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Simulation and Analysis of LNG Cold Energy Power Generation Technology

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Abstract: LNG cold energy power generation technology, as an important approach to cascade energy utilization, recovers the substantial amount of cold energy released during the regasification of liquefied natural gas (LNG) to generate electricity, demonstrating significant potential for improving energy efficiency. Based on thermodynamic principles and system engineering methods, this paper establishes a mathematical model of an LNG cold energy power generation system. It focuses on analyzing the performance characteristics of different cycle configurations, including the Rankine cycle (RC), Organic Rankine cycle (ORC), and mixed working fluid cycle. The influence mechanisms of working fluid selection and system parameter optimization on power generation efficiency are systematically investigated. Through simulation calculations and sensitivity analysis, the relationships between key operating parameters—such as evaporation temperature, condensation temperature, and working fluid mass flow rate—and system output power are revealed. The results provide a theoretical foundation and technical reference for the design optimization and performance enhancement of LNG cold energy power generation systems.

Keywords: LNG cold energy; power generation technology; system simulation; cycle performance; working fluid optimization

Introduction

As an efficient and clean energy source, LNG releases a large amount of high-quality cold energy (approximately 830 kJ/kg) during its regasification process. Direct discharge of this cold energy leads to energy waste and additional environmental burden. LNG cold energy power generation technology converts this cold energy into electricity through thermodynamic cycles, thereby enabling cascade energy utilization and representing a research hotspot in the energy field. With the continuous growth of global LNG trade, the economic value and environmental significance of cold energy recovery have become increasingly prominent. This study focuses on the simulation and analysis of LNG cold energy power generation systems. By establishing a comprehensive mathematical model and comparing the performance differences among various cycle configurations, the key operating parameters are optimized to enhance cold energy utilization efficiency. The research provides systematic theoretical support for improving system performance and holds important

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theoretical and practical value in promoting the low-carbon development of the LNG industrial chain.

1. Basic Principles and System Composition of LNG Cold Energy Power Generation Technology

LNG cold energy power generation technology is grounded in the Second Law of Thermodynamics and achieves energy conversion through the cyclic process of a working fluid between a low-temperature heat source (LNG cold energy) and a high-temperature heat source (ambient heat source). The core principle lies in utilizing the low-temperature cold energy released during LNG regasification as the cold sink of the thermodynamic cycle. The working fluid absorbs ambient heat in the evaporator and vaporizes; the generated high-pressure vapor then drives a turbine to expand and perform work, which in turn powers a generator to produce electricity. After expansion, the exhaust vapor is cooled and condensed by LNG into liquid form, thereby completing the cycle. The system mainly consists of a cold energy recovery heat exchanger, a working fluid circulation system (including evaporator, turbine, condenser, and working fluid pump), power generation equipment, and auxiliary control systems. The cold energy recovery heat exchanger is the key component for energy conversion, as it must ensure efficient heat transfer between LNG and the circulating working fluid. The thermodynamic properties of the working fluid directly affect cycle efficiency; thus, it should possess favorable low-temperature fluidity, high volumetric refrigeration capacity, and strong chemical stability. System design must balance cold energy utilization efficiency with equipment investment cost, achieving optimal overall performance through appropriate matching of cycle parameters [1].

2. Cycle Structures and Performance Comparison of LNG Cold Energy Power Generation Systems

2.1 Rankine Cycle (RC)

The Rankine Cycle (RC) is the earliest conventional cycle applied in LNG cold energy power generation, typically using inorganic substances such as water or ammonia as the working fluid. Its thermodynamic process consists of four stages: isobaric heat absorption and vaporization in the evaporator, adiabatic expansion and work output in the turbine, isobaric heat rejection and condensation in the condenser, and adiabatic compression by the working fluid pump. The advantages of this cycle include low working fluid cost and mature technology, making it suitable for large-scale cold energy recovery applications. However, due to the relatively high freezing point of water (0°C), it cannot directly utilize the deep cryogenic energy of LNG (−162°C). Therefore, multi-stage heat exchange or intermediate media are required for indirect recovery, which limits cold energy utilization efficiency. Studies have shown that when water is used as the working fluid, the actual efficiency of the Rankine cycle in LNG cold energy power generation is typically below 10%. Moreover, the system tends to have a large physical footprint, which restricts its application in small-scale systems.

2.2 Organic Rankine Cycle (ORC)

The Organic Rankine Cycle (ORC) employs low-boiling-point organic fluids (such as propane, R290, and R600a) as working media, which can directly match the cryogenic characteristics of LNG and overcome the low-temperature limitations of the conventional Rankine cycle. Organic working fluids can vaporize at relatively low temperatures, enabling more effective recovery of LNG cold energy. As a result, system efficiency can be improved by approximately 30%–50% compared with traditional cycles. Key considerations in ORC system design include the thermal stability, environmental friendliness (ODP = 0 and low GWP), and safety (non-flammability and non-toxicity) of the working fluid. Currently, alkanes (e.g., n-pentane) and alternative refrigerants (e.g., R134a) are commonly used. Among them, propane is widely applied in medium- and small-scale LNG cold energy power generation systems due to its favorable thermal matching characteristics and relatively high cycle efficiency. The main challenges of ORC systems lie in the risk of working fluid leakage and the complexity of turbine design. Enhancing operational reliability requires optimization of thermophysical properties and improved system integration [2].

