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The Utilization of LNG Cold Energy: Current Status, Challenges, and Future Prospects

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Abstract

Liquefied Natural Gas (LNG) cold energy utilization has emerged as a promising technology for enhancing energy efficiency and reducing environmental impact. This paper reviews the current status of LNG cold energy utilization, identifies key challenges, and explores future prospects. The analysis covers various applications, including power generation, air liquefaction, seawater desalination, and food freezing. The potential for further integration of LNG cold energy into multi-generation systems is also discussed, highlighting the need for comprehensive approaches to maximize efficiency and minimize emissions.

Keywords

LNG Cold Energy; Power Generation; Seawater Desalination; Air Separation.

1. Introduction

In the era of global emphasis on energy conservation and emission reduction, LNG, as a clean energy source, releases a large amount of cold energy during gasification [1]. When LNG transitions from a liquid to a gaseous state under normal temperature and pressure, this physical change is accompanied by the release of cold energy, which is a valuable but often under-exploited resource.

LNG has a low temperature of around -162℃ under normal conditions and is mainly composed of methane, along with small amounts of other components. Its extremely low temperature and specific chemical composition endow it with unique properties for various applications. For instance, in air separation, cold energy can be used to liquefy and separate oxygen, nitrogen, and other gases at a relatively lower energy cost compared to traditional methods. In food storage, it can provide a stable and ultra-low-temperature environment to maintain the freshness and quality of perishable goods.

The utilization of LNG cold energy not only improves overall energy utilization efficiency but also reduces energy waste. In a world with increasing energy demands and limited traditional energy resources, making full use of every available energy source is of utmost importance. Additionally, understanding the current situation of LNG cold energy utilization can offer valuable insights for the development and optimization of relevant industries, aligning with the global trend of sustainable development.

2. Current Status of LNG Cold Energy Utilization

2.1. Power Generation

LNG cold energy can be utilized for power generation through several technologies [2], each with its working principles, advantages, and disadvantages.

The direct expansion method is one of the common approaches. In this method, LNG is first compressed into a high-pressure liquid. Then, it is heated to a normal temperature state by passing through a heat exchanger with seawater. Subsequently, the high-pressure gas expands

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through a turbine to do external work and drive the generator to produce electricity. The principle is relatively straightforward. However, its efficiency is relatively low, with a cold energy recovery rate of only about 24%. Moreover, it mainly utilizes pressure differences, and there is room for improvement in terms of overall energy utilization. For example, in some small-scale LNG gasification stations, this method can be applied considering its simple process and relatively low requirements for equipment and system complexity. Zhang et al. [3] proposed three kinds of generation processes, which are the processes of single-stage direct expansion, single-stage recycling direct expansion, and multi-stage recycling direct expansion. Found that the generation rate of each process at the same initial and final states are calculated, are separately 19.1%, 20.1%, and 28.7%. The LNG cold energy of the multi-stage recycling process is used more efficiently, but the number of equipment and the cost of investment are also much more. He et al. [4] proposed a novel LNG cold energy cascade utilization (CES-ORC-DC-LNG) system by integrating cryogenic energy storage (CES), organic Rankine cycle (ORC), and direct cooling (DC) to recover LNG cold energy in the low, middle, and high-temperature ranges, respectively.

Rankine cycle power generation is a common method of cold energy power generation. The cold energy of LNG (Liquefied Natural Gas) is used as a low-temperature heat source. Low-boiling working fluids (such as propane, butane, etc.) are heated and vaporized through an evaporator. The resulting high-temperature and high-pressure steam drives a steam turbine to generate electricity. After doing work, the steam enters a condenser, where it is condensed into a liquid under the action of cooling water. Then, it is pumped back to the evaporator by a working fluid pump, thus completing a cycle. Liu et al. [5] proposed a comparative study for the practical power generation from LNG cold energy with the Organic Rankine Cycle (ORC) + Direct Expansion (DE) combined cycle, the ordinary ORC and the irreversible Carnot cycle, found that for applying the higher LNG vaporizing pressure, the efficiency of the combined cycle is considerably superior to the ordinary Rankine cycle. Wang et l. [6] proposed and optimized a double-Rankine cycle power generation system that incorporates heat exchange between LNG cold energy utilization and a propane-ethylene cycle working medium.

