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A Pinch Analysis-Based Method for LNG Cold Energy Multi-Level Temperature Cascade Utilisation

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LNG releases much cold energy during regasification, which has great valorisation potential. Efficient use of LNG cold energy is a crucial way to achieve future clean energy transition. In this study, existing methods for LNG cold energy utilisation are reviewed. This includes air separation process technology, cold energy in power generation, light hydrocarbon separation, cryogenic CO_2 capture, cryogenic comminution of waste rubber, dry ice production, seawater desalination process, and cold storage. Then the LNG cold energy cascade utilisation is studied using Pinch Analysis. Based on the method, this study proposes a cryogenic air separation – cold energy in a power cycle two-stage cascade utilisation process. The total temperature of the cold energy cascade utilisation and integration system is optimised to achieve the target of fully utilising LNG cold energy resources. A case of cryogenic air separation - cold energy in power generation in an LNG cold energy cascade utilisation system is studied to test how much cold energy is left. The results showed that the Pinch Point temperature is -150 °C, and 44.6 kW residual cold energy.

1. Introduction

With the fast growth of clean energy, the global imports of liquefied natural gas (LNG) reached 409 Mt in 2022, which is 5.8 % higher than in 2021 (Paraskova, 2023). At standard atmospheric pressure, natural gas is liquefied into LNG at low temperatures for storage and transportation. LNG transport features a relatively low cost for a large amount of LNG. The LNG must undergo regasification at the receiving terminal before being delivered to the users. When LNG temperature rises from - 162 °C to 20 °C, it wastes much cold energy. The energy absorbed during the regasification is 830 kJ/kg (He et al., 2019). Most contemporary LNG terminals use seawater as the heat source for the LNG regasification process, which causes cold pollution of seawater and wastes the energy that can be extracted from this cold resource. To address this issue, LNG cold energy recovery and cascade utilisation technology have been studied by many scholars. He et al. (2020) studied the two-stage cascade utilisation system, which combines air separation and a power generation cycle. Lian et al. (2015) showed that the regasification process of LNG was combined with the comminution of waste rubber, production of dry ice, and cold storage to develop a three-stage cascade system of heat exchange. Zhang et al. (2019) proposed an integrated system for the air separation, dry ice production, air conditioning system, and ice maker system with LNG cold energy, which realised a four-stage cascade utilisation system. LNG cold energy recovery cascade utilisation technology has two main issues, heat exchange and temperature level matching. This technology is the direct action of low-temperature cold energy to hot water or high-pressure steam and other heat flow, and the purpose is to convert low-temperature cold energy into high-temperature heat energy for different temperature level energy demand to achieve cascade heat exchange to improve the efficiency of

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cold energy utilisation. For increasing the utilisation rate of LNG cold energy, this study applies the Pinch Analysis to optimise the cascade utilisation system of LNG cold energy, which provides a reference for the studies on cascade utilisation of cold energy resources.

2. Methodology of Pinch Analysis

Pinch Analysis was developed to optimise heat exchanger networks (HENs) for over 40 y (Klemeš et al., 2013). As a mature energy analysis method for process integration systems, it has achieved a remarkable energy-saving effect in the process industry, and it is mainly applied to energy analysis and efficient utilisation of whole-process integration. Based on energy optimisation, the method attempts to allocate limited energy in the most efficient way. Linnhoff et al. (1983) succeeded in defining the basic principle of minimisation of energy utilities by optimising the combinations of hot and cold streams, including the inlet or outlet temperature.

2.1 Key concept of Pinch Analysis

In the process industry, there are usually several cold streams that need to be heated and several hot streams that need to be cooled. The hot Composite Curve and cold Composite Curve can be used to represent multiple hot and cold streams. To visualise the heat exchange of each stream, a temperature-enthalpy graph can be used. Assuming the heat capacity flow rate of the stream is Cp (kW/°C), if only one stream provides heat within the temperature range from T_1 to T_2, the heat value of this stream is $Cp \times (T_1 - T_2) = Q$.
The heat transfer temperature difference at the Pinch Point is ΔT_{min}, which is the minimum heat transfer between the cold and hot streams. It limits the energy of the further recovery process system to reach the minimum utility load. Insufficient heat energy is available in the hot streams situated above the Pinch to fulfil the total heat requirements of the cold streams, and external heating is required. Below the Pinch, insufficient cold energy is available in the cold streams to fulfil the overall cooling demand of the hot streams, and external cooling is required.
The minimum allowed temperature difference has been confirmed according to the most economical investment cost for heat exchangers and operating cost in energy. The cold and hot Composite Curves can only be moved horizontally until their vertical distance equals ΔT_{min} at a location defined as the Pinch Point of the process system. Taking the case of Nemati-Amirkolaii et al. (2019) as an example, Figure 1 shows the Composite Curves and energy recovery target.

