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Optimization and Analysis of an LNG Cold Energy Power Generation Model with Different Multi-energy Complementary Systems

Chenchen Li[1,2], Xinli Lu [1,2*], Wei Zhang [1,2*], Hao Yu [1,2*], Jiali Liu[1,2*], Shuhui Li[1,2*]

1 Tianjin Geothermal Research and Training Center, College of Mechanical Engineering, Tianjin University, Tianjin 300350, China

2 Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, College of Mechanical Engineering, Tianjin University, Tianjin 300350, China
(*Correspondence: xinli.lu@tju.edu.cn)

ABSTRACT

In this paper, based on analyzing the existing LNG cold energy utilization power generation system and aiming at the existing problems, and also combined with using geothermal resources, seawater and seawater-source heat pump systems, a multi-energy complementary LNG cold energy power generation model is established. In the process of LNG gasification, the proposed system uses seawater as the high-temperature heat source, and LNG as the low-temperature heat source to generate electricity first, and then combines with green energy heating, such as using geothermal or seawater-source heat pump, to meet the heat load requirement in the LNG gasification process. Several kinds of organic working fluids were selected to maximize the net power output and the cycle thermal efficiency, so as to achieve the best operating effect. The system parameters are optimized and the influences of the parameters, such as the inlet and outlet pressures of the turbine, on the system performance have been analyzed. It is found that, using propane as the working fluid, the power generation system can generate 2.47MW electricity in winter and 4.25MW in summer. The optimal evaporation and condensing pressures are 7.3 bar and 0.85 bar respectively, corresponding to a power cycle thermal efficiency of 13.34%. The results show that the proposed system can meet the heat load required for LNG heating and achieve the goal of energy saving, as well as reducing the emission of $C0_2$, which is of great significance for promoting the realization of carbon neutrality Future investment needs to be carried out to further analyze the techno-economics of the proposed system.

Keywords: LNG cold energy power cycle, Multi-energy systems, Thermal performance, Optimization

NONMENCLATURE

Abbreviations	
LNG	Liquefied natural gas
ORC	Organic Rankine cycle
ODP	Ozone depletion potential
GWP	Global warming potential

1. INTRODUCTION

Liquefied Natural Gas (LNG) is mainly composed of methane, as well as a small amount of ethane and propane. It is colorless, odorless, non-toxic, and non-corrosive. It is compressed and cooled into liquid by natural gas, usually stored in low-temperature storage tanks, and then re gasified when used. The combustion of liquefied natural gas causes very little air pollution, but it emits a huge amount of heat and is a relatively advanced energy source. LNG can provide a large amount of cold energy by increasing the inlet temperature from -162 ° C to room temperature. If cold energy can be reasonably recycled and utilized, it will bring great environmental and economic benefits. In the face of increasingly serious ecological and environmental pollution, in order to optimize the energy consumption structure, improve the atmospheric environment, and achieve sustainable economic development strategy, natural gas, as a clean and efficient low-carbon fossil energy, shoulders the important mission of transitioning the energy consumption structure from fossil energy to renewable energy [1].

Nowadays, advanced environmental countries in the world are promoting the use of LNG, and its main industrial use for power generation is LNG. There are

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many gas-steam combined cycle power plants built around the world that use natural gas or liquefied natural gas as fuel. Although power generation is an effective way to recover cold energy from liquefied natural gas, LNG is directly used for power generation, with low cold energy utilization rate, small power generation capacity, and continuous power generation of the system, which cannot cope with the fluctuating electricity demand of users. The organic Rankine cycle has simple configuration, low operating cost, and can effectively recover low-temperature waste heat. Using liquefied natural gas as its cold source can significantly reduce condensation temperature and improve system efficiency. Therefore, combining organic Rankine cycle with LNG cold energy utilization to recover LNG cold energy is an effective utilization plan. This not only reduces carbon emissions, but also fully utilizes the cold energy of LNG.