Alexander Kalina conceived the Kalina cycle [7], which was superior to the steam power cycle. Much research has been devoted to the Kalina cycle using ammonia-water mixture. In this cycle, the mixture absorbs heat from a low-temperature heat source like LNG cold energy in the evaporator. Due to the different boiling points of ammonia and water, the vapor-phase ammonia concentration increases during evaporation. The mixture then enters a separator, and the vapor-phase ammonia drives a turbine to generate electricity. After that, it is condensed in the condenser. The liquid-phase mixture is pumped back to the evaporator to complete the cycle. The advantages of the Kalina cycle for cold-energy power generation include the high-efficiency utilization of low - temperature heat sources. The temperature-glide characteristic of the ammonia-water mixture enables better matching with variable-temperature heat sources, enhancing the cycle's thermal efficiency. Also, it offers high system flexibility as the composition of the working fluid and system parameters can be adjusted. Peng S et al. [8] proposed a new solar tower thermal power system integrating the intercooled gas turbine top cycle and the Kalina bottoming cycle. The Kalina cycle is used to recover the waste heat from the gas turbine to generate power. Dezfouli, AHM, et al. [9] proposed a novel combined geothermal power plant cycle (GTPPC) that integrates the Kalina cycle, transcritical Carbon Dioxide (T-CO2) cycle, with the injections of the Liquid Natural Gas (LNG) stream, and geothermal water (GTW) stream is proposed to provide cold and hot sources of the system.

The Brayton cycle, with air or other gases as the working medium, consists of a compressor, heat exchanger, turbine, and generator. The low - low-temperature and low-pressure gas is compressed in the compressor and then cooled in the heat exchanger by absorbing cold energy. Subsequently, it expands in the turbine to generate electricity.

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The Brayton cycle has a relatively simple system structure, which is easy to design, install, and maintain. It can adapt to various low - temperature heat sources, not limited to LNG cold energy. Moreover, through parameter optimization, it can achieve relatively high power-generation efficiency. XIAHOU et al. [10] proposed based on exergy analysis. It consists of the nitrogen Brayton cycle, nature gas direct expansion, and ammonia-water Rankine cycle. In the new process, middle-low-temperature waste heat is used as a heat source, and LNG cold energy is divided into the low-temperature latent cold energy and the high-temperature sensible cold heat. The nitrogen Brayton cycle recovers low-temperature latent LNG cold energy, while the ammonia-water Rankine cycle recovers the high-temperature sensible LNG cold heat, whereby the graded use of energy can be realized. The exergy efficiency of LNG cold energy utilization can be effectively improved. MS et al. [11] proposed a cost-effective multigeneration system that integrates a supercritical carbon dioxide (sCO2) power cycle with a liquefied natural gas (LNG) regasification process. Utilizing the temperature difference between the sCO 2 cycle and the LNG thermal sink, an ammonia-water-based absorption refrigeration cycle (ARC) recovers waste heat from the sCO 2 power cycle, producing cooling. The elevated ammonia concentration at the ARC's condenser outlet is leveraged by a heat pump system for heating production.

2.2. Air Liquefaction and Separation

LNG cold energy can be effectively utilized in air liquefaction processes, which require low temperatures. This application is particularly relevant for industries that require high-purity gases, such as medical and industrial gas suppliers.

The extremely low temperature of LNG, typically around -162℃, provides a natural and valuable cold resource. When the warm air from the environment comes into contact with LNG or its cold energy recovery systems in air separation units, heat exchange occurs. Through heat exchangers and proper process designs, the heat in the air is transferred to the LNG, causing the air temperature to drop rapidly. As a result, the air can be liquefied at a relatively lower energy consumption compared to using conventional refrigeration techniques. For example, in some industrial air separation plants, the use of LNG cold energy has reduced the electricity consumption for air cooling and liquefaction by a significant percentage. This not only cuts down on operating costs but also aligns with the goals of energy conservation and emission reduction in the industrial sector.

Moreover, the integration of LNG cold energy into the air separation process can improve the overall process stability. Since LNG can provide a continuous and reliable cold source, it helps maintain a stable low-temperature environment within the air separation system, ensuring the consistent liquefaction and separation of air components with high purity. This is crucial for industries that rely on high-quality oxygen, nitrogen, and other gaseous products, such as the chemical industry, metallurgy, and electronics manufacturing.

