

Overall Design and Performance Evaluation of Cascade Cold Energy Utilization and Thermoelectric Power Generation System for LNG-Powered Ships

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Abstract. Against the background of green and low-carbon transformation of the shipping industry, LNG has become a mainstream clean energy for ships. However, a large amount of high-quality cold energy released during LNG gasification is seriously wasted, and the traditional gasification heating mode causes dual energy loss and marine cold pollution. To solve these problems, this paper designs a novel LNG cold energy comprehensive utilization system integrating thermoelectric power generation and adaptive cascade utilization technology. Taking ship exhaust gas as the heat source and low-temperature LNG as the cold source, the system adopts stacked high and low-temperature thermoelectric chips to realize stable power generation under ultra-large temperature difference, and completes LNG preheating. Adopting the R600/R11 dual refrigerant circulation system and intelligent feedback control, it accurately distributes cold energy for ship air conditioning, cold storage, seawater desalination and air compressor cooling. The experimental results show that the system's comprehensive cold energy utilization rate exceeds 90%. The thermoelectric generation unit can save 8.84 tons of ship fuel annually with a payback period of 1.13 years. This system features high safety and strong working condition adaptability, providing a reliable technical scheme for efficient utilization of ship LNG cold energy.

Keywords: LNG-powered ship, cascade utilization of cold energy, thermoelectric power generation, dual refrigerant cycle, adaptive control, energy saving and consumption reduction

1. Introduction

1.1. Research background and significance

With the transformation of the global energy structure and increasingly strict requirements for environmental protection, liquefied natural gas, as a clean, efficient and economical energy source, has been more and more widely used in the shipping industry [1, 2]. Compared with traditional fuel-powered ships, LNG-powered ships can significantly reduce emissions of sulfur oxides, nitrogen oxides and particulate matter [3], and thus have become an important development direction of the

current shipbuilding industry. However, before use, LNG needs to be gasified from a liquid state at -162°C to room temperature, and a large amount of cold energy is released during this process. The cold energy released per kilogram of LNG gasification is as high as about 830 kJ [4]. At present, most LNG-powered ships rely on diesel engine jacket cooling water or boiler steam to provide the heat required for gasification, which not only wastes high-quality cold energy but also consumes additional heat energy, resulting in double waste of energy [5, 6]. Meanwhile, the direct discharge of LNG cold energy will also cause "cold pollution" to the marine ecological environment and affect the living conditions of organisms in local waters [7]. On the other hand, ships have continuous demand for cold energy during operation, such as air conditioning refrigeration, cold storage preservation, interstage cooling of air compressors, and seawater desalination. If the cold energy released during LNG gasification can be used to meet these demands [8], it can not only replace the traditional compression refrigeration method and greatly save electric energy, but also improve the comprehensive energy utilization efficiency of ships [9, 10]. As a means of directly converting temperature difference into electric energy, thermoelectric power generation technology has the advantages of simple structure, no moving parts, no noise and long service life, and is especially suitable for use in the vibration environment of ships [11]. Therefore, designing a set of LNG cold energy utilization system for LNG-powered ships based on thermoelectric power generation and cascade utilization of cold energy has important energy-saving and environmental protection significance and remarkable economic benefits.

1.2. Main work of this paper

Aiming at the problem of cold energy waste in LNG-powered ships, this paper designs a cold energy utilization system. Taking LNG as the cold source and exhaust gas from the exhaust gas boiler as the heat source, the system realizes thermoelectric power generation through the stacked arrangement of high-temperature and low-temperature thermoelectric chips, and at the same time raises the temperature of LNG before it enters the main refrigerant circulation system. The system adopts a dual-cycle architecture with main refrigerant (R600) and auxiliary refrigerant (R11), and accurately distributes cold energy to air conditioners, cold storages, seawater desalination devices and air compressors through intelligent feedback control. This paper presents the overall design scheme of the system, expounds the core principles of thermoelectric power generation technology and adaptive cascade utilization technology, carries out theoretical calculation and supply-demand balance analysis on LNG cold energy supply and cold demand of each cold-using device, and finally evaluates the economic benefits of the system. This research aims to provide a feasible technical scheme for the cold energy utilization of LNG-powered ships and fill the technical gap in related fields in China.

