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Design and Optimization of a Full-Generation System for Marine LNG Cold Energy Cascade Utilization

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Abstract: This paper took a 100,000 DWT LNG fuel powered ship as the research object. Based on the idea of "temperature matching, cascade utilization" and combined with the application conditions of the ship, a horizontal three-level nested Rankine cycle full-generation system which combined the high-temperature waste heat of the main engine flue gas with the low-temperature cold energy of LNG was proposed in this paper. Furthermore, based on the analysis and selection of the parameters which had high sensitivity to the system performance, the parameters of the proposed system were optimized by using the genetic algorithm. After optimization, the exergy efficiency of the marine LNG gasification cold energy cascade utilization power generation system can reach 48.06%, and the thermal efficiency can reach 35.56%. In addition, this paper took LNG net power generation as the performance index, and compared it with the typical LNG cold energy utilization power generation system in this field. The results showed that the unit mass flow LNG power generation of the system proposed in this paper was the largest, reaching 457.41 kW.

Keywords: LNG, cold energy utilization, CO_2, transcritical, Rankine cycle, genetic algorithm

1. Introduction

With the booming economy, various environmental pollution and energy shortages that come with it. LNG is strongly promoted by the international energy community because of its environmental protection and large reserves [1–2]. LNG is a low-temperature energy source, which is generally stored at −162°C. According to the needs of end users, LNG needs to undergo the re-gasification process to reach the corresponding pressure [3]. For example, steam power station requires 6 bar; combined cycle power station requires 25 bar, and long-distance transmission needs 70 bar. The traditional LNG regasification is heated by using various low temperature residual heats. This method not only causes a large amount of cold energy and low temperature residual heat to be lost, but also consumes a large amount of pump work [4]. Therefore, scholars have conducted a lot of research on LNG cold energy recovery, such as the use of LNG cryogenic air separation, light hydrocarbon separation, intermediate cooling for power generation, seawater desalination, shallow cold for cold storage, refrigeration and air conditioning, and so on [5–6]. Among them, LNG cold energy generation is the most economical and convenient method. There are six main types of power generation, namely direct expansion method, Rankine cycle method, combined cycle method, Brayton cycle method, Karina cycle method and multi-stage compound cycle method [7]. Chen et al. [8] analyzed various LNG power generation methods, compared their advantages, disadvantages and adaptability, introduced nine new methods that have not

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been applied yet, and put forward suggestions to improve the efficiency of LNG cold energy power generation. Gong [9] analyzed the current mainstream LNG cold power generation processes (direct expansion power generation method, Rankine cycle power generation method and combined power generation method). The results showed that the combined power generation method has the highest power generation efficiency and the widest application scope due to the comprehensive utilization of LNG low temperature exergy and pressure exergy. Yang et al. [10] designed a three-stage Rankine cycle power generation system utilizing LNG cold energy based on the principle of "cascade utilization". It was found that there is a inflection point temperature in the LNG evaporation section under different pressures, and the inflection point temperature as the outlet temperature of the LNG in the second Rank Rankine cycle can maximize the system power generation.

With the rapid increase in the number of ships powered by LNG, the utilization of LNG gasification cold energy of LNG power ship has also been highly concerned. On the currently operating LNG power ship, LNG is heated by the seawater or cylinder liner cooling water to a certain temperature and then enters the combustion chamber of the engine. It not only consumes a lot of cold energy, but also wastes low-grade heat energy in the cylinder liner cooling water. In response to the combined utilization of low-grade thermal energy and LNG cooling energy, Hisazumi et al. [11] first proposed the use of industrial waste heat or condensed steam as a heat source to form a Rankine cycle with low-temperature LNG. Refs. [12–16] used different heat sources (industrial waste heat, geothermal energy, solar energy, etc.) to utilize the cooling energy of LNG by Rankine cycle, and made detailed analysis of the key parameters such as the evaporation pressure and condensation pressure of working medium. Ma et al. [17] designed a LNG cold energy utilization system for a LNG dual fuel power ship, which used LNG cold energy for the air conditioning refrigeration and cooling cylinder liner cooling water. Economic analysis found that the system could reduce the power consumption of the ship substantially. Based on the idea of "cascade utilization", Sun et al. [18] designed a cold energy utilization system scheme for LNG power ship to use LNG cold energy for low-temperature cold energy power generation, seawater desalination, low-temperature cold storage, high-temperature cold storage and air-conditioning modules. However, due to the mature energy utilization scheme of the traditional fuel-powered ship waste heat utilization system, and the temperature span of the LNG re-gasification process on the new LNG power ship is very large, it is still a key issue for LNG power ships that how to comprehensively consider the reintegration of various low grade residual heat and LNG gasification cold energy on the ocean LNG power ship, and propose more effective energy utilization schemes from the perspective of "temperature counterpart, cascade utilization".

