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Combined Exergy-Pinch Analysis to Improve Cryogenic Process

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In several industrial processes under operation at low temperature, refrigeration system is energy intensive due to compression of refrigeration consuming high energy, resulting in high operating cost of shaft work required. To minimize the shaft work, it is accomplished by a combination of pinch and exergy analysis. Pinch analysis illustrates the simple information diagrams such as composite curves and grand composite curve as tools for process modifications. However, the weakness of pinch analysis is that it cannot deal with power or shaft work. Exergy analysis is a tool to utilize power or shaft work and identifies thermodynamic imperfection of process such a magnitude of exergy loss in each unit. Both strengths are combined to help improve process efficiently. This methodology is applied to case study of LNG simulated by commercial software ProII and a graphical exergy-pinch analysis is applied to help improve processes such as reducing shaft work and increasing the exergy target.

1. Introduction

Low temperature processes in many chemical processes are an energy demanding parts which consume a large amount of energy to drive refrigeration compressor units. It is important to design refrigeration system according to save energy consumption. Pinch analysis (PA) is a general methodology for design of thermal and chemical processes by applying exchanger-matching between hot and cold streams. The PA method has two graphical representations; Composite Curves (CCs) and Grand Composite Curves (GCCs) which represent the minimum energy requirement. However it has the limitation where only temperature is the main design variable. In the case of operating below ambient temperature where expansion and compression of a stream are required pressure becomes the variable for design. Linnhoff et al. (1982) has proposed the onion diagram which indicates the sequence of design that including compressors and expanders inside the heat recovery system. If pressure of a stream is manipulated, the utilities requirement and energy consumption may be reduced, therefore, pressure should be included in the stream data like temperature. Exergy analysis (EA) is a tool to utilize power or shaft work where temperature, pressure and composition are the process variables used to calculate exergy content in the process. Linnhoff and Dhole (1992) have combined PA and EA methods which are represented in graphical method called Exergy Composite Curves (ECCs) and Exergy Grand Composite Curves (EGCCs) based on Carnot factor. The ECCs shows the area of hot and cold composites curves provides the exergy losses due to heat transfer and EGCCs shows the exergy losses related to heat transfer between the process and utilities system. They help find appropriate placement of load, level and number of refrigeration cycles. However, exergy targeting is not explicit because it is not linear relation. Aspelund et al. (2007) has proposed the Extened Pinch Analysis and Design (ExPAnD) to utilize heating and cooling obtained by pressure changes to minimize work consumption by utilizing ten heuristic rules to accomplish the target. Marmolejo-Correa and Gundersen (2012) has proposed a new graphical method for exergy targeting explicitly where the axes of diagram are exergetic temperature and temperature based exergy which are linear relation. The goal of this research is to reduce the energy and power consumption by considering exergy targeting in early stage of design. By applying these graphical

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methodologies such as shaftwork targeting (Linnhoff and Dhole, 1992), ExPAnD method (Aspelund et al., 2007) and novel exergy diagram (Marmolejo-Correa and Gundersen, 2012) for minimizing exergy requirement, it helps obtain the improved process with minimum work required. In addition, this methodology is applied to case study of complex LNG (multistage cascade cycle) under subambient temperature.

2. Methodology

There are many design options to reduce power consumption where the conceptual of design improvement is illustrated on Pinch-Exergy graphical method.

For the first option, Linnhoff and Dhole (1992) proposed the methodology combining Pinch-Exergy using exergy composite curves (ECCs) by replacing temperature in composite curve (CCs) with Carnot factor, $\eta_c = 1 - (\frac{T_0}{T})$. This method helps to design or manipulate pressure to reduce area between hot and cold in ECCs that is proportional exergy loss due to heat transfer. The steps are as follows. First, a stream table is created which consists of temperature, pressure and enthalpy of each stream. Second, temperature is transformed to Carnot factor for constructing ECCs where T_0 is the temperature of environment (condensation of refrigerant) and T is temperature of a stream to be cooled. Third, process is improved by adjusting the pressure where the area between hot and cold in ECCs is directly related to work equivalent losses due to heat transfer by assuming process does not change. Fourth, manipulating pressure to reduce shade area results in shaft work reduction.