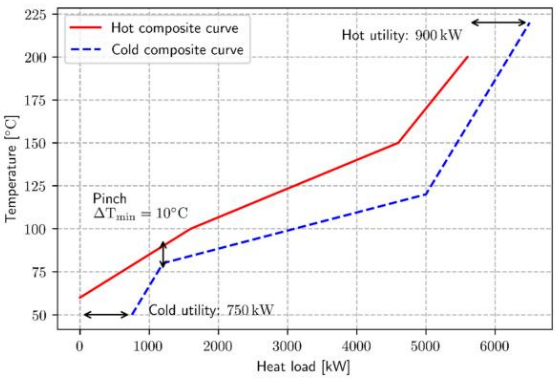

Figure 1: An example of using Pinch Analysis for energy saving, adapted from Nemati-Amirkolaii et al. (2019)

The design principles of the Pinch method are:
(1) There can be no heat transfer across the Pinch Point.
(2) The cooling load of the utility cannot be added above the Pinch Point.
(3) The heating load of the utility cannot be added below the Pinch Point.

2.2 History of LNG cold energy Pinch development

The concept of the cryogenic energy in air separation unit (CEASU) was introduced by Chen et al. (2018), which used Pinch Analysis of the heat exchange process between LNG and N_2, and studied its effect on the CEASU. The effect of Pinch Point temperature, temperature difference, the pressure of N_2 on mass flow ratio (N_2/LNG), the energy consumption of the condensing unit and cryogenic energy utilisation rate were analysed in detail. The result shows that the different value of the Pinch Point increases the approach temperature difference, and choosing a lower temperature difference at the cold end is beneficial to reduce energy consumption. Compared

with the conventional processes in which cryogenic energy is only used for cooling nitrogen or feeding air, the energy consumption of CEASU is reduced by 5~12 %. But the cryogenic energy of LNG could not be fully used. Ghorbani et al. (2020) introduced an integrated power generation system that uses liquefied natural gas regasification to provide cold energy for the hybrid system. The Pinch Analysis method was used to extract the heat exchange network related to a multi-stream heat exchanger in an integrated system. The effect of air/ fuel molar ratio on system performance was studied in parameter analysis. The result shows that the total thermal efficiency of the system increases by 56.15 %.
Jiang et al. (2023) proposed a process for natural gas helium concentration and LNG co-production (He-LNG). The key parameters were optimised based on Pinch Analysis. The result shows that when the cold box Pinch Point temperature in the liquefaction plant exceeds 3 °C, the process is more productive and energy-saving than other similar processes.

2.3 Significance of Pinch Analysis in LNG cold energy utilisation

The Pinch Analysis can be used to evaluate the efficiency of the LNG cold energy cascade utilisation system with different parameters. In an LNG cascade utilisation system, there are residual cold energy and emissions, which can be optimised through Pinch Analysis by determining the optimal material temperature, pressure, and other parameters to improve the energy efficiency of the system, reduce energy consumption and operation costs, and reduce the system's environmental impact. This method can also evaluate the stability of the system with different parameter settings, identify problems, and optimise and improve the existing problems so as to determine the best design scheme and improve the cold energy utilisation rate of the system.

3. LNG cold energy cascade utilisation technology

LNG is the cryogenic form of natural gas. The lower the temperature of cold energy, the higher the value. And the wider the temperature range of LNG can be utilised, the more obvious energy saving effect. LNG cold energy utilisation includes direct utilisation, indirect utilisation, and cascade utilisation. The cascade utilisation determines the optimal heat transfer temperature at different temperature levels according to the cold characteristics of heat exchange equipment and cold energy users to establish the theoretical optimal scheme of LNG cold energy recovery. LNG cold energy cascade utilisation according to the temperature bands of deep cold, medium cold, and shallow cold, considering the different cold needs of users at all levels. LNG deep cold utilisation technologies include air separation, light hydrocarbon separation, cryogenic CO_2 capture, etc. LNG medium cold utilisation consists of dry ice production, cryogenic comminution of waste rubber, seawater desalination process, etc. LNG shallow cold utilisation includes an air conditioning unit, combined cycle power plant, inlet gas cooling of a gas turbine of cold, heat, and power triplex system, etc.