In this paper, a horizontal three-stage nested LNG cold energy cascade full power generation system is designed by using the low-temperature Rankine cycle of ethane, the medium-temperature Rankine cycle of propane and the high-temperature transcritical CO_2 Rankine cycle for a 100,000 DWT LNG fuel powered ship, which combines the low-grade thermal energy of the main engine flue gas and LNG cold energy. The thermodynamics analysis was carried out for the preliminary design system, and the parameters that had a great influence on the system thermodynamic performance were selected as variables. The genetic algorithm was used to optimize and analyze the system, in order to provide support for the design of high-efficiency energy utilization scheme for the LNG power ship.

2. Marine LNG Cold Energy Multi-Stage Utilization System Design

2.1 Parameters of marine main engine

The 100,000 DWT LNG fuel-powered ship adopts WARTSILA2-S DF as the main engine. In view of the continuous operating power of most marine engines at 70%–75% of rated power, this paper designs the cold energy utilization system with the parameters of the LNG power ship at 70% of rated power. The parameters of the LNG power ship are shown in Table 1.

Table 1 Parameters of the LNG power ship

Parameter	Value
Main engine power/kW	25480
Gas consumption/kg·h^{-1}	2560
Main engine intake pressure/MPa	1.6
Main engine intake temperature/°C	0–60
Exhaust temperature/°C	380
Exhaust volume/kg·h^{-1}	5000

2.2 System integration ideas and processes

As the most economical, convenient and widely applicable way of LNG cold energy utilization, LNG cold energy generation is mainly realized by Rankine cycle at present. Based on the idea of "temperature counterpart, cascade utilization", this paper preliminarily estimates the distribution of LNG cold energy in different temperature zones, and combines with the application conditions of ships, uses the following system integration ideas to design the system:

According to the analysis of the LNG evaporation curve under different pressures given in the literature [10], the liquid phase and wet steam segment on the LNG vaporization curve account for more than 90% of the total exergy. When establishing the LNG cold energy power generation system, we fully considered the matching of the *T-S* curve of the Rankine cycle working fluid with the corresponding gasification curve of LNG, which can minimize the exergy loss caused by the large heat transfer temperature difference. Therefore, this paper uses a stepwise segmentation method to construct a two-stage LNG cold energy Rankine cycle power generation system within the temperature range of −162°C–−40°C to make full use of the LNG liquid phase and wet steam segment cold energy. Although LNG from the second Rankine cycle still has cold energy with temperature difference of more than 50°C which can be utilized, yet which is less than 10% of the total exergy, the power generation capacity of this part of cold energy is very small. Traditionally, this section of cold energy is wasted or used for other cooling functions, and the waste is relatively large. Considering waste heat utilization of the exhaust gas emitted by the ship's main engine, using it as a heat source and constructing a CO_2 transcritical Rankine cycle with LNG cold energy between −40°C and 0°C, can obviously improve the utilization efficiency of LNG cold energy in shallow cooling zone and waste heat of main engine exhaust gas. Due to the limited space of engine room, the number and size of equipment should be reduced as much as possible in the design of this LNG cold energy utilization power generation system. For this reason, a horizontal three- stage nested Rankine cycle is adopted. The circulating working fluids that complete the expansion work in the second and third stages serve as heat sources in the first-stage Rankine cycle and the second-stage Rankine cycle, avoiding an increase in the number of heat exchange devices due to the use of other heat sources.

Based on the above system integration ideas, the horizontal three-stage nested Rankine cycle can realize the comprehensive utilization of LNG cold energy and low-grade residual heat energy carried by the ship's main engine gas. The final designed system process flow is shown in Fig. 1.

Working principle: LNG-1 from storage tank is pressurized and then enters heat exchanger 1 (HE1), heat exchanger 2 (HE2) and heat exchanger 3 (HE3) for heat exchange. Then high-pressure LNG-5 from heat exchanger 3 enters turbine 1 (T-1) to expand. Low-temperature LNG-6 from turbine 1 outlet enters heat exchanger 3 for heat exchange again and then enters ship main engine for combustion. In the ethane circulation loop, ethane from turbine 2 (T-2) enters heat exchanger 1, then enters heat exchanger 2 and heat exchanger 3 in turn for heat exchange, and finally enters turbine 2 to expand and complete the cycle. In the propane circulation loop, propane from turbine 3 (T-3) is condensed in heat exchanger 2 and pressurized. Then it enters heat exchanger 3 for heat transfer, and finally enters turbine 3 to expand to complete the cycle. In the transcritical CO_2 Rankine cycle, CO_2 from turbine 4 (T-4) enters heat exchanger 4 (HE4) for pre-cooling, then is cooled again by heat exchanger 3, and then pressurized. CO_2 then exchanges heat through heat exchanger 4 and heat exchanger 5 (HE5) in turn, and finally enters turbine 4 to expand to complete the cycle. In the preliminary design of the marine LNG cold energy power generation system, the key parameters of each flow referred to Ref. [19], are shown in Table 2.