For the second option, ExPAnD method is proposed by Aspelund et al. (2007). This method is used parallel with the novel exergy diagram (Marmolejo-Correa and Gundersen, 2012) to estimate exergy target (minimizing exergy destruction). The steps are as follows. First, the total exergy is determined in hot and cold streams in order to find the exergy efficiency. Second, the traditional CCs are constructed in order to find the minimum utilities and the room for improvement. In addition, exergy diagram is constructed by transforming temperature in CCs to exergetic temperature (T^{E^T}) which use the square bracket factor in Eq. (1) and calculating the exergy component ($\dot{E}^T$) for supply and target conditions when ambient condition is T_0 = 25 °C and P_0 = 1 atm in order to estimate exergy destruction. Third, process is developed by selecting heuristic rules (Aspelund et al., 2007) to manipulate pressure of streams. Fourth, the new exergy efficient and exergy diagram are determined in order to see the improvement.

$$\dot{E}^T = \dot{m}C_p\left[T_0\left(\frac{T}{T_0} - ln\frac{T}{T_0} - 1\right)\right] = \dot{m}C_pT^{E^T} \tag{1}$$

3. Case study

Table 1: Initial stream data of multistage cascade refrigeration of LNG process

	T_s (°C)	T_t (°C)	P_s (atm)	P_t (atm)	ΔH (MMkW)
H11	12.34	-1.36	4.48	4.48	-0.1842
H12	8.6	-1.36	16.5	16.5	-0.0056
H13	30	-1.516	39.47	39.47	-0.0083
H14	35.8	25.43	9.5	9.5	-0.2323
H21	-12.31	-23.57	2.12	2.12	-0.1414
H22	-1.36	-23.63	16.5	16.5	-0.0127
H23	-1.52	-23.57	39.47	39.47	-0.0060
H31	-23.63	-36	16.5	16.5	-0.1223
H32	-24.33	-35.57	6.02	6.02	-0.0035
H33	-23.57	-36.17	39.47	39.47	-0.0036
H41	-35.57	-65.73	6.02	6.02	-0.1002
H42	-36.17	-65.7	39.47	39.47	-0.0104
H51	-75.08	-86.94	2.45	2.454	-0.0344
H52	-41.13	-86.9	35.5	35.5	-0.0205
H53	-65.7	-86.98	39.47	39.47	-0.0315
H61	-86.9	-90.57	35.5	35.5	-0.0307

Table 1(continued): Initial stream data of multistage cascade refrigeration of LNG process

	T_s (°C)	T_t (°C)	P_s (atm)	P_t (atm)	ΔH (MMkW)
H62	-86.98	-90.11	39.47	39.47	-0.0040
H71	-89.09	-125.21	9.40	9.40	-0.0148
H72	-110.19	-125	3.54	3.54	-0.0003
H73	-90.11	-125	39.47	39.47	-0.0161
H81	-125	-143.65	3.54	3.54	-0.0047
H82	-125	-143.7	39.47	39.47	-0.0070
H91	-143.7	-155	39.47	39.47	-0.0040
C1	-4.36	-4.36	4.08	4.08	0.1981
C2	-26.58	-26.58	1.89	1.89	0.1600
C3	-38.95	-38.95	1.15	1.15	0.1294
C4	-68.7	-68.7	5.37	5.37	0.1106
C5	-89.96	-89.9	2.12	2.12	0.0864
C6	-93.24	-93.24	1.8	1.8	0.0328
C7	-128.21	-128.21	815	815	0.0312
C8	-146.63	-146.6	2.94	2.94	0.0117
C9	-161.56	-161.56	1	1	0.0039

