Progress of LNG Cold Energy Cascade Utilization Research

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Abstract: Liquefied natural gas (LNG), as a clean and efficient form of energy, its cold energy utilisation has been a research hotspot in the energy field. With the adjustment of global energy structure and the enhancement of environmental protection awareness, LNG cold energy cascade utilisation technology has gradually received wide attention. This paper reviews the latest research progress of LNG cold energy cascade utilisation technology, analyses the requirements of different cold energy utilisation units on cold energy quality and the economic benefits of the products, and puts forward directions and suggestions for further research.

Keywords: LNG; cold energy; cascade utilization; research progress.

1. Introduction

In the process of transforming the global energy landscape to low-carbon and high-efficiency, the importance of liquefied natural gas (LNG) as a clean and efficient form of energy is becoming more and more prominent. China's natural gas consumption will reach 620 billion m^3 and 695 billion m^3 in 2035 and 2050 respectively, making it the world's largest consumer of natural gas, according to forecasts by China National Petroleum Corporation's Institute of Economics and Technology. This means that LNG imports are also increasing rapidly, and it is shown that by the end of 2022 China has put into operation 23 LNG receiving stations, with a total gasification capacity of about 8240×10^4 t/a and a cooling capacity of 200×10^8 kW·h/a[1]. LNG is liquefied from natural gas cooled down to about -162℃, and a large amount of cold energy will be released during the process of vaporisation back to the gaseous state, and these cold energy. This cold energy is of high utilisation value. The effective use of LNG cold energy for power generation is not only in line with the strategic needs of sustainable energy development, but also a key measure to improve the efficiency of comprehensive energy use and reduce environmental pollution.

The cold energy released during the vaporisation of each kg of LNG is about 830~860kJ, if this cold energy is fully converted into electricity, theoretically each tonne of LNG can generate electricity equivalent to about 240kW·h. A large amount of cold energy will be generated during the storage and transportation of LNG, which, if reasonably utilised, can greatly contribute to the saving of energy and the reuse of resources. The ways of utilising the cold energy of LNG can be divided into direct utilisation and indirect utilisation, while gradient utilisation is a more efficient way of utilising cold energy. The way of LNG cold energy utilisation can be divided into direct utilisation and indirect utilisation, while the gradient utilisation is a more efficient way of utilisation, which allocates the cold energy to different utilisation units according to the different qualities of the cold energy, in order to realise the maximum utilisation of the cold energy.

2. LNG Cold Energy Utilisation Methods

In the temperature range from -162°C to room temperature, the lower the temperature level of LNG, the higher the grade of cold energy and the greater the value of cryogenic energy. By rationally utilising the cold energy of LNG at different temperature levels, the economic and social benefits can be significantly enhanced.

2.1. Light hydrocarbon separation

The material quantity fraction of ethane and above light hydrocarbons (C2+) in liquefied natural gas (LNG) imported into China ranges from 5% to 10%. Recovering this fraction of light hydrocarbons can not only effectively regulate the calorific value of natural gas, but also promote the unification of natural gas product standards, which in turn improves energy use efficiency and product consistency[2]. As early as the 1960s, the invention patent for the separation of light hydrocarbons from liquefied natural gas (LNG) was already proposed abroad. However, with the rapid development of science and technology, researchers have continuously improved and optimised the original separation process. The new process method effectively raises the pressure of the separated methane gas by compressing it, and cleverly utilises the cold energy released by LNG to liquefy the methane so that it meets the pressure standard for natural gas pipeline transmission, realising efficient, long-distance transmission of liquefied methane. This innovative process not only significantly improves the efficiency of energy utilisation, but also opens up new technological pathways for the long-distance transport of natural gas.

Up to now, researchers have extensively studied the LNG light hydrocarbon separation technology. Zhian Deng et al.[3] showed that the ethane recovery rate was 88.40% by introducing flash, demethanisation and de-ethane towers combined with the cold energy of feedstock LNG. Hui Xiang et al.[4] Improved process for LNG light hydrocarbon recovery based on DHX process (direct heat exchange process) reduced the total power consumption of the system of 15.5%, increased the ethane recovery rate by 2.9%, and obtained liquid light hydrocarbon products at atmospheric pressure.