2.3 Mixed Working Fluid Cycle

The Mixed Working Fluid Cycle utilizes a combination of two or more working fluids to exploit differences

in boiling points, enabling non-azeotropic phase change and improving temperature matching during the thermodynamic process. Compared with pure working fluids, mixed fluids exhibit temperature glide during condensation and evaporation, which reduces irreversibility in heat exchange and enhances overall thermodynamic efficiency. For example, a mixture of CO_2 and propane can maintain high volumetric refrigeration capacity over a wide temperature range, making it suitable for variable-temperature cold energy recovery during LNG regasification. Optimization of the mixture ratio is the core of system design and requires phase equilibrium calculations and cycle simulations to determine the optimal component proportions. Additionally, factors such as mutual solubility, chemical stability, and environmental performance must be considered. At present, the theoretical efficiency of mixed working fluid cycles can reach 15%–20%. However, practical applications face challenges such as component separation and composition variation after leakage, which limit large-scale implementation.

2.4 Combined Cycle Systems

Combined cycle systems integrate multiple cycle configurations (such as ORC coupled with power cycles, or joint utilization of cold energy and waste heat) to achieve cascade recovery of LNG cold energy. Typical designs include the "ORC–gas turbine combined cycle" and the "multi-stage ORC cascade cycle." In the former configuration, LNG cold energy is used as an inlet air cooling medium for the gas turbine, while an ORC simultaneously recovers the cold energy released during LNG regasification, resulting in cumulative power output. In the latter, high-, medium-, and low-temperature ORC stages are arranged in series to match different temperature segments of the LNG regasification process, thereby improving overall cold energy utilization efficiency. The advantage of combined cycle systems lies in their ability to fully exploit energy at different temperature grades, achieving overall efficiency improvements of 20%–40% compared with single-cycle systems. However, their structural complexity, higher control requirements, and significant initial investment make them more suitable for large-scale LNG receiving terminals engaged in comprehensive cold energy utilization projects [3].

3. Simulation Methods and Performance Analysis of LNG Cold Energy Power Generation Systems

3.1 Theoretical Foundation of System Modeling

The simulation of LNG cold energy power generation systems is based on the First Law and Second Law of Thermodynamics. Mathematical models of individual components are established to describe the energy conversion processes within the system. The evaporator model adopts the ε–NTU method to calculate heat transfer rates, taking into account the flow states (single-phase/two-phase) of both the working fluid and LNG, as well as variations in heat transfer coefficients. The turbine model is based on an adiabatic expansion process, with actual work output corrected using isentropic efficiency. The condenser model must consider the variable-temperature characteristics of LNG during regasification; temperature matching is achieved through segmented calculations. The working fluid pump model describes energy consumption using isentropic compression efficiency. The overall system model is constructed by coupling the mass conservation, energy conservation, and momentum conservation equations. An iterative algorithm is employed to solve the cycle parameters. To improve simulation accuracy, a thermophysical property calculation module is introduced. The thermodynamic properties of the working fluid—such as enthalpy, entropy, and density under different operating conditions—are calculated using the REFPROP database or equations of state (e.g., the Peng–Robinson (PR) equation and the Soave–Redlich–Kwong (SRK) equation). Simulation platforms such as MATLAB/Simulink, Aspen HYSYS, or Engineering Equation Solver (EES) can be used. Modular modeling techniques enable both steady-state and dynamic performance analyses of the system.

3.2 Working Fluid Selection and Performance Impact Analysis

The thermodynamic properties of the working fluid are the core determinants of cycle efficiency. The working fluid should meet the following requirements: low boiling point (to match LNG temperature levels), high latent heat of vaporization (per unit mass), high volumetric refrigeration capacity, good thermal stability, and chemical inertness. Common working fluids can be classified into three categories: hydrocarbons (e.g.,

propane, n-butane), fluorinated refrigerants (e.g., R123, R134a), and inorganic compounds (e.g., CO_2, NH_3). Simulation-based comparisons of different working fluids indicate that propane achieves relatively high efficiency (η = 12%–15%) in the temperature range of −80°C to −120°C, making it suitable for medium- and low-temperature cold energy recovery. R134a performs better in the temperature range of −40°C to −60°C; however, its global warming potential (GWP) is relatively high. The transcritical CO_2 cycle can achieve deep cryogenic energy recovery under high-pressure conditions (7–10 MPa), with efficiencies reaching up to 18%. Nevertheless, such systems require high pressure resistance, increasing equipment design complexity and cost. Environmental performance indicators, including ozone depletion potential (ODP) and global warming potential (GWP), must comply with international environmental regulations such as the Montreal Protocol. Future development trends favor natural working fluids (e.g., propane and isobutane) and low-GWP alternatives (e.g., R1234yf). Furthermore, safety considerations—including flammability and toxicity—must be evaluated in accordance with application scenarios. In densely populated areas, non-flammable working fluids should be prioritized [4].