2. Overall system design

The system consists of three parts: thermoelectric power generation device, main refrigerant circulation system and auxiliary refrigerant circulation system, realizing the integrated design of "power generation-transmission-cascade utilization" of LNG cold energy. The overall structure of the system is shown in Figure 1.

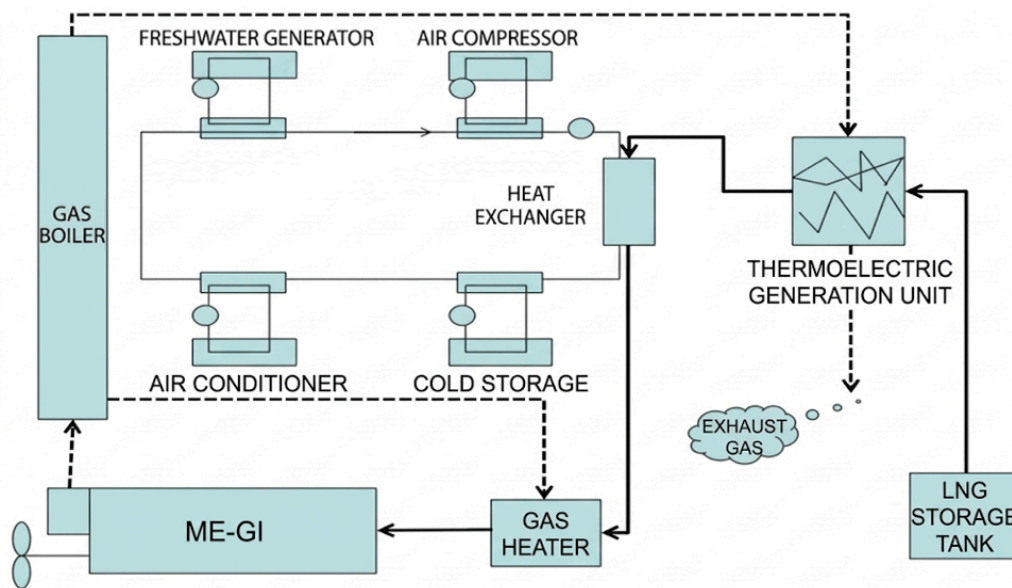


Figure 1. Overall structure diagram of LNG cold energy utilization system for LNG-powered ships

The working process of the system is divided into two stages of cold energy utilization. The first stage is thermoelectric power generation: taking liquefied natural gas (about -162°C) provided by the LNG storage tank as the cold source and high-temperature exhaust gas (about 250°C) discharged from the exhaust gas boiler as the heat source, the temperature difference is converted into electric energy through the thermoelectric power generation device, and at the same time the temperature of LNG is raised to about -70°C to prepare for subsequent utilization. After power generation, LNG enters the ME-GI main engine for combustion through a gas heater. The second stage is cascade distribution of cold energy: the gasified LNG exchanges heat with the main refrigerant in the main heat exchanger, transferring cold energy to the main refrigerant; the main refrigerant transports cold energy to each auxiliary heat exchanger through pipelines, conducts secondary heat exchange with each auxiliary refrigerant, and finally transfers cold energy to air conditioners, cold storages, seawater desalination devices and air compressors.

Aiming at the temperature difference as high as 412°C between LNG and exhaust gas, the device adopts a solution of stacked arrangement of high-temperature and low-temperature thermoelectric chips, so that both types of chips operate within their respective allowable working temperature ranges, which not only realizes efficient power generation but also completes the first-stage utilization of cold energy. According to theoretical calculation, the output power of a set of stacked units is about 4.9 W, and the voltage and power requirements of different electrical equipment can be met through series-parallel combination.