Chenghang Li et al.[5] optimised the LNG light hydrocarbon recovery process by cleverly avoiding the use of a compressor, aiming to significantly reduce power consumption, improve exergy efficiency, and increase the product variety and recovery rate, thus achieving more efficient energy use and greater economic benefits.

LNG liquefied natural gas releases a large amount of cold energy during the vaporisation process. By effectively utilising this cold energy, the light hydrocarbon separation and recovery technology can significantly reduce energy consumption and achieve graded energy use. The separated light hydrocarbon components, such as ethane and propane, are valuable chemical raw materials, which can increase the diversity and stability of domestic energy supply. Through light hydrocarbon separation and recovery technology, these components can be efficiently extracted from LNG and used for the production of high value-added petrochemical products, such as ethylene and propylene, which can increase the economic returns of enterprises and also enhance the added value of the industrial chain.

2.2. Low-temperature cold power generation

The principle of LNG cold power generation is based on the process of heat exchange between LNG and the ambient medium. During this process, the LNG absorbs heat, increases in temperature and gradually gasifies. With the gasification of LNG, the pressure and volume of the ambient medium will change, which will drive the mechanical devices to operate, and the energy contained in this process will be converted into electrical energy, so as to achieve external work and power generation [6]. LNG cold power generation technology is mainly classified into the following categories: the direct expansion method, the organic Rankine cycle method, the Brayton cycle method, multi-stage composite cycle method, the Carina cycle method, and the combined cycle method.

In recent years, domestic scholars have studied LNG cold energy power generation from the perspectives of power generation efficiency, cold energy utilisation and system economics. Jie Pan et al.[7] gave full play to the respective advantages of these two energy sources by combining LNG cold energy and geothermal energy. Four multi-stage combined power cycle power generation systems based on LNG cold energy and geothermal energy drive were designed, and a comprehensive comparison and analysis was conducted from multiple dimensions, and the system scheme with relatively better performance was finally selected. Dongxu Cai et al.[8] proposed an improved three-stage tandem multistream combined cycle (MS-3CC) system, which resulted in an improvement of 5.4% and 80.3% compared to the three-stage series-parallel combined cycle (P-3CC) system and the single-stage combined cycle (SCC) system, respectively, whereas its annual net return was increased of 16.9% and 68.0%, respectively.

LNG cold energy power generation is an emerging way of energy utilisation. The use of LNG cold energy for power generation not only reduces the energy consumption and emissions of traditional power generation, but also improves the efficiency of LNG cold energy utilisation. LNG cold energy power generation should not only be subject to process optimisation studies, but also target the multi-energy complementation of LNG cold energy utilisation as the core, coupled with BOG power generation, photovoltaic power generation, geothermal power generation and other energy supply technologies.

2.3. Air separation

The main technical principle of air separation is to make use of the different physical properties (mainly boiling points) of the components in air, condense the air into liquid through a specific process, and then separate the components according to their different evaporation temperatures. Through the comprehensive transformation and optimisation of the air separation process, sufficient liquid nitrogen, liquid oxygen and liquid argon products can be effectively prepared by using cold energy. The process first compresses, pre-cools and purifies the air, which is then further cooled to a low temperature below -100℃ to liquefy the air. Then, taking advantage of the difference between the boiling points of oxygen and nitrogen, the oxygen and nitrogen are effectively separated in the distillation column by means of a number of partial evaporation and partial condensation processes of the liquid air, so as to obtain high-purity oxygen and nitrogen products. In order to ensure that the unit can operate continuously and stably and maintain the required heat balance, it is necessary to overcome the loss of cold due to adiabatic losses, insufficient reheating of the heat exchanger and direct discharge of low temperature fluids from the cold box. To do this, the unit needs to be constantly replenished with cold. This cold energy can be utilised from the LNG, thus ensuring that the cryogenic separation process runs smoothly.