The example of subambient process for LNG is illustrated. The multistage cascade refrigeration is applied for LNG process. This process consists of three pure refrigerants, methane, ethylene and propane, which have three different boiling points. First, natural gas is cooled in propane cycle then it is cooled in ethylene, finally it is liquefied to -155 °C in methane cycle. The multistage cascade has been simulated using commercial software ProII version 9.1. The fluid package chosen to provide thermodynamics properties is Peng Robinson equation of state. The ambient condition is assumed to be 25 °C (298.15 K), 1 bar. The NG feed gas temperature and pressure are assumed to be 30 °C and 40 bar**.** The feed gas mass flow is assumed to be 450 mmscfd. The NG molar composition is: 90 % C1, 7.32 % C2, 0.35 % C3, 0.00075 % iC4, 0.0001 % nC4, 0.04 % iC5, 2.3 % N_2, 0.0005 % CO_2. The compressor and expander adiabatic efficiency is assumed to be 75 %.The design begins with generating the basic diagram as known as CCs including pressure effect and then ECCs are generated with exergy components by commercial software PROII. The initial stream data are shown in Table 1. In this case study is presented in which different option for decreasing power consumption.

3.1 Improved case by shaft work targeting technique

The ECCs is applied for shaft work targeting as introduced by Linnhoff and Dhole (1992). The concept of methodology is to replace the temperature of CCs with Carnot factor $\eta_c = 1 - (\frac{T_o}{T})$ resulting in ECCs as shown in Figure 2a and 2b. For cascade in multistream exchanger, the reference temperature is temperature that adsorbs heat as shown in Figure 1 (red line represents hot streams reject heat to cold stream in each exchanger).

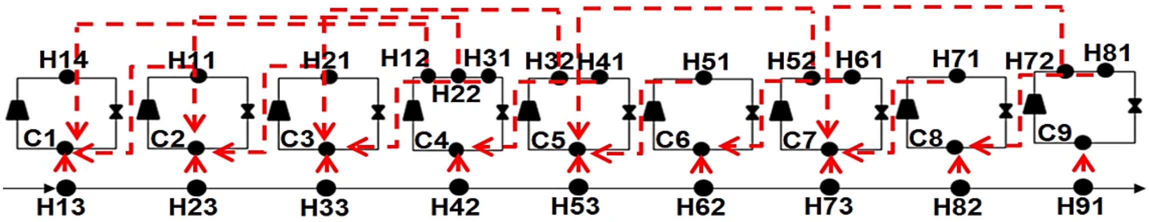


Figure 1: Scheme of multistage cascade refrigeration of LNG process

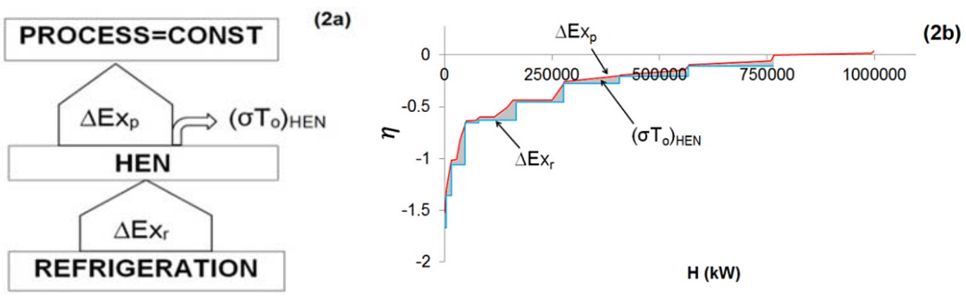
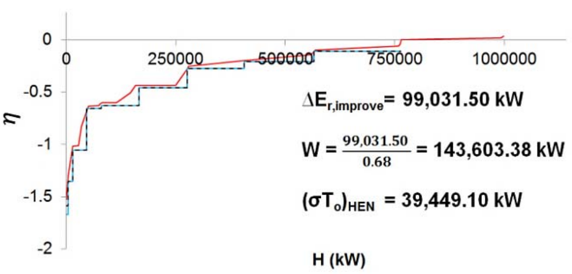


