.8		
E4	48.4	E8	312.8	E13	66.7	E18	97.6	E22	301.2	HU3	599.1		

Figure 5: Grid diagram of GSP2 case study from HEN improvement step

References

Anantharaman R., Jordal K., Berstad D., Gundersen T., 2013, The role of process synthesis in the systematic design of energy efficient fossil fuel power plants with co2 capture, Chemical Engineering Transactions, 35, 55-60.

Barbaro A., Bagajewicz M.J., 2005, New rigorous one-step MILP formulation for heat exchanger network synthesis, Computers and Chemical Engineering, 29, 1945-1976.

Hohmann E.C., 1971, Optimum networks for heat exchange, PhD thesis, University of Southern California, Los Angeles, USA.

Klemeš J.J., Kravanja Z., 2013, Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (MP), Current Opinion in Chemical Engineering, 2(4), 461-474.

Linnhoff B., Hindmarsh E., 1983, The pinch design method for heat exchanger networks, Chemical Engineering Science, 38(5), 745-763.

Linnhoff B., Vredeveld D.R., 1984, Pinch Technology has come of Age, Chemical Engineering Progress, 80(7), 33-40.

Siemanond K., Kosol S., 2012, Heat exchanger network retrofit by pinch design method using stage-model mathematical programming, Chemical Engineering Transactions, 29, 367-372.

Yee T.F., Grossmann I.E., 1990, Simultaneous optimization models for heat integration—II. Heat exchanger network synthesis, Computers and Chemical Engineering, 14(10), 1165-1184.