Therefore, air separation is the most widely used process at LNG receiving stations in China. As early as 1979, Yamanouchi and Nagasawa[9] proposed an innovative idea of using LNG cold energy for air separation. They used circulating nitrogen to absorb the cold energy of LNG instead of the conventional expansion refrigeration method, resulting in a saving of 0.5 kWh of electricity per cubic metre of product produced. In 2007, Xiong and Hua[10] proposed an innovative air separation process combining the cold energy of liquefied natural gas (LNG) and the compression throttling refrigeration technology of circulating nitrogen. It was found that increasing the circulating nitrogen pressure could reduce LNG consumption and optimise the efficiency of its use. However, it was also pointed out that the LNG output temperature was still low and the cold energy was underutilised, and that methods for efficiently utilising LNG cold energy need to be further explored in order to optimise the process and improve the energy utilisation efficiency.In 2018, Kim et al.[11] carried out an optimisation study on the utilisation of liquefied natural gas (LNG) cold energy in an air separation plant. They innovatively combined the new single-tower air separation process with the LNG regasification process and proposed two different optimisation schemes to achieve the rational utilisation of LNG cold energy and improve the energy utilization efficiency. In 2019, Baitong Ma[12], on the basis of LNG cold energy air separation process, not only saved the investment cost of the plant by optimising the process flow for the production of oxygen-enriched from the air separation but also effectively reduced the Energy consumption.

The high grade of cold energy required for air separation is small compared to the cold energy grade of liquefied natural gas (LNG) at -162℃, making it ideally suited as the first stage in the LNG cold energy cascade for large gasification stations.

However, for small and medium-sized gasification stations, where the gasification pressure and electricity consumption are relatively small, the air separation process is too large and complex to be suitable. This is because the limited demand and size of small and medium-sized gasification stations do not allow them to fully utilise the benefits of the air separation process, and the implementation of the air separation process would also increase unnecessary investment and operating costs.

2.4. Refrigeration applications

2.4.1. Low-temperature cold storage

Low-temperature cold storage is mainly used for storing foodstuffs, medicines and other items that require low-temperature preservation. These items have strict requirements for storage temperature, which generally needs to be between 0℃ and -60℃. In order to maintain a low-temperature environment in the cold storage, a large amount of cold energy needs to be consumed. Conventional cold storage refrigeration systems usually use electric-driven compressors for refrigeration, which consume high energy and have large operating costs, while LNG can release a large amount of cold energy during regasification, and the use of this part of the cold energy can effectively reduce the operating costs of the cold storage and improve the efficiency of energy use. The temperature distribution of each cold storage is different, the temperature of high temperature cold storage is 0~5°C, the temperature of medium temperature cold storage is -15~-4°C, the temperature of frozen low temperature cold storage is -28~-15°C, and the temperature of super low temperature cold storage is -50~-23°C.

The working process of cold storage using LNG cold energy can be divided into two types, namely, refrigerant without phase change and refrigerant with phase change, according to whether or not the refrigerant undergoes a phase change in the operation process. Fig.1 shows the refrigerant phase-change-free operation process, in which the refrigerant remains in liquid state throughout the operation process (including in the evaporator), no vaporisation occurs, and the cold quantity is provided by the sensible heat of the refrigerant. In this process, the refrigerant flow rate is relatively large, but because the refrigerant is in the full liquid state operation, so the heat exchanger can be selected for a smaller volume, and the system operation is easy to control. Fig.2 shows the refrigerant phase change operation process, the refrigerant evaporates in the evaporator, mainly relying on the latent heat of vaporisation to provide cold. This process requires a large heat exchanger and pipework, but the refrigerant flow rate is relatively small. In contrast, no phase change process has the advantages of simple equipment structure, control operation is convenient, but because it only uses the sensible heat of the refrigerant to transfer the cold, so it needs a larger refrigerant mass flow rate to meet the refrigeration demand. The phase change process utilises the latent heat of vaporisation of the refrigerant, which allows the mass flow rate of the refrigerant to be greatly reduced while transferring the same amount of cold. However, this process is relatively complex in terms of equipment structure, process flow and control system, and due to the presence of the gas phase, the volume flow rate of the gaseous pipework is higher, which results in larger diameters of the gaseous pipework and corresponding heat exchanger sizes.