Figure 2: (a) The flow diagram of work or exergy losses $(\sigma T_o)_{HEN}$ (b) ECCs of base case multistage cascade refrigeration of LNG process

Figure 2a shows the flow diagram of work or exergy losses $(\sigma T_o)_{HEN}$ in which the refrigeration system supply exergy (ΔE_r) to HEN then HEN supply to process (ΔE_p). From ECCs in Figure 2b, ΔE_r of base case equals to 99,366.76 kW and 39,784.30 kW of $(\sigma T_o)_{HEN}$ lose due to heat transfer. Shaft work from simulation is 144,089.53 kW. The real shaft work can be estimated from ECCs by $W = \frac{\Delta E_r}{\eta_{ex}}$ while η_{ex} that equals to 0.68.



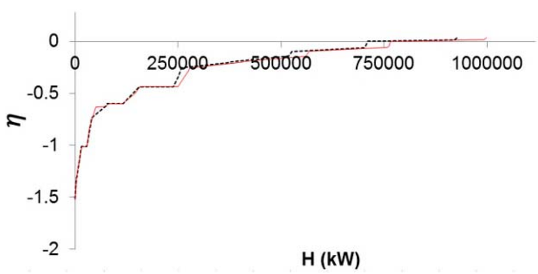


Figure 3: ECCs of improved multistage cascade refrigeration of LNG process

Figure 4: Process change by using ECCs

The exergy losses are reduced, resulting in reduce shaft work. Therefore the refrigeration system is improved as shown in Figure 3. From ECCs, the improved condition of utility helps to reduce $(\sigma T_o)_{HEN}$ around

39,449.10 kW. Compared between value from simulation of 143,840.90 kW and one from this methodology of 143,603.38 kW, it gives small error about 0.165 %.
Next, the change in process condition using the CCs to improve the process is done first. The change of pressure in hot streams affects the shape of hot composite curve. From Figure 4 the process stream or hot composite curve is shifted (dashed line) closer to cold composite one results in reducing the energy consumption.When process is changed, ΔE_p is reduced so $(\sigma T_o)_{HEN}$ increases as shown in Figure 5a, we have to shift $(\sigma T_o)_{HEN}$ by changing the level of refrigeration as shown in Figure 5b. The shaded area will be reduced, resulting reducing shaft work to 127,953.13 kW.

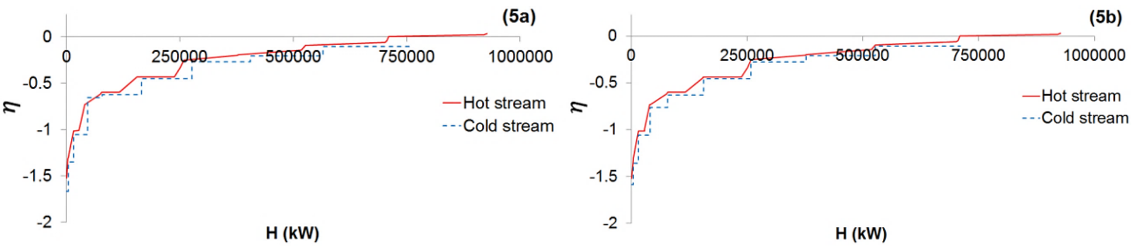


Figure 5: (a) ECCs of changed process condition (b) ECCs of improved cold stream condition

3.2 Improved case by the Extended Pinch Analysis and Design methodology and novel exergy diagram

Aspelund et al. (2007) has proposed the Extended Pinch Analysis and Design (ExPAnD) methodology which combines between Pinch Analysis and Exergy Analysis for minimum external heating, cooling and irreversibility. The use of expander and compressor helps the streams act as utilities. Therefore this methodology is chosen to help to improve process. Starting with base case, the first step estimates the exergy efficiency based on the ratio of total exergy inlet and outlet of streams equals to 97.95 %. The second step performs traditional CCs as shown in Figure 6 where 232,600 kW of cold utility as cooling water is required. However 144,089.53 kW of compressor work is required.

