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Transportation of Liquefied Natural Gas (LNG) via Long-Distance Low-Temperature Pipeline and Cascade Utilization of Cold Energy

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ABSTRACT

In addition to methane, liquefied natural gas (LNG) typically contains valuable light hydrocarbons such as ethane, propane, and butane. Establishing LNG receiving stations for imported LNG can effectively alleviate regional energy supply-demand conflicts, optimize energy consumption structures, promote sustainable regional economic development, and improve ecological environments. The technology for long-distance low-temperature pipeline transportation of LNG facilitates the efficient transfer and cascading utilization of the cold energy contained in LNG, allowing for deep coupling with cold networks and natural gas pipelines, thereby promoting the integrated development of LNG, cold energy, and natural gas transportation. This paper systematically summarizes the current status of LNG long-distance low-temperature pipeline transportation technology, cold energy cascading utilization technology, pipeline regulation technology, and multi-network integration technology. It analyzes the key challenges these technologies face under new strategies and looks ahead to future development trends, aiming to provide scientific insights and directions for the application of LNG long-distance low-temperature transportation and multi-network integration in China.

KEYWORDS

LNG; Cold Energy Utilization; Pipeline Transportation and Regulation; Multi-Network Integration.

1. INTRODUCTION

Driven by the goals of "carbon peak and carbon neutrality," natural gas has gradually become one of the main energy sources in modern clean energy systems. According to data from the General Administration of Customs of China, in 2023, China's natural gas imports reached 165.56 billion cubic meters, with LNG imports via sea accounting for 98.42 billion cubic meters, or 59.4%. As an important channel for ensuring national energy security, sea-based LNG will continue to be a major import form for the foreseeable future.

Currently, LNG in China is typically regasified at coastal receiving stations using seawater heat exchange and then transported through long-distance natural gas pipelines to inland cities. However, this process significantly impacts marine ecosystems and does not fully utilize the cold energy contained in LNG. Calculations show that the calorific value of natural gas is approximately 4.62×10^8 MJ/ton, with cold energy from LNG accounting for about 3.5% of this value. In 2023, the cold energy contained in imported LNG exceeded 1.15×10^{11} MJ, theoretically allowing for electricity generation of up to 1.68×10^{10} kWh. However, the cold energy utilization rate is less than 10%, far below Japan's and South Korea's rates of 20% to 30%. This discrepancy arises from the wide geographical distribution and varying scales of cold energy demand in China, leading to significant spatial and temporal misalignment between LNG regasification and cold energy utilization.

Therefore, developing LNG long-distance low-temperature pipeline (LNG pipeline) transportation technology is crucial. Compared to gaseous transportation, liquid transportation has higher energy density and lower transportation costs, enabling large-scale, long-distance transport of LNG while distributing cold energy to demand points along the route for full utilization. Additionally, the LNG pipeline system can deeply integrate with urban cold networks and natural gas pipelines, promoting significant advancements in integrated energy transportation.

However, low-temperature transportation poses challenges for pipeline insulation and mechanical stability. Currently, there are no successful international cases of long-distance low-temperature pipeline transportation, with only kilometer-scale applications observed in a few scenarios such as coastal receiving stations. The cold energy quality of LNG along the pipeline gradually decreases, necessitating regulation to meet the differing demands for natural gas and cold energy at various stations, while also achieving cascading utilization of cold energy, which involves complex coupling issues.

In summary, this paper analyzes the development status and key challenges of LNG long-distance low-temperature pipeline transportation technology, cold energy cascading utilization technology, pipeline regulation technology, and integration with multi-network systems. It also summarizes development trends, aiming to provide relevant recommendations for the advancement of LNG long-distance low-temperature pipeline transportation and cold energy utilization technology in China.