3.1 Overall integration process of LNG cold energy cascade utilisation

LNG enters the natural gas high-pressure pipeline network through pressurisation and gasification, and the temperature of LNG after pressurisation increases from - 162 °C to about - 150 °C. A part of it can be directly used for light hydrocarbon separation, and the temperature of LNG after light hydrocarbon separation is about - 110 °C. It can be used in ethylene engineering at temperature levels - 100 °C, - 75 °C, - 55 °C, and the remaining cold energy can be used for cold energy power generation (about - 70 °C), cold storage, and fruit refrigeration (- 60 °C ~ 0 °C). Another part can be used for deep cold rubber crushing (- 130 °C ~ - 80 °C) and air separation technology (- 190 °C), or applied to make dry ice (- 100 °C). Finally, it is added to the seawater vaporizer (0 °C~ 5 °C), or into the gas turbine inlet air cooling system (5 °C ~ 7 °C) to provide cold energy for gas, to make it close to the required gas supply temperature, and finally, the normal atmospheric temperature natural gas is injected into the gas transmission network to satisfy the demand of natural gas users.

3.2 Air separation process - production of dry ice - cold storage three-stage cascade utilisation

It is a three-stage cascade utilisation scheme for LNG cold. The first cascade utilisation is used for air separation, and the air separation process is generally carried out between - 191 °C and - 150 °C, and the temperature is about - 100 °C after heat exchange. The second cascade utilisation can make dry ice (solid carbon dioxide). The temperature of dry ice is - 78.5 °C. Dry ice can rapidly reduce the temperature of freezing objects, and when melted, it is directly sublimated from a solid to a gaseous state without producing any liquid or water. The third cascade utilisation can be used to design multi-stage cold storage through the dry ice production device after the heat exchange temperature becomes -56°C. Based on different functional uses of the ice storage, the temperature level can be roughly divided into the following three kinds: freezing room - 30 °C ~ - 18 °C, freezing objects refrigerated room - 23 °C ~ - 15 °C, cooling objects refrigerated room 0 °C ~ 16 °C. Finally, through the gas supply pre-processing device, the output gas pipeline transports natural gas to users.

3.3 Air separation process - cold energy in power generation cycle two-stage cascade utilisation

Mehrpooya et al. (2016) showed that the regasification process of LNG was combined with low-temperature air separation and power generation cycle processes to form an integrated heat exchange system. The cold energy of LNG at - 162 °C is raised to - 129.7 °C in the air separation unit process, and part of the cold energy is recovered, where the air is decomposed from 25 °C to O_2 and N_2 at 7 °C in the air separation unit; then, LNG leaves the process at -129.7 °C and enters the power generation cycle, where it is used as a cold source and raised to - 7.1 °C after heat exchange; finally, the heat exchanger passes seawater raises the temperature of the exported natural gas to about 5 °C, while the LNG regasification process is completed.

3.4 Air separation process - light hydrocarbon separation two-stage cascade utilisation

Zhang et al. (2020) proposed an integrated system for the air separation process and LNG light hydrocarbon recovery with LNG cold energy, which realised the cascade utilisation of LNG cold energy and also the resource recovery of light hydrocarbon energy from LNG. The optimal key process conditions are determined: the outlet gas stream temperature for the air separation process is - 129.6 °C, and the outlet gas stream temperature for the light hydrocarbon recovery process is - 106.8 °C.

Table 1: Summary of previous LNG cold energy cascade utilisation system

Researchers	Level 1	Temperature range of LNG/°C	Level 2	Temperature range of LNG/°C	Level 3	Temperature range of LNG/°C	Level 4	Temperature range of LNG/°C
Mehrpooya et al. (2016)	Air separation	-162~-129.7	Power generation cycle	-129.7~-7.1				
He et al. (2020)	Air separation	-162~-56	Power generation cycle	-56~15				
Zhang et al. (2020)	Air separation	-162~-129.6	Light hydrocarbon separation	-129.6~-106.8				
Sultan et al. (2021)	CO2 capture	-163~-95	Power generation cycle	-95~0				
Li et al. (2022)	Power generation cycle	-163~-20	Cold storage	-20~5				
Lian et al. (2015)	Comminution of waste rubber	-162~-100	Production of dry ice	-100~-60	Cold storage	-60~25		
Zhang et al. (2019)	Air separation	-160.98~-122.43	Production of dry ice	-122.43~-77.95	Air conditioning system	-77.95~-49.75	Ice maker system	-49.75~27.8

4. Case study

The energy exchange between LNG cold energy cascade utilisation systems requires a complete heat exchange network to utilise the LNG cold energy capacity fully. The Pinch Analysis is usually the most widely used heat exchange network method in designing energy exchange processes. The Pinch Analysis method is an overall optimisation design method for energy saving of process systems, which can be used to obtain system optimisation by drawing graphs and using the data of inlet and outlet temperatures, heat capacity flow rate, and heat load of each stream, and reflecting the pinch point temperature with hot and cold stream curves and total combination curves. To illustrate the overall optimisation design method for energy saving of process system based on Pinch Analysis, this paper studies the cryogenic air separation - cold energy in power generation in LNG cold energy cascade utilisation system.