2.3 Selection of working fluids

From the current research, the low temperature Rankine cycle using LNG cold energy for power generation mostly uses organic working fluid. When selecting the working fluid, factors such as environmental performance, thermodynamic performance, physical and chemical properties and safety characteristics of the refrigerant should be considered. In addition, the size of the latent heat of vaporization of the circulating fluid has a great influence on the heat transfer and work process. Therefore, referring to Ref. [19], considering the working

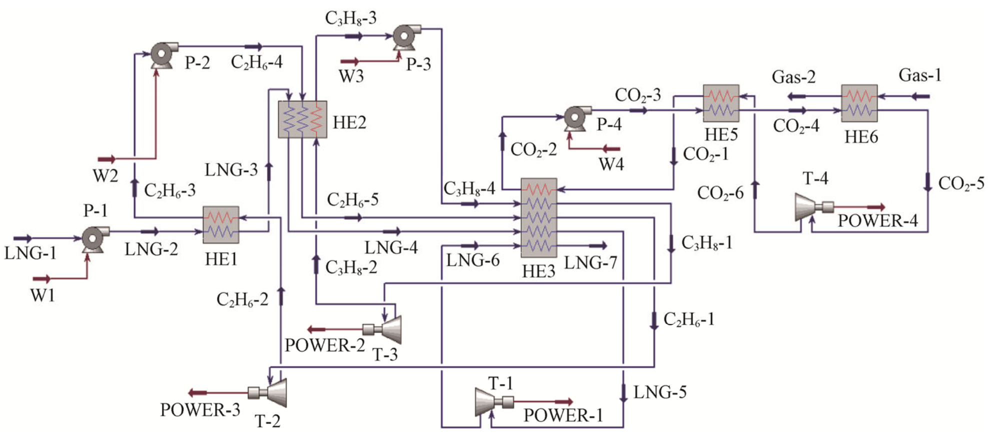

Fig. 1 Flow chart of multistage utilization of LNG cold energy for marine

Table 2 Key thermodynamic parameters of each flow in the system [19]

Stream name	T/°C	P/kPa	m/ kg·h^{-1}	S/ kJ·kg^{-1}·K^{-1}	H/ kJ·kg^{-1}
LNG-1	−162	600	2560	4.551	−5399
LNG-2	−161.2	2000	2560	4.564	−5395
LNG-3	−85	2000	2560	8.344	−4662
LNG-4	−35.89	2000	2560	8.982	−4662
LNG-5	2	2000	2560	9.324	−4575
LNG-6	−9.601	1600	2560	9.351	−4596
LNG-7	2	1600	2560	9.448	−4569
C_2H_6-1	2	700	2898	5.787	−2874
C_2H_6-2	−60.34	110	2898	5.926	−2958
C_2H_6-3	−89.18	110	2898	3.094	−3488
C_2H_6-4	−88.81	700	2898	3.096	−3486
C_2H_6-5	−35.89	700	2898	5.531	−2939
C_3H_8-1	2	400	4414	3.252	−2406
C_3H_8-2	−27.89	130	4414	3.305	−2444
C_3H_8-3	−38.84	130	4414	1.462	−2881
C_3H_8-4	−38.66	400	4414	1.462	−2880
CO_2-1	10	3500	9603	3.092	−9006
CO_2-2	−7	3500	9603	2.112	−9274
CO_2-3	5	18000	9603	2.131	−9254
CO_2-4	45	18000	9603	2.446	−9160
CO_2-5	220	18000	9603	3.305	−8828
CO_2-6	92.99	3500	9603	3.385	−8912
Gas-1	380	100	5000	8.446	−10880
Gas-2	90.54	100	5000	7.023	−11510

temperature range of the first-stage Rankine cycle and the second-stage Rankine cycle, ethane (boiling point −88.6°C, freezing point −183.3°C) and propane (boiling point −42.2°C, freezing point −187.67°C) with higher vaporization latent heat values were selected as the working fluids of the first and second Rankine cycles, respectively. A transcritical organic Rankine cycle is constructed between the engine exhaust gas and LNG at −40°C. The high flow density and good thermal conductivity of CO_2 working fluid in the transcritical region are fully utilized to reduce the size of compressors, heat exchangers and turbines to meet the compactness requirements of the ship engine room for the cycle system and to achieve high energy utilization efficiency in the temperature region.