2. CURRENT DEVELOPMENT STATUS AT HOME AND ABROAD

2.1. LNG Long-Distance Low-Temperature Pipeline Transport Technology

LNG long-distance low-temperature pipeline transport technology has made significant progress both domestically and internationally, becoming an important means of ensuring energy security. In particular, in the United States, Australia, and Europe, LNG pipeline technology is relatively mature, employing advanced monitoring and automation control systems to improve transport efficiency and safety. For example, the U.S. has utilized efficient real-time monitoring and forecasting technologies in LNG export projects, enabling flexible scheduling and optimal utilization. Meanwhile, Australia has achieved breakthroughs in cold energy management and flow control, effectively enhancing transport efficiency.

In China, the construction of LNG pipelines has rapidly developed in recent years alongside the advancement of clean energy policies. Relevant enterprises are actively researching intelligent control systems to achieve real-time monitoring and optimization of the transport process. Additionally, national investment in infrastructure and support for technological innovation has created a favorable environment for industry development. However, despite progress in technology both domestically and internationally, challenges remain regarding pipeline compatibility and technological integration. In the future, with the application of emerging technologies, the transport technology of LNG long-distance low-temperature pipelines is expected to further improve, promoting global energy security and sustainable development.

2.2. LNG Long-Distance Low-Temperature Pipeline Cold Energy Cascading Utilization Technology.

The technology for cold energy cascading utilization in long-distance low-temperature LNG pipelines has rapidly developed both domestically and internationally, aiming to improve energy efficiency and reduce environmental impact. In regions such as Europe and North America, effective recovery and utilization of cold energy have already been achieved. For example, many LNG-receiving terminals have adopted cold energy recovery systems that leverage the low-temperature characteristics of LNG for power generation or cooling, enhancing overall energy utilization rates. Additionally, Western European countries have conducted a series of demonstration projects focusing on cold energy cascading utilization across various sectors, including industrial cooling and heating.

In China, as the LNG industry grows, cold energy cascading utilization technology has begun to receive increased attention. Some large LNG receiving stations and distribution centers are exploring applications for cold energy recovery, implementing technological upgrades to recycle cold energy, and promoting the collaborative development of related industry chains. However, due to factors like technology maturity and economic viability, the cascading utilization of cold energy is still in its early stages domestically, facing challenges related to technology integration and cost control.

Looking ahead, with ongoing technological advancements and supportive policies, the cold energy cascading utilization technology for long-distance low-temperature LNG pipelines is expected to see broader applications, contributing to energy structure optimization and environmental protection.

2.3. Development Status of LNG Long-Distance Low-Temperature Pipeline Control Technology

The development of LNG long-distance low-temperature pipeline control technology has garnered increasing attention both domestically and internationally, aiming for efficient and safe transportation and utilization of liquefied natural gas (LNG). In regions like Europe and North America, a range of mature pipeline control systems has been established. These systems use advanced monitoring and control technologies to dynamically adjust flow rates and temperatures within the pipelines, ensuring the stability and safety of LNG during transit. For example, many countries employ SCADA (Supervisory Control and Data Acquisition) systems for centralized monitoring and automated management, enhancing operational efficiency.

In China, the rapid growth of the LNG market has also spurred the swift development of long-distance low-temperature pipeline control technology. Many LNG projects have integrated intelligent control systems that utilize big data analysis and artificial intelligence to optimize pipeline operating parameters, improving responsiveness to supply and demand fluctuations. However, challenges remain, such as the lack of unified technical standards and regulations, which hinder real-time data integration and response capabilities in certain regions.

Looking ahead, with ongoing technological advancements and policy support, LNG long-distance low-temperature pipeline control technology is expected to see broader applications, enhancing overall energy utilization efficiency and ensuring the safety and reliability of LNG transport. This will provide important support for the global energy transition and sustainable development.

2.4. The integration technology of LNG long-distance low-temperature pipelines with multi-network systems

The integration technology of LNG long-distance low-temperature pipelines with multi-network systems is gradually becoming an important direction in energy management. Internationally, European and American countries have already initiated various research projects on energy network integration, particularly focusing on the interconnection of liquefied natural gas with electrical and thermal networks. For instance, some countries have implemented Integrated Energy Systems (IES) models that allow for the coordinated scheduling of LNG with renewable energy sources, enhancing energy utilization efficiency and reducing carbon emissions.

