Progress of liquefied natural gas cold energy utilization

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Abstract. Over the past decades, a variety of different approaches to realize the utilization of liquefied natural gas (LNG) cold energy have been undertaken. By reviewing on the existing LNG cold energy utilization ways and considering the suggestions of taking advantage of the principle of temperature counterpart and cascade utilization, this paper proposes a novel method that LNG cold energy can be used in liquid air energy storage (LAES) system. Because of a high match in temperature between LNG gasification process and air liquefaction stage, LAES system combined with LNG cold energy has an improved efficiency compared with the conventional LAES system. Additionally, the cold energy of LNG can be taken full advantage of.

1. Introduction

LNG is obtained at close to atmospheric pressure by cooling natural gas to -162 °C, which accounts for about 1/600 of the volume of natural gas[1]. Its existence increases the flexibility of natural gas storage and transportation and expands the scope of application of natural gas. LNG releases plenty of cold energy when vaporized, and the theoretically available cold energy of 1 ton of LNG vaporization process is about 230 kWh[2]. Actually, partial cold energy is usually discarded in LNG evaporators, resulting in quantities of energy waste. Therefore, considerable economic and social benefits can be achieved through the recovery of LNG cold energy.

LNG cold energy utilization technology has been used in many countries. Japan used LNG cold energy earlier in these fields such as in air separation, electricity generation, making dry ice and refrigerating[3]. South Korea, Australia and France mainly use LNG cold energy for air separation and light hydrocarbon separation[4]. The United States, Russia, the European Union and other countries and regions have also carried out relevant research. Fig. 1. shows the temperature level of several low-temperature applications that are suitable for exploiting LNG exergy.

Fig. 1. Temperature levels for several applications that can use the cold from LNG-regasification.
2. LNG cold energy utilization applications

2.1 LNG cold utilization systems in power generation

Cryogenic power generation is currently the most widely used application of LNG cold energy [5], which mainly uses the cold energy of LNG as a cold source of circulation, and reduces the circulating condensation temperature to obtain high power generation efficiency.

The research of LNG cold energy utilization for power generation can be dated back to 1970s. The basic cycle includes: direct expansion cycle, Rankine cycle and Brayton cycle[6]. Because of the limitations of the basic cycle in efficiency, numerous theoretical studies have been carried out to improve the efficiency of LNG cold energy generation. On the basis of direct expansion cycle proposed a multi-pressure LNG direct expansion cycle. In view of the mismatch between the condensation curve of working fluid and LNG gasification curve in Rankine cycle, a Cascade Rankine cycle has been developed, and the thermal efficiency and exergy efficiency reached 12.5% and 65.2%, respectively. Furthermore, a novel combined generation cycle, which is composed of direct expansion, Brayton cycle and Rankine cycle, proves that the thermal efficiency of the power plant can be as high as 56.72% [7-9].

However, cryogenic power generation has low demand for cold energy grade, the high-grade cooling capacity of LNG is converted into low-grade energy in the process of cold energy power generation. It leads to the decrease of the exergy of cold energy recovery. Therefore, cryogenic power generation is not the best way to use LNG cold energy from the perspective of economic efficiency and cold energy utilization.

2.2 Direct cooling application

2.2.1 Air separation processes. One of the solutions to utilizing LNG cold energy is supplying it to an air separation unit (ASU)[10]. A cryogenic ASU requires lots of energy to produce high purity oxygen and nitrogen. Since the cryogenic ASU requires very low temperatures (-173°C to -193°C), high exergy can be achieved by combining the LNG gasification process with the air separation process, which can effectively reduce energy consumption.

Up to now, researchers have conducted extensive research on LNG cold energy air separation technology. Xu et al.[11] based on chemical packing separation technology and high-efficiency heat exchanger network proposed a new air separation process cooled by LNG cold energy. The operating temperature range of LNG cold energy is extended from 133K-203K to 113K-283K and air separation pressure is reduced from 0.5MPa to about 0.35MPa. Moreover, LNG consumption decreased by 44.2% and exergy efficiency increased by 42.5%. What’s more, research on new integrated cycles is evolving. Mehrpooya et al.[12] investigated the integrated air separation processes, cold energy recovery of liquefied natural gas and carbon dioxide power cycle. LNG cold energy is used for pre-cooling the feed air. It greatly reduces the energy consumption of the compressors located before the columns by more than 55.6%.

LNG cold energy only participates in the heat exchange system in the course of the liquid nitrogen cycle, and does not mix with the fraction during the air separation processes, which improves the reliability of LNG utilization. However, there are still some issues. The temperature of LNG is close to -100°C after the cold energy air separation[13], and there is still plenty of cold energy between -100 °C and normal temperature. In order to improve the efficiency of comprehensive use of cold energy, it is necessary to realize further utilization.

2.2.2 Seawater desalination processes. Freezing seawater desalination is another process which requires a high amount energy. Adding LNG cold energy can reduce power input.
Cravalho et al.[14] first proposed a net zero work system for the recovery of refrigeration available from LNG in the course of regasification. In theory, the maximum fresh water output per kilogram of LNG can achieve 6.7 kg. Cao et al.[15] studied the process of freeze seawater desalination on flake ice maker utilizing LNG cold energy and the most suitable seawater crystallization temperature was provided. The results show that the consumption of 1 kg equivalent LNG cold energy can obtain about 2 kg ice melt water. Jiang et al.[16] synthetically analyzed seawater desalination technology represented by membrane method, distillation method and freezing method and pointed out that hybrid desalination process combined with LNG cold energy is a significant technical development direction for seawater desalination.