3. System Simulation and Analysis

When simulating the proposed system, using the appropriate state equation to calculate the thermodynamic properties of the various working fluids in the LNG cold energy utilization system is the premise for ensuring the accuracy of the system simulation results. Li et al. [20] examined the accuracy of the physical parameters of the LNG evaporation process by using the state equations such as PR, SRK and LKP. The results showed that the accuracy of PR equation is the highest when the phase equilibrium parameters and thermodynamic parameters are considered comprehensively, and the prediction error is about 3.77%. In Ref. [21], a combined cycle of Rankine cycle power generation and LNG direct expansion power generation was studied, and the circulating working fluids (ethane, propane and CO_2, etc.) in the Rankine cycle were screened. In the simulation process, the physical parameters of the working fluid are calculated by using the PR state equation, and the results are in good agreement with the experimental data.

3.1 Simulation parameters

The working fluids involved in the simulation system are LNG, ethane, propane and CO_2. The main components of LNG fuel are shown in Table 3.

Table 3 The components of LNG

composition	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}
Molar/%	0.07	95.85	3.1	0.85	0.12	0.01

The parameters of the system equipment are described as follows:

(1) The efficiency of the turbine and pump is 75%.

(2) The pressure loss of each device is 0.

(3) The subcooling degree is 2°C, and the minimum difference of the lower end of the heat exchanger is 8°C.

3.2 Thermodynamic analysis of the system

The thermodynamic analysis of the marine LNG cold energy utilization system is carried out under the condition that the above initial parameters and constraints are satisfied. The exergy efficiency of devices or system is defined as the ratio of the exergy ($E_{x,u}$) that is effectively utilized or benefited to the exergy ($E_{x,p}$) of the payment or consumption during the energy conversion process in Eq. (1). The thermal efficiency of system is defined as the ratio of the net output power to the heat supplied by the flue gas in Eq. (2).

$$\eta_e = \frac{E_{x,u}}{E_{x,p}} \tag{1}$$

$$\eta_h = \frac{W_{\text{net}}}{H} \tag{2}$$

Table 4 gives the calculation results of the thermodynamic analysis of the marine LNG cold energy utilization system. It can be found that the loss of the system is mainly concentrated in the heat exchanger. The LNG is evaporated in the heat exchanger 1 to release a large amount of cold energy. Therefore, the loss of exergy in heat exchanger 1 is as large as 122.43 kW. The high-temperature flue gas in the heat exchanger 5 releases a large amount of heat energy, and the exergy loss of the heat exchanger 5 is 99.78 kW, which is the second only to the heat exchanger 1. The heat exchanger 1 and the heat exchanger 5 with higher loss have lower exergy efficiency, which are 67.75% and 66.39%, respectively. Therefore, reducing the exergy loss of the heat exchanger 1 and the heat exchanger 5 is the effective way to optimize the whole system. Fig. 2 shows the heat transfer curves of the refrigerants in each heat exchanger. The heat exchanger 4 has less loss, so it is neglected.

Table 4 Thermodynamic analysis of system

Equipment	Exergy analysis of each equipment			
	Exergy income/ kW	Exergy consumption/ kW	Exergy loss/ kW	Exergy efficiency /%
Heat exchanger 1	257.25	379.68	122.43	67.75
Heat exchanger 2	149.32	187.24	37.92	79.75
Heat exchanger 3	69.87	103.42	33.55	67.56
Heat exchanger 4	3.7	14	10.3	26.43
Heat exchanger 5	197.12	296.9	99.78	66.39
Pump 1	0.17	3.021	2.851	5.6
Pump 2	0.59	1.159	0.569	50.9
Pump 3	0.46	0.79	0.33	58.23
Pump 4	33.26	53.4	20.14	62.28
Turbine 1	14.84	19.91	5.07	74.54
Turbine 2	68.26	101.98	33.72	66.93
Turbine 3	51.8	73.25	21.45	70.72
Turbine 4	225	289.88	64.88	77.62
η_e	44.6%			
η_h	33.24%			
System net output work/ kW	301.53			

