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CONSTRUCTION AND ANALYSIS OF LNG COLD ENERGY UTILIZATION SYSTEM

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КОНСТРУКЦИЯ И АНАЛИЗ ЭНЕРГИИ ПОПУТНОГО СЖИЖЕННОГО ПРИРОДНОГО ГАЗА

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Abstract. The theme of this research is the intermediate fluid vaporizer (IFV) gasification system for an offshore liquefied natural gas floating storage regasification unit (LNG-FSRU). Based on reducing the loss of heat exchange and improve the cold energy utilization, an LNG cold energy utilization system combined with Rankine cycle power generation and desalination is proposed. On this basis, six different schemes of working medium combination are simulated and analyzed, and the optimal scheme of working medium combination is found. The results show that the net output power of the system is 5591 kw, and the system exergy efficiency is 30.38%. The annual economic benefit is CNY 39.4 million.

Аннотация. Темой настоящего исследования является система газификации промежуточного жидкостного испарителя для морской плавучей установки регазификации сжиженного природного газа. На основе снижения потерь теплообмена и повышения эффективности использования холодной энергии предложена система утилизации холодной энергии в сочетании с выработкой электроэнергии по циклу Ренкина и опреснением. На этой основе смоделированы и проанализированы шесть различных схем комбинирования рабочих сред, а также найдена оптимальная схема комбинирования рабочих сред. Результаты показывают, что чистая выходная мощность системы составляет 5591 кВт, а эксергетический КПД системы — 30,38%. Ежегодная экономическая выгода составляет 39,4 миллиона юаней.

Keywords: cold energy utilization, Rankine cycle, desalination.

Ключевые слова: утилизация уходящих газов, цикл Ренкина, опреснение.

Introduction

With the increasingly severe environmental conditions and the rising prices of oil and other resources, natural gas is becoming more and more popular as a clean and environmentally friendly energy source. LNG releases about 830KJ/kg of cold energy from liquid to gaseous state [1], because the LNG regasification process contains a large amount of cold energy, it can separates air and light hydrocarbons in the low-temperature region, cold energy generates power and desalinates seawater in the low middle-temperature regions, cold storage and air conditioning and refrigeration application in the normal temperature region [2-3]. In recent years, there are mainly six kinds of LNG cold energy power generation technologies. They are direct expansion method, Rankine cycle method, combined cycle method, Brayton cycle method, Karina circulation method and multi-stage compound circulation method. Lv Jianxiong etc [4] compared and analyzed the cold energy utilization processes of the above six schemes, and found that the direct expansion method and the Rankine cycle method can be used in small gasification stations and LNG-FSRU because of simple process, the multi-stage compound circulation method and the Karina circulation method is more suitable for large-scale receiving stations for cold power generation because of complex process. Kenichi Kaneko etc. [5] proposed a MGT (mirror gas turbine) multi-stage compression and expansion LNG cold power generation scheme. Using multi-stage compression and multi-stage heat exchange, LNG cold energy can be used step by step. Cui Guobiao etc. [6] established one to five Rankine cycle cold energy utilization schemes based on the principle of cold energy cascade utilization. Analysis shows that the LNG cold energy utilization rate and the cold efficiency recovery rate of the multi-rank Rankine cycle are much higher than that of the simple Rankine cycle. However this solution is too complex and too large to be used in LNG-FSRU systems, Yang Hongchang etc. [7] constructed a horizontal three-rank Rankine cycle system based on the principle of LNG cold energy sub-utilization, and built a longitudinal three-rank Rankine cycle and two-stage pumping optimization scheme based on the reduction of cycle losses. Gao Yuan etc. [8] proposed a secondary media method based on the purpose of reducing heat transfer losses. This method transfers seawater heat to liquid intermediate medium, and the intermediate medium absorbs heat and vaporizes to generate electricity through the turbine. Heat exchange with LNG after work, reduce system energy loss by reducing temperature difference. He Hongming, Zhang Lei etc [9-10] compared the efficiency of the commonly used Intermediate media of the Rankine cycle and found that R290, R125, R1270 and R134a have higher working efficiency and are more suitable for LNG cold energy recovery. Huang Meibin etc. [11] conducted a comparative analysis of the direct refrigerant freezing method, indirect freezing method, and vacuum evaporation freezing method. The study found that direct freezing method has high heat transfer efficiency, small equipment size, and less auxiliary equipment. The indirect freezing technology is relatively mature, but the heat transfer efficiency is not as good as the direct method, and the equipment too much that is not easy for LNG ship. The vacuum evaporation type is strictly controlled near the triple point of seawater, which is difficult to control and difficult to operate. It is not suitable for seawater desalination. Jiang Kezhong etc. [12] used the traditional LNG cold energy freezing method seawater desalination as background, The analysis shows that the combination of LNG cold energy cryogenic distillation and cryogenic distillation or LNG cold energy freezing combined with other membrane processes is the new direction for the development of new technologies using LNG cold desalination. However, from the existing literature reports, there are still relatively few studies on the utilization of LNG cold energy on the emerging FSRU platform. The theme of this research is the intermediate fluid vaporizer (IFV) gasification system for an offshore liquefied natural gas floating storage regasification unit (LNG-FSRU). Based on reducing the loss of heat exchange and improve the cold energy utilization, a comprehensive utilization system combining Rankine cycle power generation and desalination is proposed provide technical support for LNG-FSRU cold energy utilization system.