Domestic and foreign scholars have conducted many related research on how to efficiently utilize LNG cold energy. Na Zhang et al. [2] established a power plant model using liquefied natural gas as fuel. The power plant adopts a subcritical CO2 organic Rankine cycle, which is coupled with the LNG evaporation system. The condensation process of the cycle can be achieved under conditions far below the ambient temperature, and high-pressure liquid CO2 can be obtained without consuming additional electricity. Bao [3] studied the impact of the stages of the condensation process on the performance and economy of the LNG cold energy power generation system, optimized the system, and found that the net power output of the three-stage combined cycle is the highest. However, considering the difficulty of the control system, it is recommended to use a two-stage combined cycle. Xue et al. [4] analyzed and optimized a two-stage organic Rankine cycle with exhaust gas as the heat source and LNG as the heat sink, with the unit net power output cost as the objective function. They also optimized the influence of system parameters such as the inlet pressure and working fluid flow rate of the expander. Choi et al. [5] proposed a cascaded Rankine cycle power generation system for recovering LNG cold energy, analyzed the impact of system parameters on its performance, and compared its economic performance with traditional methods. Zhang et al. [6] proposed a combined cycle utilizing LNG cold energy, including cascaded and parallel Rankine cycles. Mosaffa et al. [7] optimized and compared four different organic Rankine cycles utilizing LNG cold energy and geothermal energy using thermal efficiency, thermal efficiency, cost to power ratio, and annual cost as objective functions under different inlet pressures of NG expanders and working fluid expanders. Some scholars [8-12] have also studied the economy of ORC cycle systems with unit power generation cost as the objective function. The above researchers have provided new ideas for the comprehensive and complementary application of clean and renewable energy, as well as the efficient utilization of energy cascades, by complementing the utilization of LNG with other different energy sources and combining the application characteristics of various energy forms. Especially in terms of coupling with low-temperature organic Rankine cycle power generation systems, a lot of work has been done. Therefore, in order to improve the efficiency and economy of ORC systems, the optimization research of ORC power generation systems is also extremely important. The research on ORC technology mainly focuses on several aspects such as system structure, parameter optimization, and working fluid matching analysis. In power generation systems, the matching of working fluids with cold and heat sources, the physical properties of working fluids, and the operational efficiency and safety of the system are closely related.

In order to better utilize geothermal resources, seawater resources, and LNG cold energy, this paper proposes a new type of power generation system, analyzes the practicality of the cycle, and calculates its thermal load and power generation capacity. In addition, the optimal working fluid is selected based on its working environment conditions. Finally, the performance of the system was analyzed.

2. THE PROPOSED COMBINED POWER SYSTEM

2.1 *System scheme description*

During the LNG gasification process, seawater thermal energy is used as the heat source, while LNG cold energy is used as the cold source to generate electricity first. Combined with supplementary green energy such as geothermal or seawater source heat pumps for heating, it meets the heat load requirements of the LNG gasification process. During the gasification process, the principle of cold cascade utilization is adopted. In addition to meeting the system's operational energy consumption, LNG cold energy power generation can achieve surplus output from the external power grid, eliminate the consumption of fossil fuels such as natural gas, and achieve zero energy consumption and negative carbon emissions in the system.

As shown in Fig. 1, the temperature of LNG increases after entering the condenser of the ORC power generation system, and then enters the geothermal heating device. After geothermal water is produced, it is cooled and recharge by heat exchange with LNG through heat exchanger. After LNG absorbs heat, the temperature increases and is transported to the user. In the ORC power generation system, the working fluid absorbs the heat of seawater in the evaporator and enters the expander for power generation. Then, it enters the condenser to transfer the heat to LNG. In other non-winter seasons, seawater is used to heat the LNG after heat transfer through the condenser.