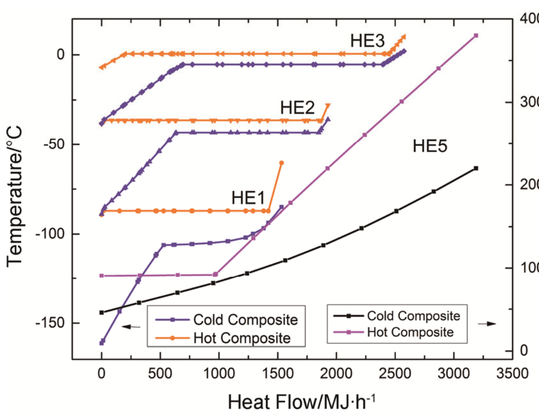

Fig. 2 Heat transfer curves of cold and hot working fluid in each heat exchanger of system

4. Parameters Selection

4.1 Influence of single parameter on system thermodynamic property

There are many adjustable parameters in the LNG cold energy multi-stage utilization system. Firstly, the influence of single parameter on the system exergy efficiency and thermal efficiency is investigated and analyzed. Based on the results, through the sensitivity of the investigated parameters to the system efficiency and thermal efficiency, the parameters that have great influence on the thermodynamics of the system are selected for subsequent optimization.

From Fig. 3, it can be seen that the raise of LNG evaporation pressure increases the system exergy efficiency and thermal efficiency significantly. This is because with the increase of LNG evaporation pressure, the heat transfer curve of the LNG is more closely matched to the heat transfer curve of hot working fluid in heat exchanger, and the increase in LNG evaporation pressure also makes the ability of doing work of LNG in the turbine 1 improved. The increase of the LNG outlet temperature in the heat exchanger 1 is not significant to the thermodynamic performance of the system, because most of the heat exchange in the heat exchanger 1 is concentrated in the gradual latent heat section, while the outlet temperature of the LNG in the heat exchanger 1 is in the steep submerged heat section. Increasing the LNG outlet temperature in the heat exchanger 1 can improve the heat transfer performance of the steep submerged heat section, but has little effect on improving the overall heat transfer performance of the heat exchanger 1. In addition, in order to avoid the temperature crossing of the heat exchanger 1, the increase of the outlet temperature of the LNG in the heat exchanger 1 is quite limited, so the effect of the parameter on the exergy efficiency and thermal efficiency of the system is not considered.

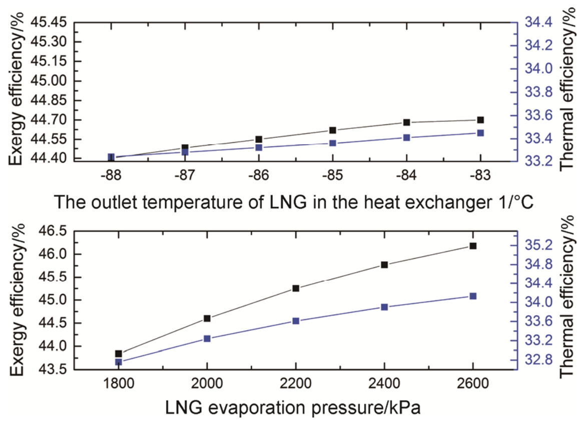

Fig. 3 Effect of LNG parameters on system thermodynamic property

Fig. 4 is a single-parameter analysis of the influence of ethane side parameters on the thermodynamic performance of the system. The results show that although the increase of ethane evaporation pressure increases the inlet pressure of expander 2 and makes the heat transfer curve of the refrigerant in heat exchanger 2 more matched, the improvement of the thermodynamic performance of the system is not obvious. The decrease of the condensation pressure of ethane makes the outlet pressure of the turbine 2 lower, which makes the ability of doing work of the turbine 2 increase. Moreover, the reduction of condensation pressure can increase the matching degree of the heat transfer curve of the cold and hot working fluid in the heat exchanger 1. The heat exchanger 1 is the equipment with the largest loss in the whole system. Therefore, the reduction of the condensation pressure of the ethane can greatly increase the thermodynamic performance of the system, that is, the condensation pressure of the ethane is the main parameter affecting the exergy efficiency and thermal efficiency of the system.