Material and research methods

As shown in Figure 1, the system is a combined of Rankine cycle power generation and desalination, which uses the LNG cold energy cascade utilization principle to recover LNG high-grade and low-grade cold energy, respectively. The system consists of four parts, the first three parts are Rankine cycle power generation, which is used to recover LNG high-grade cold energy, and the fourth part is seawater desalination cycle, which is used to recover LNG low-grade cold energy. LNG from storage tank is vaporized and heated by four LNG heat exchangers after pressurization, and finally regulated by LNG exchanger 5 to send out the user's demand temperature. Seawater as the sole heat source provides heat to LNG exchanger 5 and working fluid evaporator 3, and the working fluid of the third-stage Rankine cycle turbine outlet is diverted as the second-stage Rankine cycle working medium evaporator heat source and LNG heat exchanger 3 heat source respectively, Similarly, the working fluid of the second-level Rankine cycle turbine outlet is used as the heat source of the first-stage Rankine cycle working medium evaporator and the LNG heat exchanger 2, and the first-stage Rankine cycle working medium is used as the heat source of the LNG heat exchanger 1. Thus, a longitudinal three-stage Rankine cycle power generation and seawater desalination composite system is formed.

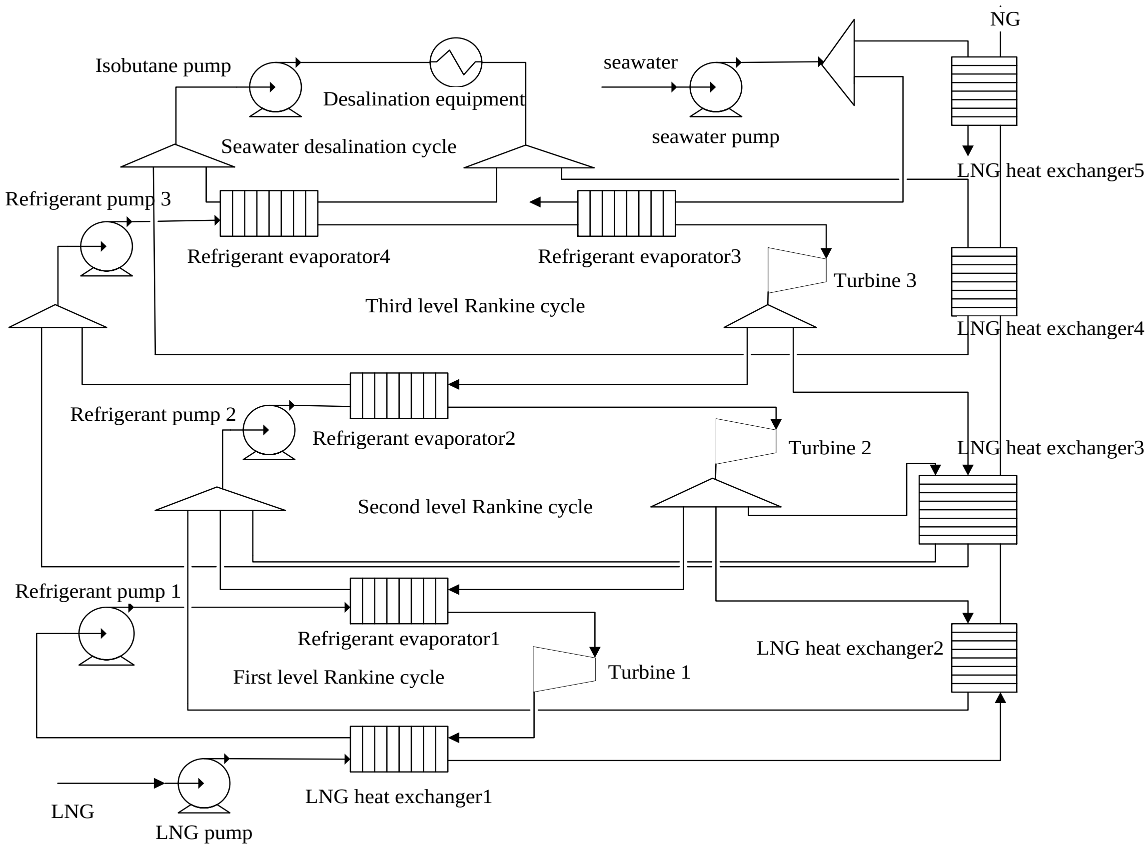

Figure 1. Flow chart of cold power generation and desalination.

As shown in Figure 2, The system recycled the cold energy that originally flowed into the sea through the middle working fluid. Then processed desalination of seawater by freezing, the intermediate working medium of seawater desalination recovers the cold energy of LNG and the third working medium first, and then heat exchanged in the crystallizer with the seawater. And then formed a circulation with the LNG heat exchange liquefaction, the ice brine in the crystallizer is

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separated in the scrubber using fresh water washing. The scrubbing water separates part of the produced fresh water and is used exclusively for washing. In the ice melting device, seawater is used to melt the ice crystals, and at the same time, the seawater can also be precooled so that it can be continuously making fresh water.

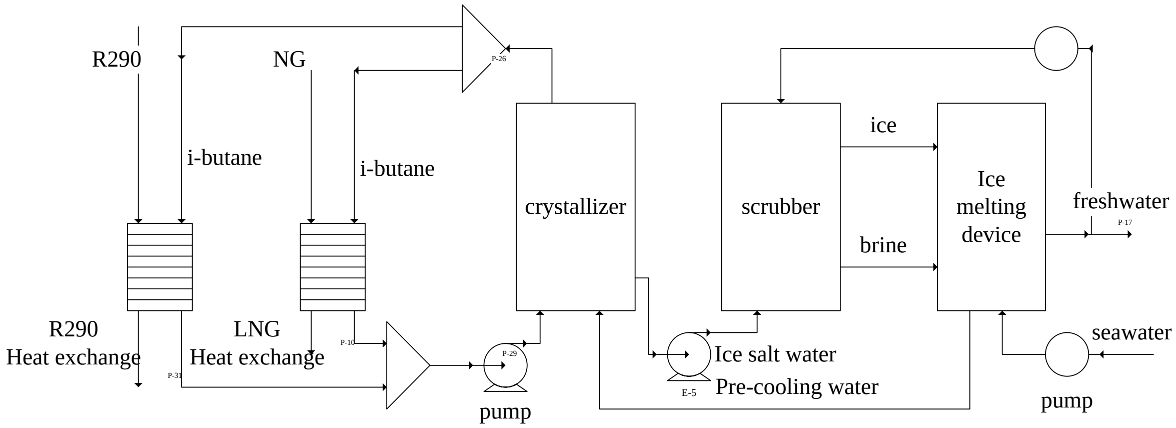

Figure 2. Seawater desalination flow chart.