The refrigerant circulation system adopts a main-auxiliary dual-cycle architecture. The main refrigerant is R600, which absorbs LNG cold energy in the main heat exchanger and then centrally transports the cold energy to each auxiliary heat exchanger; the auxiliary refrigerant is R11, which conducts secondary heat exchange with the main refrigerant in the auxiliary heat exchanger and transfers cold energy to each cold-using device. Each auxiliary system is equipped with a temperature sensor and an auxiliary flow control valve, forming an intelligent feedback control system: when the sensor detects that the actual temperature deviates from the set value, the signal processing unit automatically adjusts the opening of the auxiliary flow control valve to realize adaptive and accurate temperature control.

The thermoelectric power generation device not only generates electric energy but also raises the temperature of LNG, reducing the heat required for subsequent gasification; the refrigerant circulation system accurately distributes cold energy to multiple cold-using devices, avoiding energy waste caused by single utilization; the system has no moving parts, adapts to the vibration environment of ships, and has low maintenance cost. Through the cooperative work of the above three parts, the system realizes efficient cascade utilization of LNG cold energy, and improves the economic benefits of ships while saving energy and reducing emissions.

3. Key technologies and design

3.1. Thermoelectric power generation technology

Thermoelectric power generation technology is based on the Seebeck effect: when there is a temperature difference in a circuit composed of two different semiconductor materials, carriers in the materials diffuse from the hot end to the cold end, thereby generating electromotive force and directly converting thermal energy into electric energy. This technology has the advantages of simple structure, no moving parts, no noise and long service life, and is especially suitable for applications with high requirements for reliability and maintainability such as ships.

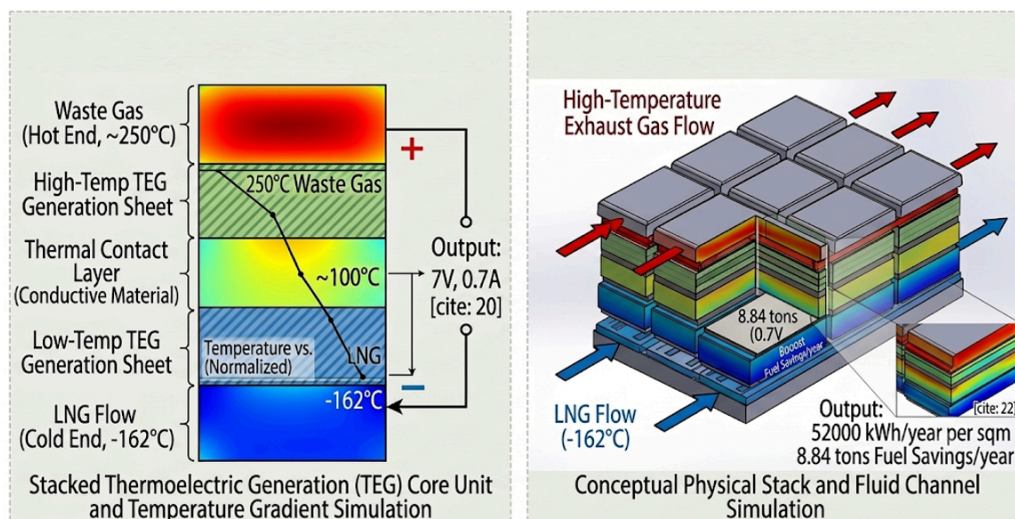


Figure 2. Schematic diagram of stacked arrangement of thermoelectric chips

This system makes full use of the huge temperature difference between the liquefied natural gas (about -162°C) provided by the LNG storage tank and the high-temperature exhaust gas (about 250°C) discharged from the exhaust gas boiler, with the temperature difference between the cold and heat sources as high as 412°C . However, common thermoelectric chips can hardly withstand such a large temperature difference directly: high-temperature chips cannot work normally at -162°C , and low-temperature chips cannot withstand the high temperature of 250°C . To solve this problem, this paper proposes a solution of stacked arrangement of high-temperature and low-temperature thermoelectric chips. The hot surface of the high-temperature chip contacts the 250°C exhaust gas, and its cold surface temperature is controlled at about 100°C ; the cold surface of the low-temperature chip contacts -162°C LNG, and its hot surface is connected to the cold surface of the high-temperature chip through a heat conduction layer, with a temperature of about -70°C . This gradient arrangement enables both types of chips to operate within their respective allowable

working temperature ranges, and at the same time maximizes the use of temperature difference for power generation. The principle of the stacked arrangement of thermoelectric chips is shown in Figure 2.