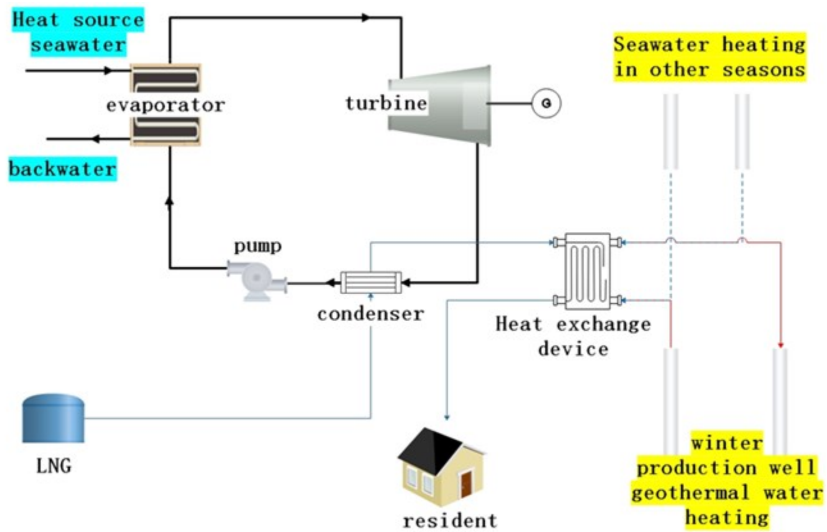

Fig. 1 System Process Flow Diagram

2.2 Calculation modeling

The processes of the organic Rankine cycle are shown in Fig. 2.

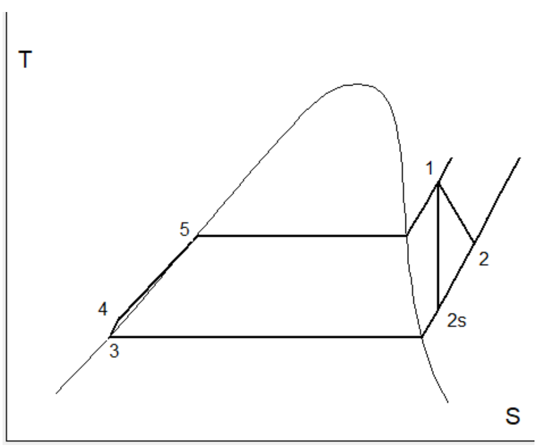

Fig. 2 T-S diagram of the organic Rankine cycle

2.2.1 Evaporator

The organic working fluid absorbs heat from seawater in the evaporator, as shown in Fig.2 4-5-1 process, changing from liquid to superheated steam. The sea water flow is m_h. The inlet and outlet temperatures are T_{in}, T_{out}. Working fluid flow rate is m_s.

Heat release from seawater:

$$Q_h=m_h*c_p*(T_{in}-T_{out}) \quad (1)$$

Heat absorption of ORC:

$$Q_1=m_s*(h1-h4). \quad (2)$$

2.2.2 Turbine

The organic working fluid expands and does work in the turbine. The isentropic expansion process is 1-2s, and the actual expansion process is 1-2.

Gross power output of geothermal power generation unit:

$$W_t=m_s*(h1-h2). \quad (3)$$

2.2.3 Condenser

The organic working fluid from the turbine transfers heat to LNG in the condenser, as shown in Fig.2 2-3.

Heat release of ORC:

$$Q_2=m_s*(h2-h3) \quad (4)$$

2.2.4 Pump

The working fluid is pumped to a high pressure by pump. The required pump work is defined as W_p.

$$W_p=m_s*(h4-h3) \quad (5)$$

2.2.5 Efficiency

Net power output of geothermal power generation unit:

$$W=W_t-W_p \quad (6)$$

Net power generation efficiency of geothermal power generation unit:

$$\eta = W/Q_1 \quad (7)$$

2.2.6 Heat balance calculation

The seawater temperature is set at 25°C in summer and 0°C in winter. The working fluid absorbs heat from seawater. LNG needs to absorb a total of 34MW of heat from -162°C to 0°C, of which 27.58MW is absorbed in the condenser. Then, 6.42MW is absorbed from the geothermal well, and the temperature rises to 0°C. The temperature of geothermal resources is set at 65°C, and each well produces 80m³/h water. The depth of the well is about 2000m and the geothermal water flow rate is about 128.4m³/h.