In the system simulation, LNG takes 95% methane, 3% ethane, 2% propane, and the re-vaporization pressure of FSRU is designed 8 MPa.

According to the above system flow chart 1, when using HYSYS to simulate, use the following initial settings:

1. LNG flow rate is 175 000 kg/h, neglecting all heat exchanger pressure loss, and the pressure after gasification heating is 8 MPa.

2. The condensation pressure of the initial working fluid is 0.11 Mpa.

3. In all heat exchangers, the outlet supercooling degree of heat flow working substance is 2°C.

4. The minimum end difference of heat exchanger is 2°C.

5. The working state of the turbine inlet is saturated gas.

6. Ignore all heat exchanger leakage loss;

7. Turbine expander efficiency is 80%, pump efficiency is 75%.

8. The temperature of sea water is 20 C and the ambient temperature is 2°C.

The physical parameters of seawater and ice are shown in Table 1 below.

Table 1.

PHYSICAL PROPERTIES OF SEAWATER AND ICE

project	*parameter*
Freezing point °C	-2
Seawater specific heat capacity KJ/(kg.°C)	4.096
Ice specific heat capacity KJ / (kg. ° C)	2.100
Solidification exotherm KJ/(kg.°C)	334.7
Mass flow rate kg/h	237572
Inlet temperature °C	20

The crystallization load Q required for seawater desalination is simulated by Aspen Hysys, and then the seawater flow and freshwater flow are calculated by the following formula (1).

$$Q = m_{(seawater)} c\Delta t + m_{(ice)}\gamma \quad (1)$$

Where, Q is crystallization load, $m_{(seawater)} c\Delta t$ is a load of seawater cooling to the freezing

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point, $m_{(ice)}\gamma$ is the seawater crystallization load, c is the specific heat capacity of seawater, Δt is the temperature drop in seawater cooling, γ is the ice melting heat.

Total efficiency of the system:

$$\eta_{nx} = \frac{W_{net}}{Ex_{LNG} + Ex_{seawater}} \quad (2)$$

In the formula, Wnet is determined as the sum of turbine output power and seawater desalination recovery refrigerant, ExLNG is the exergy of LNG entering the system, and Exseawater is the exergy of seawater entering the system.

Considering the amount of LNG cold energy released on the FSRU and the cascade matching of LNG cold energy release and recovery, the selection of working medium is very important. A set of matching working medium can effectively reduce the loss of cold energy and improve the efficiency of cold energy utilization. The condensation temperature of common working medium under 110kpa is shown in Table 2.

Table 2.
CONDENSATION TEMPERATURE OF COMMON WORKING MEDIUM UNDER 110KPA

R1150	*R170*	*R23*	*R116*	*R1270*	*R143a*	*R290*	*R717*	*R134a*	*R152a*	*R600a*
102.6°C	87.22°C	80.53°C	77.20°C	46.16°C	45.38°C	40.55°C	31.44°C	24.24°C	22.61°C	9.93°C

Considering that the higher the temperature of liquefied natural gas is, the lower its cold energy grade will be, and the lower the power generation efficiency will be, and natural gas exported by LNG heat exchanger 3 is used for desalination. Therefore, the initial selected LNG heat exchanger 3 outlet gas temperature is below -45°C.At the same time, the working medium selection should meet the minimum end difference of 5°C for the heat exchanger. Therefore, according to table 2, the working medium with temperature close to - 40°C, R290, R143a and R1270 can be used as the third stage circulating working medium. However, R143a is not considered due to its high global warming potential (GWP). When R290 and R1270 were selected as the third working medium, the natural gas temperature at LNG heat exchanger 3 outlets was - 45.55°C and - 51.16°C respectively. Due to the temperature of LNG after being pressurized by pump is - 158°C, and after the third stage circulating working medium is selected, the temperature range from LNG heat exchanger 1 inlet to LNG heat exchanger 3 outlets in LNG cold energy power generation system is -158°C to -45.55°C or -158°C to -51.16°C. The working medium meeting the requirements of primary and secondary stage Rankine cycle are R1150, R170, R23, R116 and R1270 respectively. Due to R116 belongs to fluoride, it will not be considered here. When the secondary stage Rankine cycle working medium is R1270, the third Rankine cycle working medium can only be R290. The selection of working medium for desalination requires that its evaporation temperature is close to and lower than the sea water freezing point, and its solidification temperature is lower than -45°C (ensure that the desalination working medium will not solidify during heat exchange with low temperature LNG). By analyzing the physical properties of common refrigerants, R600a is the best working medium for seawater desalination. The specific combination scheme is shown in Table 3.