According to theoretical calculation, the output voltage, current and power of a set of high-temperature and low-temperature thermoelectric chip stacked unit are about 7 V, 0.7 A and 4.9 W respectively. In practical applications, multiple stacked units need to be combined in series and parallel according to the voltage and power requirements of electrical equipment. For example, when charging a storage battery, two series output units can be combined into one series-parallel output unit, and then each output unit is connected in parallel; when the electric energy generated by the thermoelectric power generation device needs to be integrated into the ship power grid, a larger number of units are required to be combined in parallel. If the number of thermoelectric chips is insufficient, the voltage can also be adjusted through a boost module to meet different power consumption demands. The series-parallel combination circuit adopted in this system is shown in Figure 3.

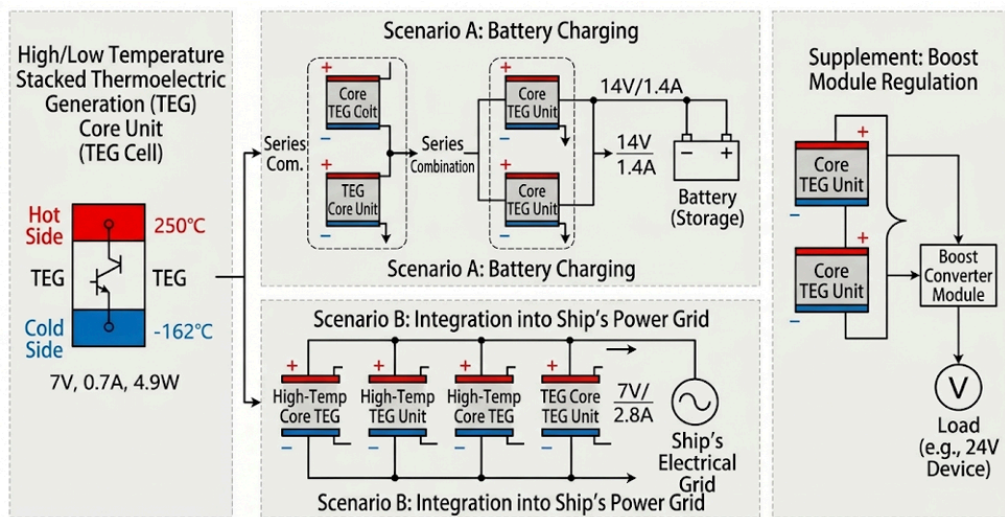


Figure 3. Schematic diagram of series-parallel combination circuit of thermoelectric power generation units

In this system, the thermoelectric power generation device is not only used for power generation, but more importantly, realizes the first-stage utilization of cold energy. LNG absorbs heat when passing through the thermoelectric power generation device, and its temperature rises from -162°C to about -70°C , which not only creates conditions for subsequent cold energy utilization but also reduces the heat consumption required for LNG gasification. It is estimated that the annual power generation per square meter of the thermoelectric power generation device can reach 52000 kWh, equivalent to saving about 8.84 tons of marine fuel oil per year, which has good energy-saving effect and economic benefits.