Step 1: List the hot and cold streams in engineering

For this system, the stream includes air, C_3H_8, seawater, and LNG, where air, C_3H_8, and seawater are hot streams, and LNG-1, LNG-2, and LNG-3 are cold streams.

Step 2: The basic parameters of each stream: inlet temperature, outlet temperature, heat capacity flow rate, and heat load.

The three hot streams are air, C_3H_8, and seawater. The three cold streams are LNG-1, LNG-2, and LNG-3. Each stream parameter is shown in Table 2. Much of the data is cited by Mehrpooya et al. (2016).

Table 2 Stream basic parameters

No	Stream	Type	Inlet temperature/°C	Outlet temperature/°C	CP/（kW/°C）	Q/kW
1	Air	Hot	25	-140	2.5	412.5
2	C_3H_8	Hot	-38.99	-43.34	8.0	34.8
3	LNG-1	Cold	-162.8	-125.8	15.52	589.84
4	LNG-2	Cold	-125.8	5	2.07	270.76

Step 3: The minimum temperature difference for heat exchange

The deep-cooling resources of LNG have a high value. To ensure the effective use of energy and to consider the issues of heat exchange area and investment cost, the minimum allowed temperature difference is taken as ΔT_{min} = 20 °C.

Step 4: The cold and hot Composite Curves

Given the basic parameters of hot and cold streams, the cold and hot streams curve is obtained with the heat exchange as the horizontal coordinate and the temperature as the vertical coordinate.
Move the combined Cold Composite Curve and Hot Composite Curve in the horizontal direction so that they are close to each other until their vertical distance at a certain place is exactly equal to the minimum heat transfer temperature difference at 20 °C. The segment is defined as the Pinch Point in the system process.

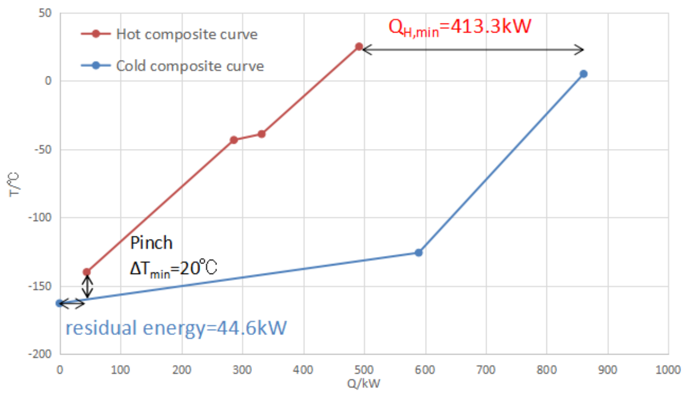

Figure 2: Composite Curves

Figure 2 shows the Composite Curves. The hot stream temperature at Pinch Point is - 140 °C, and the cold stream temperature is - 160 °C, which means the Pinch Point temperature is - 150 °C. The overlapping part of the total combination curve is the heat exchange area of the hot and cold streams inside the process. The hot and cold streams for the process under consideration are combined to yield a Composite Curve. The sink above the Pinch Point has no suitable cold streams for heat exchange at the upper end of the cold combination curve above the Pinch Point. So, the hot utility is needed to raise this part of the cold flow to the target temperature, and the minimum hot utility is 413.3 kW. In this thermal utility project, the flow rate of seawater, which is used for heat transfer from 15 °C to 12 °C, is 1,152 m^3/h. The source below the Pinch Point has 44.6 kW residual cold energy. The optimal heat exchanger network can be determined by this system, which fully uses LNG cold energy resources to achieve maximum heat and cold recovery.

5. Conclusions

In this paper, we mainly focus on the cascade utilisation and integration of LNG cold energy, and propose a cryogenic air separation - cold energy in power generation in LNG cold energy cascade utilisation system. Based on the Pinch Analysis method, we get a Pinch Point temperature of - 150 °C, a minimum hot utility of 413.3 kW, and 44.6 kW residual cold energy. In terms of the current study status, this system uses 53.2 % of LNG cold energy, which still has the potential to increase the utilisation rate, and only heat exchange of the system is studied. Next, we will investigate the conversion process of LNG cold energy to electricity. Besides, a medium or shallow-level LNG cold energy utilisation process should be integrated to complement a maximum optimisation of the LNG cold energy cascade utilisation system.

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