In HYSYS, simulation calculations are performed for different working medium combinations in Table 3. The fluid properties package is Peng-Robinson. The net output power of the system is shown in Figure 3. The working medium dryness of the three turbine outlets under each combined working medium is shown in Figure 4.

Table 3.

WORKING MEDIUM MATCHING SCHEME

Working medium combination	*First stage working medium*	*Second stage working medium*	*Third stage working medium*	*Desalination working medium*
scheme 1	R1150	R23	R1270	R600a
scheme 2	R1150	R23	R290	R600a
scheme 3	R1150	R1270	R290	R600a
scheme 4	R170	R23	R1270	R600a
scheme 5	R170	R23	R290	R600a
scheme 6	R170	R1270	R290	R600a

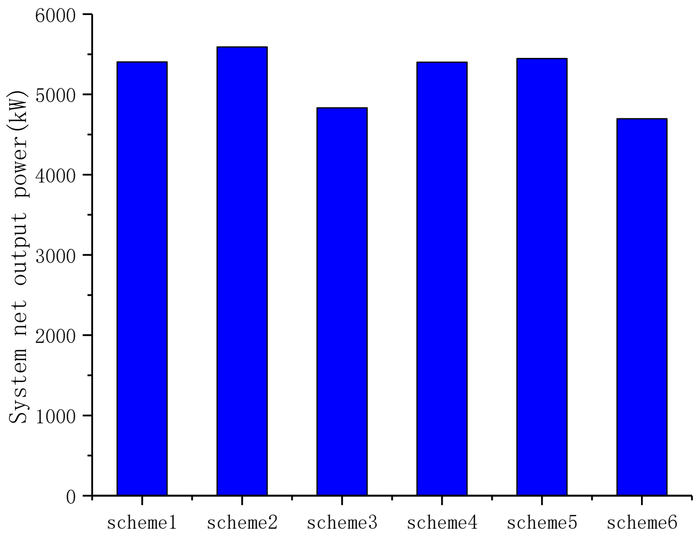

Figure 3. Net output power for each combination of working medium.

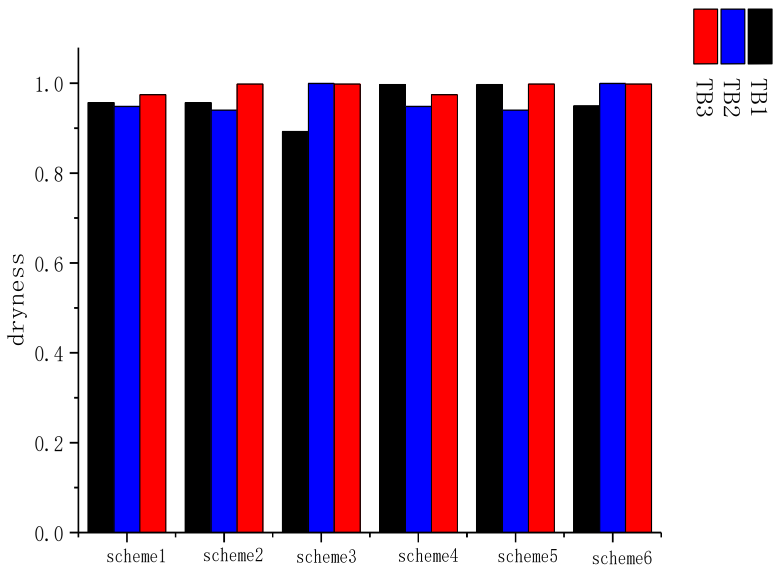

Figure 4. Working medium dryness at the three turbine outlets for each combination of working medium.