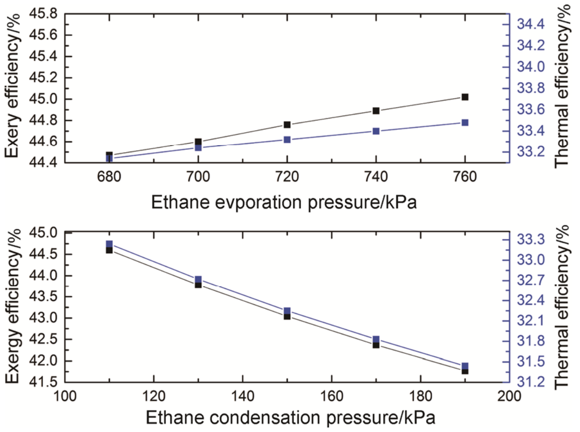

Fig. 4 Effect of ethane parameters on system thermodynamic property

Fig. 5 presents the analysis of the influence of the propane parameter on the system thermodynamic performance. From the figure, it can be seen that the reduction of the propane condensation pressure is beneficial to improve the exergy efficiency and thermal efficiency of the system, and the increase is obvious. The increase of the propane evaporation pressure in the heat exchanger 3 improves the heat transfer curve matching degree of the hot and cold working medium in the heat exchanger 3. However, the amount of heat exchange is limited by flow rate of the propane. Therefore, the increase in propane evaporation pressure has no significant effect on the system exergy efficiency and thermal efficiency.

From the single-parameter analysis of the influence of CO_2 parameters on thermodynamic performance of the system, as shown in Fig. 6, it can be seen that the

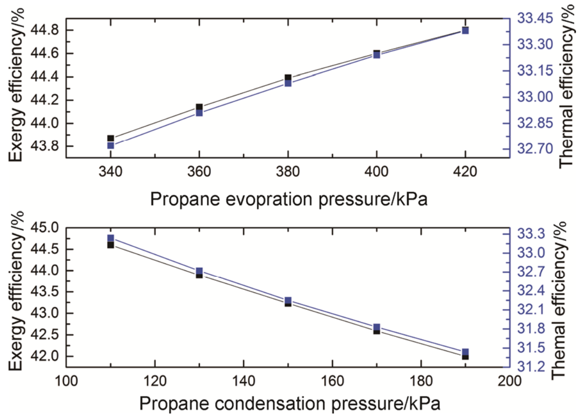

Fig. 5 Effect of propane parameters on system thermodynamic property

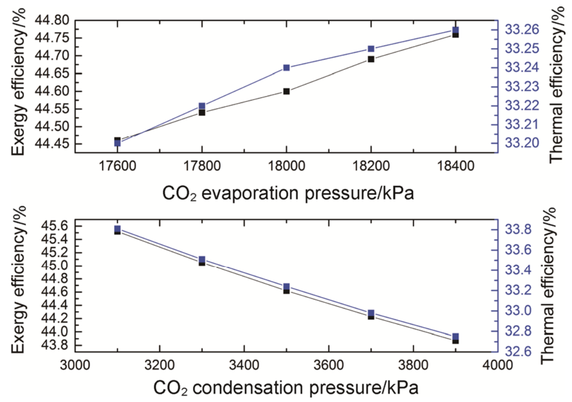

Fig. 6 Effect of CO_2 parameters on system thermodynamic property

increase of CO_2 evaporation pressure has no significant effect on the system exergy efficiency and thermal efficiency. However, CO_2 evaporation pressure has a large range of variation in the case of ensuring the system operation. So in the further optimization, the influence of the parameter on the thermodynamic performance of the system is considered. The reduction of the CO_2 condensation pressure increases the working ability of the turbine 4, and reduces the exergy loss of heat exchanger 3. It has a significant effect on the thermodynamic performance of the system.

Based on the analysis above, it is found that the LNG evaporation pressure, ethane, propane and carbon dioxide condensation pressure have a significant effect on the system thermodynamic performance. The evaporation pressure of ethane, propane and carbon dioxide has little effect on the system thermodynamic performance, while considering their coupling effect on the whole system, they are optimized together with the parameters of LNG evaporation pressure, ethane, propane and carbon dioxide condensation pressure, which have great influence on the system thermodynamic performance. That is, the selected optimization parameters are LNG evaporation pressure and evaporation, condensation pressure of ethane, propane and carbon dioxide.