2.3 *Working fluids primary selection and main parameters*

Choosing appropriate organic working fluids can not only improve system efficiency, but also effectively reduce system operating costs. The selection of organic working fluids requires consideration of their thermal properties, safety, environmental protection, and economic benefits. It is recommended to choose working fluids with stable physical properties, non-toxic properties, zero ozone depletion potential (ODP), and low global warming potential (GWP). Huang Yating [13] pointed out that the selection of organic compounds should be based on environmental friendliness, matching the temperature properties of the system heat source, in order to improve the thermal efficiency of the system. Shen Ling [14] improved the optimization objectives and methods of organic Rankine cycle system working fluids by using principal component analysis to analyze and calculate thermal performance indicators such as thermal efficiency and cycle net power. Two objective comprehensive evaluation indicators were obtained: work capacity and comprehensive efficiency. ALJUNDIIH [15] and YARI [16] found that hydrocarbons have greater potential compared to traditional organic working fluids.

In this system, the circulating evaporation and condensation temperatures are lower than conventional ORC, so other factors need to be considered. The fluid will not solidify below -55℃, and the critical temperature should be higher than -55 ℃, while paying attention to its safety performance and environmental benefits. According to the above requirements, seven working fluids were preliminarily selected for simulation research, and the corresponding parameter data is shown in Table 1. The system parameters used in the calculation are listed in Table 2.

Table 1. Physical, safety and environmental data for the working fluids.

substance	boiling point ℃	freezing point ℃	critical temperature ℃	critical pressure MPa	ODP	GWP 100yr	Safety data
R290	-42.1	-187.6	96.8	4.25	0	20	A3
R41	-79	-143.3	44.13	5.897	0	97	-
R125	-48.45	-100.6	66.05	3.592	0	2800	A1
R134A	-26.1	-103.3	101.1	4.07	0	1300	A1
R152A	-25.7	-118.6	113.5	4.50	0	140	A2
R218	-36.7	-147.7	71.9	2.68	0	8600	A1
R410A	-51.4	-	70.5	4.81	0	2100	-

Table 2. System initial parameters for calculation

Parameters	data
Seawater inlet temperature	25℃
LNG gasification capacity	175t/h
Geothermal water temperature	65℃
Recharge water temperature	22℃
Turbine’s isentropic efficiency	0.75
Pump’s isentropic efficiency	0.8
Turbine inlet temperature	15℃
Condensation temperature	-50℃
Supplied pressure for LNG	0.6MPa
User LNG temperature	0℃

3. ***RESULTS AND ANALYSIS***

Through programming, the simulation calculation of the above mentioned cycle is carried out and the results are obtained. This section will introduce and discuss the calculation results of the selected working medium, and make analysis and comparison.

Change the evaporation temperature and keep the turbine inlet and outlet pressure unchanged, and the output work of each working medium is shown in Fig.3.

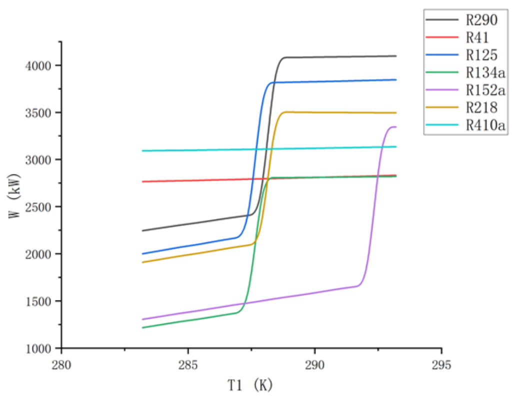

Fig. 3 Net power outputs of different working fluids with respect to evaporation temperature