In China, the rapid development of the LNG market has driven advancements in related technologies. The increasing demand for multi-energy complementarity and flexible dispatch has led many projects to explore the deep integration of LNG with electricity and heating networks. In some regions, real-time information sharing between LNG pipelines and electrical grids has been achieved, using intelligent management systems to improve overall energy utilization efficiency and safety. Additionally, policy support and technological innovation have provided strong backing for the promotion of integration technologies.

However, challenges remain, such as the lack of unified technical standards and the complexity of system integration. Looking ahead, with the maturation of digital technologies and policy incentives, the integration of LNG long-distance low-temperature pipelines with multi-network systems is expected to make significant breakthroughs, laying the foundation for a flexible, efficient, and green energy supply system.

3. KEY CHALLENGES

3.1. Efficient Utilization of Cold Energy in Long-Distance Low-Temperature Pipeline Transport

The long-distance low-temperature pipeline transport of LNG raises two new issues for the efficient utilization of cold energy. First, how to achieve accurate prediction of cold energy distribution parameters along the pipeline. During long-distance transport, LNG experiences pressure losses and thermal dissipation, causing variations in key thermodynamic parameters such as temperature and pressure along the route. Currently, there is a lack of effective research methods to accurately describe and predict the complex relationships between cold energy, temperature, pressure, and other state parameters during LNG pipeline transport. Second, how to meet the cold energy demands of urban areas over a broader spatial range. Traditional cold energy cascading utilization systems primarily serve industrial processes near LNG receiving stations. However, with the development of new cold energy utilization methods, there is a growing need to address the cooling requirements of urban areas, such as cold storage facilities and residential cooling. Therefore, new cold energy utilization methods must possess greater flexibility and adaptability to effectively respond to demand fluctuations, reduce energy waste, and lessen environmental impacts.

3.2. Regulation of Pipeline Transport Systems under Demand Fluctuations

Fluctuations in cooling and gas demand can easily lead to insufficient or excessive cold energy supply, posing challenges for regulating the pipeline transport system. The LNG regasification process primarily generates two types of energy: cold energy and natural gas. However, the demand for cooling and gas typically exhibits significant seasonal variations and daily fluctuations. In terms of seasonal variation, cooling demand increases in summer while gas demand decreases, and vice versa in winter. Daily fluctuations show higher cooling demand during the day, usually peaking in the afternoon due to increased air conditioning and industrial cooling system usage, while gas demand peaks in the morning or evening when residents are home for heating and cooking. Thus, it is necessary to study the complex and interacting physical, chemical, and thermodynamic processes involved in the coupling of LNG pipelines with urban cold networks and natural gas pipelines, achieving precise system simulation. Through the collaborative optimization and regulation of LNG pipelines, urban cold networks, and natural gas networks, a dynamic balance of supply and demand across different spatial and temporal scales can be achieved, thereby enhancing the efficiency of integrated energy delivery.

3.3. Multi-Network System Planning Integrating LNG Long-Distance Low-Temperature Pipelines

The LNG long-distance low-temperature pipeline can be coupled with urban cold networks and natural gas pipelines to improve the efficiency of integrated energy delivery. However, multi-network systems encompass various energy forms and involve complex coupling relationships among multiple energy demands. Therefore, collaborative planning of multi-network systems requires an understanding of the demand characteristics of different types of users over long time scales. This involves describing the types, sizes, distributions, and trends of demand from multiple dimensions to accurately represent user energy needs. The integration of LNG pipelines introduces additional uncertainties. While the number of uncertainty factors considered in existing research is gradually increasing, the diversity of user types in multi-network systems integrating LNG pipelines means that the categories, time scales, and spatial scales of uncertainty factors vary significantly. Further research into collaborative planning methods for multi-network systems under various uncertainty factors is necessary. Additionally, there is competition among different entities within the multi-network system regarding various energy forms and transportation methods. Different network entities (such as individuals and organizations) make decisions through game theory to maximize their own interests, leading to a state of equilibrium. The multi-network system transporting LNG, high-quality cold energy, and natural gas involves competitive and cooperative behaviors among producers, consumers, and transporters of various media, making the representation of game behaviors in multi-network systems even more complex.