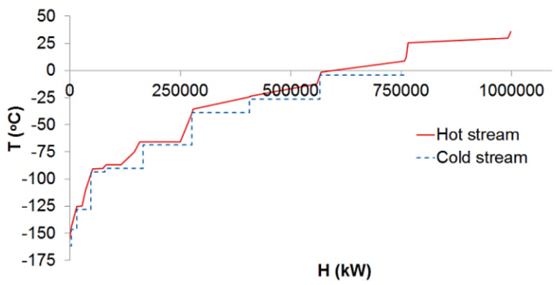


Figure 6: CCs of base case multistage cascade refrigeration of LNG process

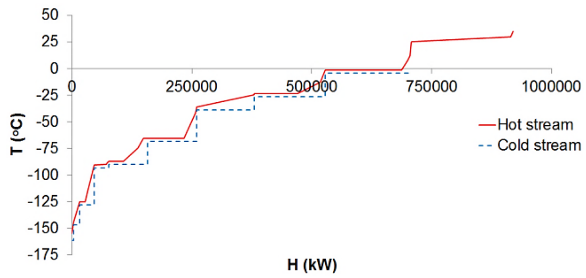


Figure 7: CCs of alternative 1A multistage cascade refrigeration of LNG process

Next, process is modified in the third step by selecting heuristic rules (Aspelund et al., 2007) in order to design the process. First, streams in subambient processes with a supply pressure higher than target pressure should be always expanded in an expander. Figure 7 shows the process which using expander instead of valve, the need for cold utility is reduced to 210,600 kW. The power consumption is reduced to 131,168.53 kW. The power generation from the expander is 9,423.26 kW. The exergy efficiency of alternative 1A is 98.6 %. When cold stream is expanded to its target pressure of 1 bar prior heat exchanger will give the lowest possible supply temperature by keeping flowrate constant to original value which shown in Figure 8. The exergy efficiency of alternative 1B is 98.3 %.
There is room for improvement design, from Figure 8 the larger temperature gap between CCs result in unnecessary irreversibility. Moreover, if the pressure of supply stream is higher than target stream, it can reduce cold utility requirements with power generation. So the improvement as shown in Figure 9, the required work and cooling duty is reduced to 118,456.83 kW and 200,300 kW respectively. In addition, the generated work is 6,895.24 kW. The exergy efficiency of alternative 1C is 98.4 %.

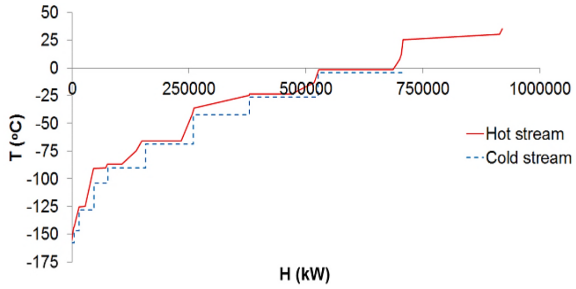


Figure 8: CCs of alternative 1B multistage cascade refrigeration of LNG process

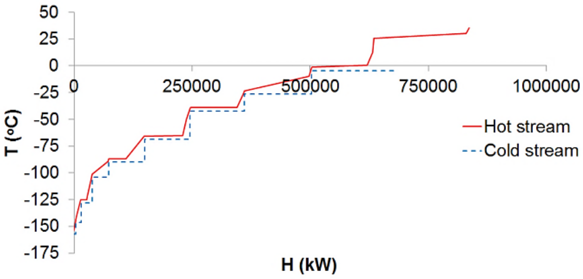


Figure 9: CCs of alternative 1C multistage cascade refrigeration of LNG process

This section represents the novel exergy diagram which introduced by Marmolejo-Correa and Gundersen (2012) has been used for determining the exergy target with maximizing exergy recovery and minimizing exergy destruction that can be read directly from the graph. This diagram can be used parallel with ExPAnD method to see the reduction of irreversibility or exergy destruction. The diagram start with base case by transforming traditional CCs of base case into exergetic temperature and temperature based exergy diagram which focus on subambient condition by Eq. (1) and the overlapping of the end temperature in hot and cold of CCs is transformed to exergetic temperature which represents exergy destruction as shown in Figure 10a and 10b.