However, the intractable problem in applying LNG cold energy to seawater desalination is the mismatch between the cold energy use temperature region and the LNG gasification temperature zone. The seawater freezing point is -2℃, which will lead to a lot of exergy loss.

2.2.3 Cryogenic CO2 capture processes. Cryogenic CO2 capture process is one of the methods to capture CO2 in the plants. Conventional liquefaction processes compress CO2 to 2.5-3.0MPa and then uses cooling equipment to liquefy. Using LNG cold energy, it is easy to obtain the low temperature, thereby reducing the pressure of the liquefaction device to about 0.9 MPa[17].

Xiong et al.[18] proposed a novel CO2-capturing natural gas combined cycle, in which the electrical exergy efficiency of the proposed cycle reaches 54.9%. Meanwhile, 90.6% CO2 could be recovered. Recently, an integrated power generation system of Kalina cycle and organic Rankine cycle with LNG cold energy exploitation and CO2 capture is introduced by Pan et al.[19]. The composite circulation system has apparent advantages in waste heat recovery and reduction of greenhouse gas emissions. Li et al.[20] proposed a novel circulatory system integrating LNG cold energy with separation of CO2, which utilizes LNG cold energy to strengthen the system heat engine performance, and the CO2 is recycled and utilized.

The cryogenic CO2 capture technology reduces the load on the refrigeration equipment and reduces the power consumption by 30%-40% compared with the traditional liquefaction process. But the liquefaction temperature of CO2 is -70℃, if the cold energy of -162℃ LNG is used directly, it still does not conform to the principle of the same grade utilization.

2.2.4 Other LNG cold energy applications. There are many other applications of LNG cold energy besides the above methods, including cold storage systems, agro-food industry, hydrocarbon separation, application in refrigerated vehicle, etc.

Except for air separation, the temperature of cold energy used in cryogenic power generation, seawater desalination processes, cold storage and so on is above -80℃, which is a serious mismatch compared with LNG gasification temperature. For air separation, not every LNG supply station requires air separation, which limits the application of LNG in air separation. Therefore, in order to achieve high efficiency and low loss utilization of LNG cold exergy, it is necessary to search for novel LNG cold energy utilization methods.

3. LNG cold energy applied to liquefied air energy storage system

The liquid air energy storage (LAES) technology is based on the traditional compressed air energy storage technology, adding a low temperature liquefied air process, cooling and liquefying the high pressure compressed air to a normal pressure for storage. It significantly increases storage density, reduces storage volume, and enables atmospheric pressure storage, which has high promotional value. The schematic of the LAES system is shown in figure 2.

The cold storage unit is the core component of the LAES system, which mainly completes
the liquefaction and rewarming process of the air. The pressure of liquefaction process is approximately equal to the outlet pressure of the last stage compressor, which is directly related to the input power of the system. The expansion pressure is equal to the outlet pressure of the first stage expander and is directly relevant to the output power of the system. Since the air has a large specific heat capacity region near the critical point, the LAES system has a strong coupling effect between air liquefaction and rewarming. From the perspective of cooling balance, the reheating expansion pressure is frequently required to be lower than the liquefaction pressure, which limits the holistic energy conversion efficiency of the system.

Fig.3. shows the process flow diagram of the LAES utilizing LNG. The combination of LAES and LNG can eliminate the coupling effect of air liquefaction and rewarming process, and achieve efficient use of LNG cold energy, at the same time, it can increase expansion pressure, improve energy storage efficiency and optimize resource allocation. To decouple the air liquefaction and rewarming process, the air temperature in the liquefaction process should be reduced to below the critical temperature (-141℃) by using LNG cold energy. The storage temperature of LNG is around -162℃. The liquid air energy storage system merely requires working in the last cold storage stage, the temperature range is about -150--180℃.

Meanwhile, in the vicinity of LNG gasification stations, a large number of industrial areas are frequently planned, resulting in tremendous electricity consumption. The demand for LNG cold energy utilization and energy storage in this area is urgent, which provides a practical basis for the combination of LNG cold energy and LAES system. Furthermore, the temperature range of air liquefaction is 80K-300K, which covers the LNG gasification temperature zone. Applying LNG cold energy to the LAES system, a good match can be achieved in the cold grade. It’s expected to be a promising new technology for LNG cold energy utilization.

4. Conclusion
In this paper, the utilization mode of LNG is reviewed. In view of the mismatch of grade in the utilization of cold energy, a novel pattern of combining LNG utilization with LAES system is put forward, and the problem that the coupling of liquefaction process and rewarming process can be removed by this way is analyzed. In order to realize the combination of LNG and LAES technology, it is necessary to do the following work: 1) In-depth analysis of the matching characteristics of LNG and LAES system, including cold energy grade, scale and other aspects. 2) Establish a thermodynamic model of the LNG cold energy utilization system based on the LAES system, and carry out the mechanism research of key influencing factors.

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