5. Parameter Optimization and Result Analysis

5.1 Objective function and optimization interval

Facing the multi-parameter and non-linear optimization problem of the marine LNG cold energy utilization system, the traditional optimization method may not achieve the desired optimization effect. As a powerful optimization tool, genetic algorithm has high optimization ability for non-linear problems and can optimize multi-variables simultaneously. Ref. [21] takes a combined cycle of Rankine cycle power generation and LNG direct expansion power generation as the research object, and uses genetic algorithm to optimize some key parameters of the system, and achieves better results. Therefore, this paper adopts genetic algorithm as the optimization method, and takes the system exergy efficiency and thermal efficiency as the objective function, in order to obtain the best matching value of each optimization parameter to make the system thermodynamic performance optimal. The exergy efficiency objective function and the thermal efficiency objective function are respectively Eq. (3) and Eq. (4)

$$\max F_1 = \eta_e = \frac{\sum_{i=1}^{4} W_i}{\sum_{j=1}^{4} P_j + E_{x1} + E_{x2}} \tag{3}$$

$$\max F_2 = \eta_h = \frac{\sum_{i=4}^{4} W_i - \sum_{j=1}^{4} P_j}{H} \tag{4}$$

where, W_i is output power of each turbine; P_j is power consumed by each pump; E_{x1} is exergy difference of import and export LNG; E_{x2} is exergy difference of import and export flue gas, and H is heat flow difference of import and export flue gas.

Based on the single parameter analysis of the influence on the system thermodynamic performance of the LNG cold energy multi-stage utilization system, the seven variables of LNG evaporation pressure and propane, ethane and carbon dioxide evaporation and condensation pressure are selected to further optimize. Through the single parameter analysis of the influence on the thermodynamic performance of the system, the following two laws are found: when the evaporation pressure is increased, the exergy efficiency and thermal efficiency of the system are improved; when the condensation pressure is lowered, the exergy efficiency and thermal efficiency of the system are improved. Therefore, on the premise of the normal operation of the system, the optimum lower limit of evaporation pressure of each working medium is slightly lower than the initial pressure; the upper limit is the maximum under the normal operation of the system. The optimum upper limit of condensation pressure of each working medium is slightly larger than the initial value, and the lower limit is the minimum to ensure the normal operation of the system. The optimization interval of each parameter is set up as shown in Table 5.

Table 5 Optimized parameter range

Parameter	Initial value	Range of value
LNG evaporation pressure/kPa	1600	1400–3000
C_2H_6 condensation pressure/kPa	110	110–200
C_2H_6 evaporation pressure/kPa	700	650–900
C_3H_8 condensation pressure/kPa	130	110–200
C_3H_8 evaporation pressure/kPa	400	330–460
CO_2 condensation pressure/kPa	3500	3100–4000
CO_2 evaporation pressure/kPa	18000	16000–20000

5.2 Optimization results and analysis

The exergy efficiency and thermal efficiency of the marine LNG cold energy utilization system are taken as the objective functions respectively. After optimization by genetic algorithm, the specific values of the system exergy efficiency, thermal efficiency and optimization variables are shown in Table 6. When the exergy efficiency is the objective function, the exergy efficiency of the system is increased by 0.78% relative to the exergy efficiency with the thermal efficiency as the objective function, and the thermal efficiency is only 0.05% lower. Therefore, the optimal variable values derived from the exergy efficiency as the objective function are the design parameters of the system. The specific values of the optimized variables are as shown in Table 6.

Table 7 shows the comparative analysis of the marine LNG cold energy cascade utilization system with the exergy efficiency as the objective function before and after optimization. It can be found that the heat exchanger 1 with the largest loss of exergy has been greatly improved, and the total system loss is reduced. The net output power of the system is increased by 23.74 kW, the system exergy efficiency increased by 3.46%, and the thermal efficiency increased by 2.32%.

5.3 Analysis of system performance evaluation

At present, there are many literatures at home and abroad that report on LNG cold energy utilization power generation system in land gasification station [13,16,19], and generally use the exergy analysis method to evaluate the performance of the system. However, in some

Table 6 Optimizing parameter value

Parameter	Exergy efficiency as objective function	Thermal efficiency as objective function
LNG evaporation pressure/kPa	2985	2788
C_2H_6 condensation pressure/kPa	110	110
C_2H_6 evaporation pressure/kPa	770	734
C_3H_8 condensation pressure/kPa	124	112
C_3H_8 evaporation pressure/kPa	420	432
CO_2 condensation pressure/kPa	3120	17636
CO_2 evaporation pressure/kPa	20000	3122
System exergy efficiency	48.06%	47.28%
System thermal efficiency	35.56%	35.61%

systems where flue gas is used as a heat source at no additional cost, the calculation of the system exergy efficiency does not take into account the exergy of flue gas waste heat, resulting in a much higher exergy efficiency than other systems using seawater as the heat source. In response to this problem, Refs. [23, 24] used a special performance index (power generation per unit mass flow LNG) to evaluate the performance of the system.