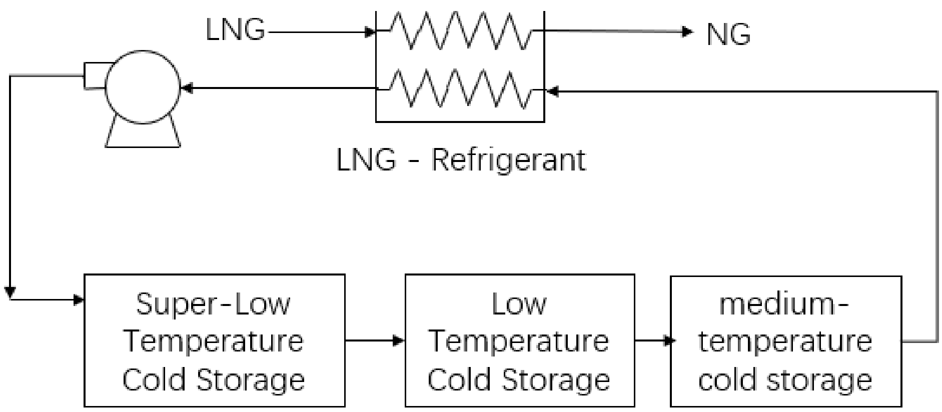

Figure 1. Refrigerant phase-change-free operation flow

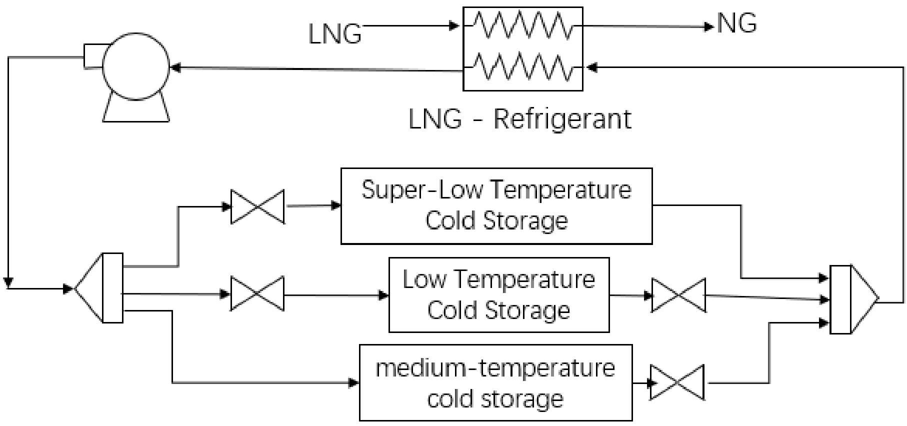

Figure 2. Refrigerant phase change operation flow

2.4.2. Low-temperature crushing

The number of used tyres produced in China each year is a relatively large number and continues to grow with the increasing number of cars. The accumulation of used tyres not only occupies a large amount of land, but may also cause fire and other safety hazards and long-term pollution of the environment. Therefore, how to effectively deal with and make use of waste tyres has become a global environmental challenge. The production of fine rubber powder, as a harmless, resourceful and industrialised treatment method, provides a new way for the recycling of waste tyres. Through special crushing and processing technology, waste tyres can be made into rubber powder with uniform particle size and stable performance. This rubber powder not only retains the basic characteristics of the original tyre rubber, but also improves its physical and mechanical properties through re-cross-linking technology, giving it better durability and stability in applications.

Low-temperature shredding of waste tyres using LNG cold energy is designed to reduce energy consumption during the shredding process, while effectively using LNG cold energy, with significant social and economic benefits. Usually using a combination of room temperature and low temperature crushing process, waste tyres first through the room temperature crushing stage, was initially crushed to about 50 purposes of rubber powder particle size. Subsequently, impurities such as fibres and steel wires are effectively removed from the rubber powder through a screening process. Next, the screened rubber powder is sent to a freezer for freezing at a low temperature of -70℃ (it is worth noting that the glass transition temperature of natural rubber is about -73℃), a process that makes the rubber powder brittle and provides favourable conditions for subsequent crushing. The embrittled rubber particles are then conveyed to a low-temperature crusher or grinder for further fine crushing, and the final particle size can reach 180~200 mesh, thus achieving the goal of producing fine rubber powder by low-temperature crushing of waste rubber, while recycling the cold energy of LNG as fully as possible.