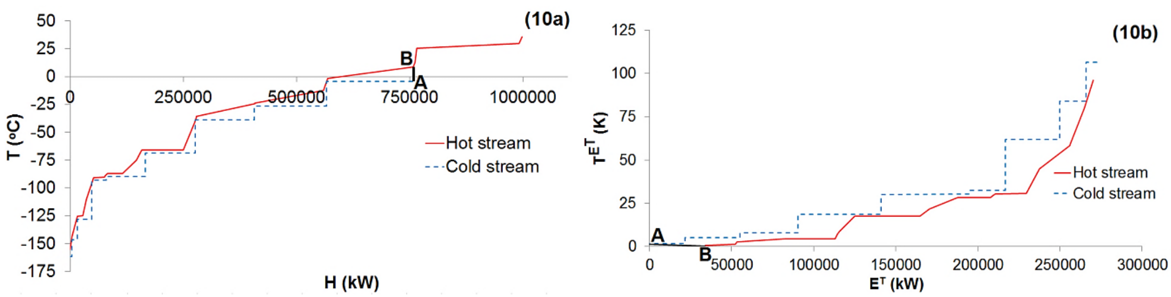


Figure 10: (a) CCs for the base case multistage cascade refrigeration of LNG process (b) Exergy diagram for the base case multistage cascade refrigeration of LNG process

In Figure 10b, the exergy destruction is shown by changing the overlapping temperature in CCs to exergetic temperature, it equals to 33,872.57 kW where focus on subambient temperature. After improved process the new exergy diagram as shown in CCs in Figure 9 is shown in Figure 11 can be visualised that exergy destruction is reduced to 23,000 kW or 32 % reduction. This was achieved by using ExPAnD method parallel with exergy diagram.

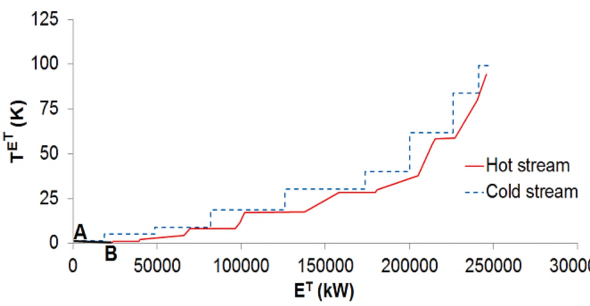


Figure 11: Exergy diagram for the improved multistage cascade refrigeration of LNG process

4. Conclusion

The processes are improved by Pinch-Exergy methodology namely shaft work targeting and ExPAnD method. These methodologies are very useful for design in early stage. For shaft work targeting, reducing the area between hot and cold lead to reduce work loss due to heat transfer. From ECCs of base case, we can see the room for improvement by manipulating cold stream to reduce area result in shaft work saving of 248.60 kW. Saving of shaft work is increased by changing process stream then shifting cold stream to reduce shaded area in ECCs causes 11.2 % savings from base case. ExPAnD method used along with exergy diagram shows the potential for minimizing energy consumption by reducing irreversibility or exergy destruction. This methodology achieves by using several heuristics to reduce energy consumption and transforming CCs to exergy diagram for exergy destruction. The results between base case and improved case (1C case) are shown in Table 2 where cooling water duty and exergy destruction decrease. Furthermore exergy efficiency is increased from 97.95 % to 98.4 % and shaft work savings is about 22.57 %.

Table 2: The results between base case and improved case (1C case)

	Base case	Improved case (1C)
Cooling water duty (kW)	232,600	200,300
Required power (kW)	144,089.53	118,456.83
Generated power (kW)	-	6,895.24
Net process power (kW)	144,089.53	111,561.59
Exergy efficiency (%)	97.95	98.4
Exergy destruction (kW)	33,872.57	23,000

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