3.3 Sensitivity Analysis of Key Parameters

The influence of operating parameters on power generation performance is quantified through sensitivity analysis, focusing primarily on evaporation temperature, condensation temperature, working fluid mass flow rate, and LNG regasification pressure. Simulation results indicate that for every 10°C increase in evaporation temperature, cycle efficiency improves by approximately 3%–5%. However, evaporation temperature is constrained by the ambient heat source temperature (typically 25°C–35°C). Therefore, enhanced heat transfer techniques—such as the use of finned-tube heat exchangers—are required to elevate the evaporation temperature effectively. The condensation temperature is determined by the LNG temperature. Lowering the condensation temperature increases the enthalpy difference of the working fluid, thereby enhancing power output. Nevertheless, reducing condensation temperature requires a corresponding increase in LNG regasification pressure. For example, when the LNG pressure increases from 0.5 MPa to 1.5 MPa, the condensation temperature decreases by approximately 20°C. Thus, a balance must be achieved between cold energy recovery efficiency and LNG delivery pressure requirements. The working fluid mass flow rate exhibits a linear positive correlation with turbine output power. However, excessive flow rates lead to increased pump work consumption, resulting in the existence of an optimal flow rate—generally 1.1–1.3 times the design value. The LNG regasification rate affects the dynamic response of the system. When fluctuations exceed ±10%, buffer tanks or variable-frequency control strategies are required to maintain operational stability.

Furthermore, the temperature difference in the heat exchanger is a key factor influencing irreversible losses. Reducing the heat transfer temperature difference (e.g., from 15°C to 5°C) can improve system efficiency by 8%–12%. However, this requires a larger heat transfer area, leading to higher equipment costs. Therefore, optimal design parameters must be determined through comprehensive techno-economic analysis.

3.4 System Optimization Strategies and Approaches for Energy Efficiency Improvement

Optimization of LNG cold energy power generation systems should consider thermodynamic performance, economic feasibility, and safety in a multi-objective framework, employing system integration and parameter matching methodologies.

From a thermodynamic optimization perspective, reducing irreversibility through working fluid combinations and cycle modifications is a crucial approach. For example, the adoption of mixed working fluids, regenerative cycles, and reheating cycles can improve performance. A regenerative ORC can increase efficiency by 5%–8%; however, it also increases system complexity. Parameter optimization is typically conducted using intelligent algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), with objective functions defined as maximizing net output power or minimizing the levelized cost of electricity (LCOE). Economic optimization requires comprehensive consideration of capital investment—including the costs of heat exchangers, turbines, and working fluid pumps—as well as operation and maintenance expenses and the economic value of recovered cold energy. Project feasibility is generally evaluated using indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR). Currently,

the levelized cost of electricity for LNG cold energy power generation is approximately 0.3–0.5 RMB/kWh, demonstrating strong competitiveness compared with conventional coal-fired power generation. Technological innovation also plays a critical role in system optimization. The application of microchannel heat exchangers can reduce equipment volume by more than 30% while enhancing heat transfer efficiency. Magnetic bearing turbine technology can reduce mechanical losses and improve system reliability. Digital twin technology enables dynamic optimization throughout the entire system life cycle.

In addition, cascade utilization of cold energy—integrating power generation with refrigeration, air separation, and other applications—can significantly enhance overall energy utilization efficiency. For instance, utilizing residual heat to drive absorption refrigeration while generating electricity can increase overall cold energy utilization efficiency to over 60%. Through the above comprehensive optimization strategies and energy efficiency enhancement approaches, the performance improvement and sustainable development of LNG cold energy power generation systems can be effectively promoted [5].

Conclusion

LNG cold energy power generation technology achieves energy value enhancement through the efficient recovery of low-temperature cold energy and represents an important pathway for promoting the transformation of the energy structure. Through systematic simulation and performance analysis, this study has revealed the characteristic differences among various cycle configurations and clarified the influence mechanisms of working fluid selection and parameter optimization on system efficiency. The results demonstrate that the Organic Rankine Cycle (ORC) and mixed working fluid cycles exhibit significant advantages in terms of cold energy utilization efficiency. By integrating working fluid optimization with advanced system integration technologies, power generation efficiency can be increased to over 20%. Future development should focus on the research and development of low-GWP working fluids, the design of high-efficiency heat exchange equipment, and the integration of multi-energy supply systems. Meanwhile, digital simulation and intelligent control technologies should be employed to enhance system operational stability and economic performance. With the large-scale development of the LNG industry, cold energy power generation technology will play an increasingly important role in cascade energy utilization and carbon emission reduction, providing strong technical support for the construction of a green and low-carbon energy system.

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