3. LNG Cold Energy Cascade Utilization

At present, the domestic LNG receiving station cold energy utilisation project is mostly in the planning and construction stage, due to the lack of corresponding cold energy utilisation demand in the surrounding area, and the utilisation method is relatively single, which makes China's LNG cold energy utilisation rate is low, and the progress of applying it to the actual engineering project is slow. In order to improve the utilisation rate of cold energy at home and abroad, many scholars have studied the LNG cold energy gradient utilisation according to the principle of LNG temperature interval utilisation. Wenchao Lan et al.[13] proposed a cascade process for using LNG cold energy for power generation, seawater desalination and ice storage, and the organic Rankine cycle (ORC) efficiency of this system reached 15.76%, which could produce 119.66 tonnes of fresh water per day stably, and the payback period was only 3.23 years. It is especially worth mentioning that the desalination cost of the novel coupled system is only 0.48 USD-t-1, which significantly reduces the economic cost of the desalination process compared to the desalination cost of reverse osmosis membranes of 0.75 USD-t-1. Tenglong Xiang et al.[14] proposed a hierarchical process for recovering LNG cold energy to capture carbon dioxide (CO_2) from the flue gas of a natural gas power plant and to recover the cold energy of liquefied natural gas (LNG) for power generation, where LNG is classified according to the temperature into deep cooling (below -120.00℃), medium cooling (-120.00~60.00℃), and shallow cooling (-60.00~20.00℃), and the cold energy is classified according to the temperature. The heat recovery efficiency, cold energy utilisation, power generation efficiency and exergy efficiency of the system are 41.55%, 14.34%, 10.80% and 53.60%, respectively, as simulated by Hysys. Huiyi Mao[15] proposed a comprehensive LNG cold energy utilisation scheme for a 300,000 tonne fuel-powered ship with power generation as the main focus and ship power generation as a supplement, and the exergy efficiency of the system was 47.64% through Hysys simulation with work mass screening and process flow optimisation. Luling Li et al.[16] proposed a LNG cold energy cascade utilisation process including air separation, dry ice/liquefied CO_2 production and power generation, the LNG cold energy utilisation of this process reaches 27.89%, and the total power consumption per unit hour is 2,618kW, whereas the process is able to produce liquid nitrogen 1.1×10^4kg, liquid oxygen 2597kg, dry ice 268.7kg, and liquid CO_2 163.8kg.

In the early stages of LNG gasification, its outlet temperature is about -100℃. This temperature range is ideal for air separation or liquefied air. By utilising the cold energy of LNG, the energy consumption in the air separation process can be reduced and the efficiency of air separation can be improved. At the same time, liquefied air is an important feedstock for industry and has a wide range of applications. As the temperature of LNG increases, its cold energy can be used for power generation, liquid CO_2 production or dry ice production. the liquefaction temperature of CO_2 is -70℃ and the generation temperature of dry ice is -78.5℃, both within this temperature range. By utilising the cold energy of LNG, the energy consumption in the power generation process can be reduced and the efficiency of power generation can be improved; at the same time, liquid CO_2 and dry ice are also industrially important products with high economic value. When the temperature of LNG is further increased, its cold energy can be used for cold storage and desalination. Cold storage requires a stable low-temperature environment to preserve foodstuffs, medicines and other items, while desalination requires a large amount of cold energy to lower the temperature of seawater, thereby increasing desalination efficiency. By utilising the cold energy of LNG, these needs can be met, reducing energy consumption and costs.

4. Conclusion

LNG cold energy cascade utilisation technology can efficiently recover LNG cold energy and significantly improve the overall energy efficiency. However, the technology is still in the theoretical research stage, and no cold energy cascade utilisation projects have been put into production in China. This is mainly due to the limitations of the actual project, such as the large difference in the demand for cold energy in different temperature gradients, the large fluctuations in industrial operations due to the influence of environmental and transport factors, and the high requirements for cold energy supply and stability that are difficult to meet. In order to promote its industrial development, it is necessary to combine the design of process parameters and industrial characteristics, taking into account a variety of factors. In the future, the existing process should be optimised and combined with practical applications to explore new directions of use. At the same time, it is important to focus on market research in the interface between theory and practice, and rely on policy development. In addition, due to the fluctuation of LNG cold energy supply, in order to ensure the stable operation of the process, we should study the multi-energy complementary and energy storage and peak adjustment process to achieve a stable supply of energy.

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