4. DEVELOPMENT TRENDS AND RECOMMENDATIONS

As the global energy structure shifts and the demand for sustainable development increases, the technological advancement of liquefied natural gas (LNG) long-distance low-temperature pipeline transportation and the cascade utilization of cold energy is progressing towards greater efficiency and intelligence. LNG, as a clean energy source, offers advantages such as low carbon emissions and reduced pollution, making it increasingly utilized in power generation, industry, and transportation sectors. In the future, with the continuous expansion of the LNG market, the construction of long-distance low-temperature pipelines will face heightened demand. In this context, enhancing the safety and efficiency of LNG transportation becomes crucial.

Firstly, the application of intelligent technologies will be key, particularly the integration of IoT, artificial intelligence, and other advanced technologies. This will enable real-time monitoring of pipeline operations, optimize flow scheduling, and improve the ability to respond to emergencies. Meanwhile, the concept of cold energy cascade utilization will emerge as a significant highlight. By recovering and utilizing the low-temperature cold energy during the transportation and usage of LNG, the overall energy utilization efficiency can be significantly improved. For instance, utilizing LNG's cold energy for power generation, heating, or cold chain logistics can not only reduce energy waste but also lower operating costs, thereby enhancing economic benefits.

However, several key challenges must be addressed in this process. The lack of technical standards and regulations may hinder effective connections and collaboration between different systems, making the establishment of unified technical standards essential. Furthermore, the promotion of cold energy cascade utilization relies heavily on supportive policies, including financial subsidies and tax incentives, to encourage active participation from enterprises. Additionally, controlling investment costs will be a vital factor for the successful implementation of cold energy utilization. Both government and industry must work together to drive technological innovation and reduce costs, ensuring the economic feasibility of cold energy utilization.

In summary, the development prospects for LNG long-distance low-temperature pipeline transportation and cold energy cascade utilization are promising. Achieving more efficient and greener energy utilization will require collaborative efforts across multiple dimensions, including intelligent technology, policy support, and standardization initiatives, ultimately contributing to global energy transformation and sustainable development.

Furthermore, future LNG pipeline transport systems need to achieve breakthroughs in control technologies and multi-network planning to address the temporal and spatial mismatches between

LNG supply and demand. This challenge necessitates the construction of an intelligent pipeline system capable of real-time monitoring and adjustment of the transport process, ensuring flexible responses during different demand peaks. Policy support is also crucial in this process, with the government encouraged to formulate relevant incentives, including financial subsidies and tax benefits, to motivate companies to actively participate in the development and application of LNG cold energy. Additionally, collaboration among industry stakeholders must be strengthened to promote the establishment and implementation of standards, facilitating effective connections and coordination between different systems. Controlling investment costs is key to achieving the cascade utilization of LNG cold energy, requiring joint efforts from both the government and enterprises to lower costs through technological innovation and large-scale application, thereby enhancing economic feasibility. With these multifaceted efforts, we can expect that China's comprehensive utilization rate and cold utilization rate of LNG will reach the forefront globally, contributing significantly to the global energy transition and sustainable development. As technology continues to advance and policies are effectively implemented, long-distance low-temperature LNG pipeline transport will evolve from merely being a means of energy transport to an essential component driving economic and environmental sustainability.

5. CONCLUSION

Cold energy, as a form of energy, has immense development potential, similar to thermal energy, electrical energy, and nuclear energy. China has become the largest LNG importer globally, and the market for LNG cold energy is substantial, making its utilization essential. Although there are currently no international precedents for long-distance low-temperature LNG pipeline transportation, China has made progress in technologies for the cascade utilization of LNG cold energy and pipeline transportation and control. Moving forward, it is necessary to develop new insulation structures and efficient heat exchange equipment and to further enhance LNG pipeline system control and multi-network planning technologies. This will address the temporal and spatial mismatches between LNG supply and demand, enable high-quality cascade utilization of LNG cold energy, and promote China's comprehensive utilization rate and cold utilization rate of LNG to be among the world leaders.

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