3.2. Adaptive cascade utilization technology

The system adopts a main-auxiliary dual refrigerant cycle architecture, and distributes the cold energy of gasified LNG after thermoelectric power generation to four cold-using devices in cascade: air conditioner, cold storage, seawater desalination device and air compressor. The control logic of the system is shown in Figure 4. R600 is selected as the main refrigerant, with a boiling point of

-42.17°C and a freezing point of -187.1°C, which is not easy to solidify when directly exchanging heat with LNG. After absorbing LNG cold energy in the main heat exchanger, the main refrigerant transports the cold energy to each auxiliary heat exchanger through pipelines, realizing centralized distribution of cold energy. The four auxiliary systems respectively adopt R11 as the auxiliary refrigerant. R11 has a freezing point as low as -111 °C and a boiling point of 23.7 °C, which is suitable for cold applications with different temperature requirements, and is not prone to phase change, facilitating flow control. The main refrigerant conducts secondary heat exchange with each auxiliary refrigerant in the auxiliary heat exchanger, transferring cold energy to the air conditioner, cold storage, seawater desalination device and air compressor. Each auxiliary system is equipped with a temperature sensor and an auxiliary flow control valve, forming an intelligent feedback control system.

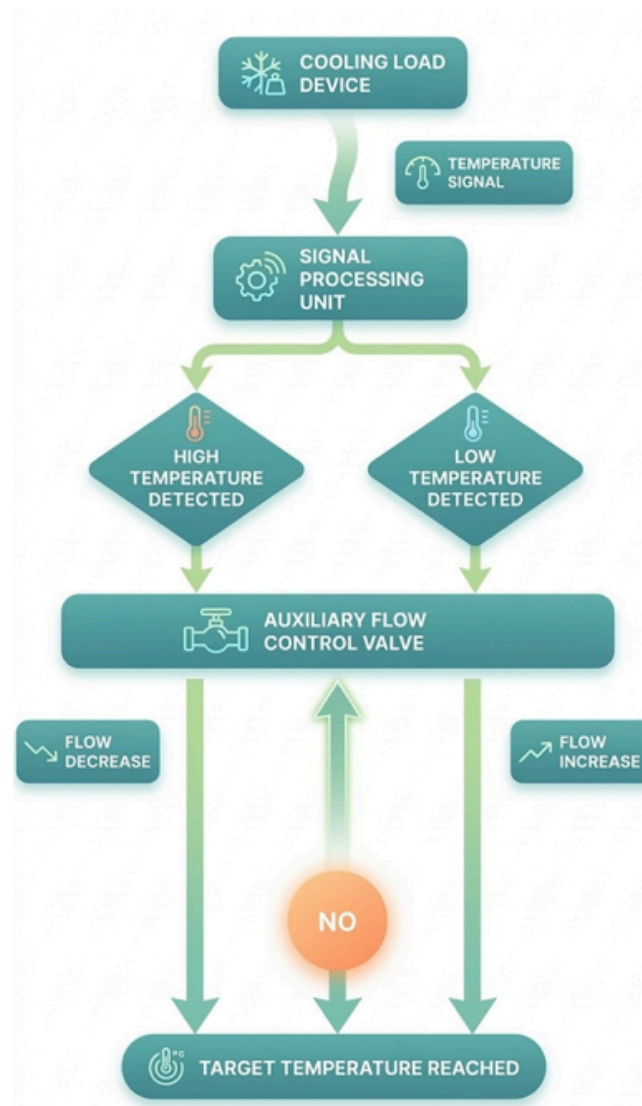


Figure 4. Flow chart of adaptive intelligent feedback control

The control principle is as follows: when the temperature sensor detects that the actual temperature of a cold-using device is higher than the set value, the signal processing unit instructs the auxiliary flow control valve to increase the refrigerant flow and the cooling supply; when the actual temperature is lower than the set value, the flow is reduced; when the target temperature is

reached, the current flow is maintained. This adaptive mechanism ensures that the temperature of each device is stable within the preset range, avoids excessive or insufficient supply of cold energy, and realizes accurate temperature control and high-efficiency energy saving.

3.3. Adaptive design of cold-using devices

Air conditioners and cold storages are the main cold-using devices on ships. The required temperature of ship air conditioners is about 22\26 °C, and cold storages are divided into high-temperature storages (0\5 °C) and low-temperature storages (-20~-18 °C). The cold energy is transferred to the R11 refrigerant through the auxiliary heat exchanger, and then released through respective fan coil units or cooling coils. Due to the high requirement for temperature control accuracy of cold storages, the adaptive feedback system can effectively avoid temperature fluctuations and ensure the quality of food storage.