From Figure 3, it can be found that when working medium combination 2 (R1150, R23, R290, R600a) is used, system can reach the maximum net output power, which are 5591kW. From Figure 4 the dryness of working medium combination 4, combination 5 and combination 6 is relatively good, but the net output power of the system is relatively low, while the dryness of working medium 1 of combination 3 is 0.892, and the water content is too large, which is easy to erode the turbine blades. The working medium at the outlet of each turbine in scheme 2 is 0.957, 0.940 and 0.998 respectively, which can ensure the normal operation of the turbine. In addition, in combination with the net output power of each working medium combination, when R1150, R23, and R290 are the first, second, and third working mediums, respectively, R600a as desalination working medium, the system performs best.

Results and discussion

The exergy analysis results of the power generation and seawater desalination system are shown in Table 4.

Table 4.

EXERGY ANALYSIS RESULTS
OF POWER GENERATION AND SEAWATER DESALINATION SYSTEM

Equipment	*Consumption exergy(KW)*	*Obtain exergy(kW)*	*Exergy loss (kW)*	*Exergy efficiency*
LNG heat exchanger1	9567.542	6296.85	3270.69	65.8%
LNG heat exchanger2	3055.403	2467.873	587.53	80.8%
LNG heat exchanger3	5368.319	3785.788	1582.53	70.5%
LNG heat exchanger4	1655.597	855.0567	800.54	51.6%
LNG heat exchanger5	250.0139	230.7083	19.31	92.3%
Refrigerant evaporator1	5389.379	4975.014	414.37	92.3%
Refrigerant evaporator2	5378.769	4629.319	749.45	86.1%
Refrigerant evaporator3	2951.861	1109.448	1842.41	37.6%
Refrigerant evaporator4	959.9272	589.9689	369.96	61.5%
Refrigerant pump 1	6.708333	1.678611	5.03	25.0%
Refrigerant pump 2	27.86111	18.94778	8.91	68.0%
Refrigerant pump 3	94.19444	26.54056	67.65	28.2%
Isobutane pump	4.502778	1.675556	2.83	37.2%
LNG pump	1095.278	98.875	996.4	9.0%
Sea water pump	1078.056	957.3025	120.75	88.8%
Turbine 1	909.15	635.2778	273.87	70.0%
Turbine 2	2627.518	1857.778	769.74	70.7%
Turbine 3	5811.068	4380.556	1430.51	75.4%
Exergy loss of the system (kW)			12812	
Net output power of system (kW)			5591	
Generation capacity (kW)			4529	
Desalination yield (t)			118	
Exergy efficiency of the system			30.38%	
Refrigerants			R1150,R23,R290,R600a	

According to Table 4, it can be found that the exergy loss of each equipment in the system is mainly concentrated in the heat exchanger. It can be considered to transform the heat exchanger or change the working medium to make the heat exchange curve more matching. The total exergy loss of the system is 12812kw, the net output power of the system is 5591kw, the generating capacity is 4529 kw/h, the desalination capacity is 118 tons/h, and the total exergy efficiency of the system is 30.38%.The economic benefits of the system are as follows: the unit price of electricity is CNY 0.86 per kW/h (The data came from China's industrial electricity sales prices, considering that there are many factors involved in the calculation of electricity price, this paper selects the minimum electricity price among various possibilities), and the unit price of fresh water is CNY 5/ton. The system's annual running time is calculated as 7300 hours [13], the system economic benefit is CNY 39.4 million per year.

Conclusion

Based on the theory of cold energy cascade utilization, a comprehensive utilization system of LNG cold energy, which is composed of power generation and seawater desalination, is constructed, and six different working medium combination schemes are matched for this system, when R1150, R23, and R290 are the first, second, and third working mediums, respectively, the system performs best.

Through the recovery of LNG gasification cold energy, it can generate 4,529 kW per hour, produce 118 tons of fresh water, and generate economic benefits is CNY 39.4 million per year, which greatly reduces the waste of cold energy and generates great economic value.

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