Since the system uses seawater as the heat source, the evaporation temperature of the working fluid should not be too high. When the evaporation temperature fluctuates at 10-20℃, it can be seen that the net output work of R290 is the largest, and its slope mutation point occurs at about 15℃. At this time, the working medium changes from saturated state to superheated steam state at the inlet and outlet of the expander, the enthalpy drop increases, and the power consumption in the working medium pump decreases. R41 and R410a do not show inflection point, and their output power increases with temperature with a small amplitude and low value, which is equivalent to the output power of R134a and far lower than that of R290. The inflection point of R152a appears late, and apparently the evaporation temperature is not high enough to satisfy its overheating condition. The R125 and R218 are similar to the R290, but their maximum output power is smaller than the R290. Therefore, R290 was selected as the working fluid and the evaporation temperature was 15℃.

As shown in Fig. 4, when the evaporation temperature of propane R290 is unchanged, the evaporation pressure and condensing pressure are changed, and the curve of the actual cycle output work and cycle thermal efficiency is obtained.

As can be seen from the Fig.4, with the increase of evaporation pressure, the net output work and cycle thermal efficiency of R290 continue to increase, and an inflection point appears at about 730kPa. This is because when the evaporation temperature remains unchanged at 15℃, with the increase of pressure, the working medium changes from superheated steam state to liquid state. At this time, the enthalpy value of the liquid working fluid is much lower than the superheated state, and cannot do work in the expansion machine, and the net output power is greatly reduced. In addition, with the increase of condensing pressure, the net output power of propane and the cycle thermal efficiency continue to decline, so it is necessary to choose a lower condensing pressure as the best operating point. When the condensing pressure is lower than 85kPa, the working medium becomes saturated at the turbine outlet. In order to ensure that it is in the superheated steam state at the turbine inlet and outlet, the condensing pressure of the selected working condition should not be too low. Taking all factors into consideration, the evaporation pressure and condensing pressure of the optimal working condition point are 730kPa and 85kPa respectively. The net output power of the system is the highest, which is 4245kW, the circulating thermal efficiency is 13.34%, and the pump power consumption is 90kW.

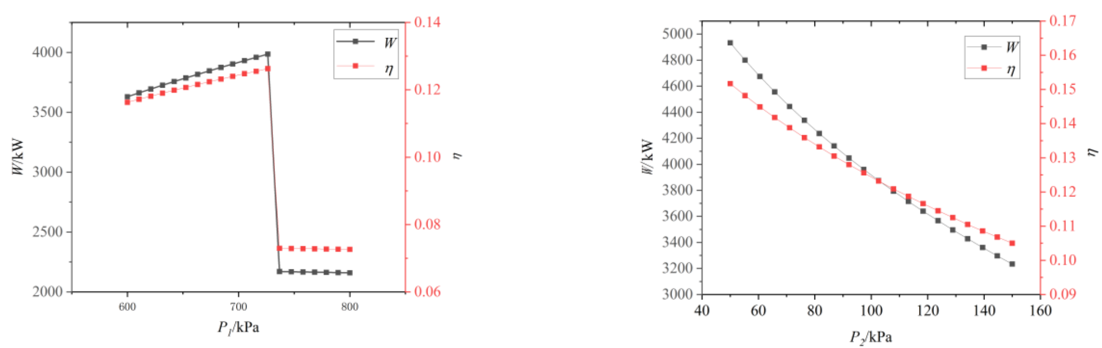

Fig. 4 The net power output and cycle thermal efficiency of propane under different inlet and outlet pressures

4. CONCLUSIONS

In this study, a multi-energy complementary LNG cold energy power generation system has been investigated numerically. Propane was selected as the best working fluid after considering all factors. Simulation showed that the proposed system can meet the required heat load. The power generation system can generate 2.47MW electricity in winter and 4.25MW in summer. It not only meets the heat load required for LNG heating, but also delivers LNG to users. The proposed system can not only make full use of the cold energy of LNG, but also reduce the emission of CO_2, achieve the purpose of energy saving and emission reduction, and obtain part of economic benefits, which is considered to be a feasible scheme. More investigation need to be carried out to further analyze the techno-economics of the proposed system.

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