The seawater desalination device adopts the indirect freezing method. Raw seawater first passes through a precooler, where it is precooled with low-temperature concentrated seawater and fresh water, and its temperature drops to about 2 °C. Then it enters the crystallizer to exchange heat indirectly with the auxiliary refrigerant (R11), and the temperature drops to about -3 °C, so as to obtain concentrated seawater and ice crystals. After that, the ice crystals are washed and the cold energy of seawater is recovered, and finally desalinated water is obtained. This process uses LNG cold energy to replace the large amount of electric energy consumption of the traditional reverse osmosis method, and the cold energy consumption per ton of seawater is about 2.048×10^4 kJ.

Marine air compressors generally adopt multi-stage compression, and the compression ratio of each stage should not be greater than 6. To improve the economy and gas delivery capacity of air compressors, interstage intermediate cooling is usually adopted. The cold energy provided by the auxiliary refrigerant circulation system is used to cool the compressed air, and the cold energy consumption of cooling water is about 7614 kJ/h. This not only improves the working efficiency of the air compressor but also reduces the corrosion of equipment caused by traditional cooling water.

The cold energy demand of the above four cold-using devices matches the total amount of cold energy provided by LNG, realizing the principle of matching supply and demand. Through the cascade distribution and adaptive control of main and auxiliary refrigerants, the system can flexibly respond to the dynamic load changes of different devices and ensure that each device operates under optimal working conditions.

4. Theoretical calculation and performance analysis

This system takes an LNG-powered ship converted from a certain type of very large crude carrier of COSCO Group as the parent ship. The daily LNG consumption of the ship is 63 tons, the latent heat of LNG gasification is 510.25 kJ/kg, and the total cold energy (including sensible heat) released during gasification is about 830 kJ/kg. The cold energy released by daily LNG gasification is conservatively calculated based on latent heat as shown in Equation (1):

$$Q_{LNG} = m \times \Delta H_v \quad (1)$$

where $m = 63000\text{kg/day}$, $\Delta H_v = 510.25\text{kJ/kg}$. The calculation result is:

$$Q_{LNG} = 63000 \times 510.25 = 3.213 \times 10^7 \text{kJ/day} \quad (2)$$

If calculated based on the comprehensive cold energy (including sensible heat) of 830 kJ/kg, it is 5.229×10^7 kJ/day. This system adopts conservative values for supply-demand balance analysis.

The cold demand of each cold-using device is calculated as follows.

Air conditioner and cold storage: the average operating load of the cold storage compressor is 10 kW, the actual operating power of the air conditioner compressor is 40 kW, and the refrigeration coefficient μ is taken as 4. The total daily cold energy consumption is calculated according to Equation (3):

$$Q_{ACR} = 24 \times 3600 \times (P_{coldstorage} + P_{airconditioning}) \times \mu \quad (3)$$

Substitute the values:

$$Q_{ACR} = 86400 \times 50 \times 4 = 1.728 \times 10^7 \text{ kJ/day} \quad (4)$$

Seawater desalination device: adopting the indirect freezing method, the cold energy consumption per ton of seawater is calculated according to Equation (5):

$$Q_{SW} = C \times M_{seawater} \times \Delta T \quad (5)$$

Take the specific heat capacity of seawater $C = 4.096 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$, $M_{seawater} = 1000 \text{ kg}$, and temperature drop $\Delta T = 5^\circ\text{C}$ (from 2°C to -3°C):

$$Q_{SW} = 4.096 \times 1000 \times 5 = 2.048 \times 10^4 \text{ kJ/t} \quad (6)$$

If 20 tons are desalinated every day, the daily cold energy consumption is $4.096 \times 10^5 \text{ kJ}$.