Several representative systems are selected in this paper, and their system exergy efficiency and power generation per unit mass flow LNG are compared with the system proposed in this paper. The results are shown in Table 8. In Ref. [22], a horizontal three-stage Rankine cycle power generation system using mixed working fluid was proposed. The three-stage Rankine cycle uses flue gas as the heat source, and its exergy efficiency is 42.63%. Ref. [23] examined the most common LNG cold energy power generation system in land large LNG receiving stations, namely the single-stage Rankine cycle combined with the LNG direct expansion power generation, and its exergy efficiency is 49.7%. Ref. [24] proposed a three-stage Rankine cycle power generation system using both seawater and flue gas as heat sources, and its exergy efficiency reached 70.21%. However, the heat sources and working fluids used in different systems are inconsistent. Different application environments have large limitations on the size and weight of the equipment. Therefore, the exergy efficiency of different systems has a large difference. It is possible to use the unit mass flow LNG power generation as an evaluation index of the system performance. The results show that the unit mass flow LNG power generation of the cold energy power generation system proposed in this paper is much larger than that proposed in other literatures. The reason why the unit mass flow LNG power generation of the system proposed in Ref. [23] is small is that part of the cold energy of LNG is used to cool the refrigerant of the air conditioning system.

Table 7 Comparison of the system before and after optimization

Design Equipment	Original system		Optimized system	
	Exergy loss/kW	Exergy efficiency/%	Exergy loss/kW	Exergy efficiency/%
Heat exchanger 1	122.43	67.75	35	89.16
Heat exchanger 2	37.92	79.75	45.6	75.12
Heat exchanger 3	33.55	67.56	14.77	85.34
Heat exchanger 4	10.3	26.43	4.5	58.7
Heat exchanger 5	99.78	66.39	100.5	66.4
Pump 1	2.85	5.6	4.70	7.5
Pump 2	0.57	50.9	0.59	49.05
Pump 3	0.33	58.23	0.33	59.6
Pump 4	20.14	62.28	19.48	68.6
Turbine 1	5.07	74.54	15.59	70.8
Turbine 2	33.72	66.93	31.53	66.78
Turbine 3	21.45	70.72	20.59	70.19
Turbine 4	64.88	77.62	71.3	77.44
System exergy loss/kW	453.99		364.48	
System net out power/kW	301.53		325.27	
System exergy efficiency/%	44.6		48.06	
System thermal efficiency/%	33.24		35.56	

Table 8 Comparison of simulation results with related literatures

Reference	Exergy efficiency/%	kW/(kmol/s)-LNG	kW/(kg/s)-LNG
Ref. [22]	42.63	4938.02	293.93
Ref. [23]	49.7	1023.0	60.50
Ref. [24]	70.21	5125.20	302.80
Original system	44.6	7118.9	424.03
Optimized system	48.06	7678.5	457.41

6. Conclusion

Aiming at the utilization of LNG cold energy of LNG power ship, this paper proposes a horizontal three-stage nested Rankine cycle power generation system that combines the high temperature waste heat of the main engine flue gas with the LNG low temperature cold energy. Further, based on the single-parameter sensitivity analysis of the variables affecting the performance of the system, the important influence variables are selected. The genetic algorithm is used to optimize the selected parameters, and the following conclusions are obtained:

(1) The high-temperature residual heat of the host flue gas is combined with the low-temperature cold energy of LNG, which can fully utilize the distribution characteristics of the exergy of the two media in the selected three temperature zones. In addition, the third-stage transcritical organic Rankine cycle is constructed by means of CO_2 working fluid, so that the proposed horizontal three-level nested Rankine cycle realizes the efficient utilization of the LNG gasification cold energy, and the system is compact and simple.

(2) Through the thermodynamic analysis of the preliminary designed marine LNG cold energy cascade utilization system, it is found that the parameters that have a significant impact on the exergy efficiency and thermal efficiency of the cold energy cascade utilization system are the LNG evaporation pressure and the condensation pressure of ethane, propane and carbon dioxide. The parameters that have less impact on the exergy efficiency and thermal efficiency of the cold energy utilization system are the LNG outlet temperature in the heat exchanger 1, the evaporation pressure of ethane, propane and carbon dioxide.

(3) LNG evaporation pressure and evaporation, condensation pressure of ethane, propane and carbon dioxide are selected as the optimization variables. The genetic algorithm is used to optimize the exergy efficiency and thermal efficiency of the system. The exergy efficiency and thermal efficiency of optimized system can reach 48.06% and 35.56% respectively. In addition, this paper takes the power generation per unit mass flow LNG as the performance index, and compares it with the typical LNG cold energy utilization power generation system in this field. The results show that the unit mass flow LNG power generation of the LNG gasification cold energy cascade power generation system proposed in this paper is the largest, reaching 457.41 kW.

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