In summary, LNG cold energy acts as a key enabler in the air separation process, offering a more efficient, simplified, and stable alternative to traditional air separation methods. TUO Hanfei et al. [12] proposed an integrated process for air separation and liquefaction of natural gas, and based on such an original idea a novel combined cycle using a nitrogen expansion refrigeration unit and producing LNG in addition to nitrogen and oxygen. Zheng et al. [13] developed an integrated air separation system and Organic Rankine Cycle (ORC) power generation system to effectively harness the inherent cold energy within LNG.

2.3. Seawater Desalination.

LNG cold energy can be effectively utilized in seawater desalination processes. By leveraging the low-temperature characteristics of LNG during regasification, the energy required for desalination can be significantly reduced. This integration not only enhances the efficiency of

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seawater desalination but also lowers the overall environmental impact. By utilizing cold energy, the energy required for cooling in multi-effect distillation (MED) or multi-stage flash (MSF) desalination plants can be significantly reduced. For example, combined systems of LNG regasification and desalination have demonstrated high energy and exergy efficiencies, making it a promising solution for sustainable water production in regions with limited freshwater resources. Eghtesad, A. et al. [14] proposed a novel low-temperature cascade power generation cycle combined with a seawater freeze desalination system to retrieve the cold energy from liquified natural gas. Cao et al. [15] proposed a novel multi-generation energy system consisting of a solar gas turbine system, multi-effect seawater desalination, an LNG cold energy recovery unit, and a double-effect absorption chiller.

2.4. Cold Storage and Refrigeration.

Another application is in cold storage and refrigeration systems [16]. LNG cold energy can be used to maintain low temperatures in warehouses and refrigeration units, reducing the need for conventional cooling systems and lowering energy consumption.

3. Challenges in LNG Cold Energy Utilization

3.1. Technological Limitations

Despite the potential benefits, the utilization of LNG cold energy faces several technological challenges. The development of efficient and cost-effective systems for cold energy recovery remains a significant hurdle. Additionally, the integration of these systems into existing LNG infrastructure requires careful planning and investment.

3.2. Economic Viability

The economic viability of LNG cold energy utilization projects is often questioned. High initial capital costs, coupled with uncertain returns on investment, can deter stakeholders from pursuing these projects [17]. Furthermore, the fluctuating prices of natural gas and electricity can impact the profitability of cold energy utilization systems.

3.3. Regulatory and Environmental Concerns

Regulatory frameworks and environmental considerations also play a crucial role in the adoption of LNG cold energy technologies [18]. Compliance with safety standards, emissions regulations, and environmental impact assessments can add complexity and cost to these projects.

4. Future Prospects

4.1. Technological Advancements

Ongoing research and development efforts are expected to yield more efficient and cost-effective technologies for LNG cold energy utilization. Innovations in materials science, heat exchangers, and thermodynamic cycles could enhance the performance of cold energy recovery systems.

4.2. Integration with Renewable Energy

The integration of LNG cold energy utilization with renewable energy sources presents a promising avenue for sustainable energy development. Hybrid systems that combine LNG cold energy with solar, wind, or geothermal energy could provide a more stable and efficient energy supply [19].

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4.3. Policy Support and Incentives

Government policies and incentives can play a pivotal role in promoting the adoption of LNG cold energy technologies. Subsidies, tax breaks, and grants for research and development can encourage investment in this field and accelerate the deployment of cold energy utilization systems.

4.4. Global Collaboration

International collaboration and knowledge {Zhang, 2020 #3} sharing can facilitate the widespread adoption of LNG cold energy utilization. By leveraging global expertise and resources, stakeholders can overcome technical and economic challenges and unlock the full potential of LNG cold energy.

5. Conclusion

The utilization of LNG cold energy offers significant opportunities to enhance energy efficiency and sustainability. While there are challenges to overcome, advancements in technology, supportive policies, and global collaboration can pave the way for a more efficient and sustainable energy future. By harnessing the cold energy stored in LNG, we can reduce energy waste, lower greenhouse gas emissions, and contribute to a more resilient energy infrastructure.

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