Air compressor cooling: adopting two-stage compression, the cold energy consumption required for interstage cooling is calculated according to Equation (7):

$$Q_{air} = C_{air} \times m \times (T_2 - T_2') \quad (7)$$

where the constant pressure specific heat capacity of air $C_{air} = 1.41 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$, air mass flow rate $m = 1800 \text{ kg/h}$, $T_2 = 229^\circ\text{C}$, $T_2' = 17^\circ\text{C}$. The calculation result is:

$$Q_{air} = 1.41 \times 1800 \times (229 - 17) = 5.38 \times 10^5 \text{ kJ/h} \quad (8)$$

Based on 8 hours of daily operation, the daily cold energy consumption is about $4.30 \times 10^6 \text{ kJ}$.

The above calculation results are summarized in Table 1.

Table 1. Summary of LNG cold energy supply and demand balance

Cold-using device	Daily cold demand (kJ/day)	Proportion of LNG cold energy (%)
Air conditioner and cold storage	1.728×10^7	53.8
Seawater desalination (20 tons/day)	4.096×10^5	1.3
Air compressor (8 h/day)	4.30×10^6	13.4

Table 1. (continued)

Total	2.188×10^7	68.5
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The cold energy provided by LNG (latent heat part) is $3.213 \times 10^7 \text{ kJ/day}$, and there is still about 31.5% surplus available for thermoelectric power generation precooling and other purposes. In the actual system, the thermoelectric power generation device has used part of the cold energy to raise the LNG temperature, and this part of cold energy is not included in the above direct utilization. Therefore, the overall cold energy utilization rate can reach more than 90%, and the balance of LNG cold energy supply and demand is shown in Figure 5.

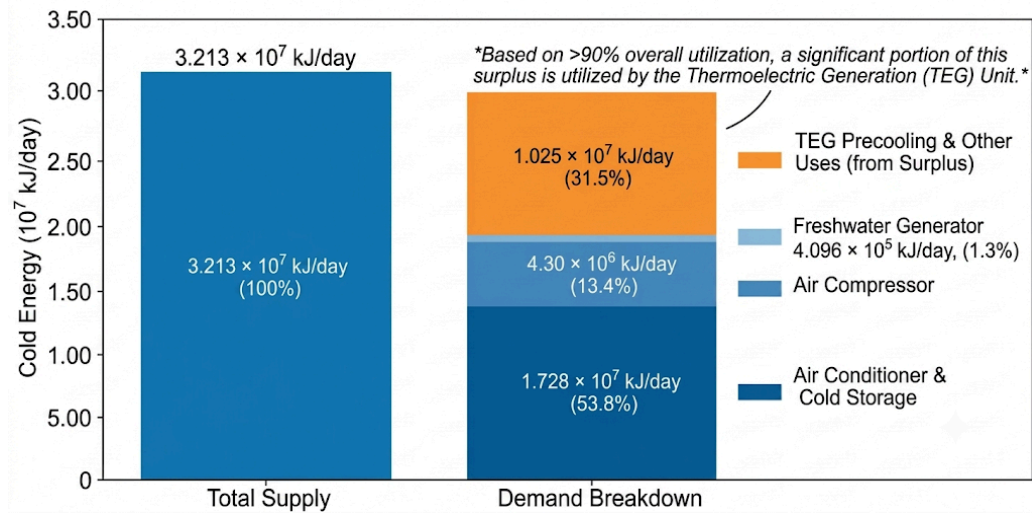


Figure 5. Diagram of LNG cold energy supply and demand balance

The power generation performance of the thermoelectric power generation device is as follows: about 500 stacked units can be arranged per square meter, and the output power of a single unit is 4.9 W, so the power generation per square meter is 2.45 kW. The ship operates 6500 hours per year, and the annual power generation per square meter is calculated according to Equation (9):

$$E = P \times T = 2.45 \times 6500 = 15925 \text{ kWh} \quad (9)$$

After adopting the optimized design, the annual power generation per square meter can reach 52000 kWh, and the corresponding fuel saving is calculated according to Equation (10):

$$M_{fuel} = E \times \text{fuel consumption rate} = 52000 \times 0.170 = 8840 \text{ kg} = 8.84 \text{ t} \quad (10)$$

Calculated at 3000 yuan per ton of fuel oil, the annual cost saving is 26520 yuan. The investment cost of the thermoelectric power generation device is about 30000 yuan per square meter, and the investment payback period is about 1.13 years.

5. Conclusion

Aiming at the problems of energy waste and environmental cold pollution caused by the direct discharge of a large amount of high-quality cold energy during the gasification process of LNG-powered ships, this paper designs a comprehensive cold energy utilization system based on

thermoelectric power generation and adaptive cascade utilization. The main conclusions are as follows:

(1) The system scheme is feasible and innovative. The integrated scheme of "power generation-transmission-cascade utilization" proposed in this paper takes LNG (-162°C) as the cold source and exhaust gas from the exhaust gas boiler (about 250°C) as the heat source. Through the stacked arrangement of high-temperature and low-temperature thermoelectric chips, it solves the engineering problem that a single chip cannot withstand the large temperature difference of 412°C ; combined with the dual-cycle architecture of main refrigerant (R600) and auxiliary refrigerant (R11) and intelligent feedback control, it realizes adaptive and accurate distribution of cold energy among four cold terminals: air conditioner, cold storage, seawater desalination and air compressor. The system structure has no moving parts, adapts to the vibration environment of ships, and has good engineering feasibility.

(2) The total supply and demand of LNG cold energy is balanced with sufficient surplus. Based on the daily LNG consumption of 63 tons of the parent ship, the latent heat cold energy of LNG gasification is 3.213×10^7 kJ/day. The total daily cold demand of the four cold-using devices is about 2.188×10^7 kJ/day, accounting for 68.5% of the total cold energy supply. The remaining 31.5% of cold energy is utilized in cascade in thermoelectric power generation precooling and other links. The overall cold energy utilization rate of the system can reach more than 90%, which proves that multi-stage distribution of cold energy can effectively avoid energy waste caused by single utilization.

(3) The thermoelectric power generation device has dual functions of power generation and precooling, with remarkable economic benefits. The theoretical output power of a single stacked unit is about 4.9 W, and the annual power generation per square meter can reach 52000 kWh, equivalent to saving about 8.84 tons of fuel oil per year. Calculated at 3000 yuan per ton of fuel oil, the annual cost saving is about 26500 yuan. While generating power, the thermoelectric power generation device raises the LNG temperature from -162°C to about -70°C , which not only creates conditions for subsequent refrigerant heat exchange but also reduces the heat energy consumption required for gasification.

(4) The adaptive cascade utilization technology realizes accurate temperature control and flexible adjustment. Through the closed-loop feedback loop formed by temperature sensors and flow control valves, each auxiliary system can dynamically adjust the refrigerant flow according to the actual load of each cold-using device, so that the air conditioner ($22\sim 26^{\circ}\text{C}$), cold storage ($-20\sim 5^{\circ}\text{C}$), seawater desalination (crystallization at -3°C) and air compressor (interstage cooling at 17°C) all operate stably within their respective target temperature ranges. This mechanism avoids excessive or insufficient supply of cold energy and improves the operation efficiency and reliability of the system.

(5) The environmental and social benefits are outstanding. The system uses the cold energy released during LNG gasification to replace the large amount of electric energy consumed by the traditional compression refrigeration method, reducing carbon emissions and power consumption during ship operation; at the same time, it avoids the "cold pollution" problem caused by direct discharge of low-temperature LNG into seawater. Calculated on the basis of annual power generation of 52000 kWh per square meter, it is equivalent to reducing standard coal consumption by about 18.5 tons and carbon dioxide emissions by about 45 tons per year, which is in line with the green and low-carbon development direction of the shipping industry.

To sum up, the LNG cold energy utilization system for LNG-powered ships designed in this paper is technically feasible, economically reasonable and environmentally friendly. It can effectively solve the problem of LNG cold energy waste and provide a feasible technical scheme for

the comprehensive utilization of cold energy of LNG-powered ships. In the future, in-depth research can be further carried out on the performance optimization of thermoelectric chips, the selection and matching of refrigerant working fluid pairs, and the intelligent improvement of multi-device cooperative control, so as to promote the engineering application and popularization of this technology.

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