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Design and Simulation Analysis of Cold Energy Utilization System of LNG Floating Storage Regasification Unit

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Abstract. This paper aims at the problem of cold energy utilization of LNG floating storage regasification unit (FSRU). A comprehensive LNG-FSRU cold energy utilization scheme was proposed based on ship-shore sharing. Using energy cascade theory and energy conservation theory to design a cold energy cascade utilization system that includes air separation, dry ice making, horizontal two-stage Rankine cycle power generation, seawater desalination, ship refrigerated storage, air conditioning and ice making. Using Aspen HYSYS to carry out system simulation calculation and parameter optimization to determine the optimal program and operating parameters. Establishing the mathematical model of the cold exergy utilization system to analysis cold energy efficiency by using the Peng-Robinson equation calculation method. The analysis results show that the using efficiency of cold exergy reaches 29.57% which proves that the cold utilization system of the floating LNG storage regasification plant is reliability with large economic value.

1. Introduction

The rapid growth of natural gas trade has promoted the development of LNG terminals. However, at the present stage, land LNG receiving stations have some problems, such as land space limitation, difficulty in examination, approval and cost which causes the construction of conventional LNG receiving stations to take a long time and produce slow development. The LNG Floating Storage Regasification Unit (LNG-FSRU) is more economical than a conventional LNG receiving station and has flexible gas supply and short construction period. It is suitable for environmentally sensitive areas or densely populated areas, and is characterized by large-scale equipment, safety, and environmental protection. In recent years, the global LNG-FSRU inventory has increased from 13 to 21 vessels, and no dismantling has been seen. From the perspective of the new orders, the LNG-FSRU transaction volume is relatively stable, with 2-4 new or modified orders each year. The LNG-FSRU gasification output volume is



determined by the gas consumption of onshore LNG users. The gasification output volume is very large, and the resulting gasification cooling energy is also huge. Take Tianjin LNG-FSRU as an example, the LNG gasification pressure is 7.2MPa, and the peak gasification volume can reach 320t/h [1]. The gasification output is divided into peak period and normal period, and the resulting cold energy is shown in Table I. However, the existing gasification technologies mainly use open-frame gasifiers (ORVs) and submerged combustion gasifiers (SCVs). The two technologies above use seawater or combustion BOG to obtain a heat source to directly heat and vaporize LNG. The enormous low-temperature cold energy generated by LNG is greatly wasted, and it will cause the sea water temperature in local sea areas to rise, and the ecological environment will also be affected. In addition, in the process of using SCV gasification technology, a large amount of BOG is consumed, resulting in waste of energy. At the same time, LNG-FSRU is located near shore and has the conditions for transporting cold energy products to shore. So, the development and utilization of LNG-FSRU cold energy have broad economic prospects and social significance.

This paper proposes a comprehensive utilization scheme of LNG-FSRU cold energy based on ship-shore sharing, aiming at the problem of cold energy utilization in re-gasification equipment for floating LNG storage. The cold energy utilization system includes air separation, dry ice making, horizontal two-level Rankine power generation, seawater desalination, ship cold storage, ship air-conditioning and ice-making, and the forms of cold energy use are determined by using energy cascade theory. Then, using Aspen HYSYS software for system to carry out simulating calculation and parameter optimization. Finally, the system is simulated and the operating parameters under different operating conditions are calculated through force-control configuration software, providing theoretical guidance and technical support for the comprehensive utilization of LNG cold energy, and providing application of LNG cold energy in other fields. Reference at the same time.

Tab. 1 Quantity of Gasification and Cold Energy

Item	Peak Period	Normal Period
Air supply Quantity, t·h ⁻¹	320	180
Air supply Quantity, t·h ⁻¹	2.251×10 ⁸	1.266×10 ⁸

2. Designing cold energy utilization solutions

2.1. Introduce the research object and operating conditions

This article takes the LNG-FSRU ship named “INDEPENDENCE” as the research object which was built by Norway Hoegh Company, and the specific operating parameters are shown in Table II:

Tab. 2 Lng-Fsru Relevant Parameter

NAME OF PARAMETER	Value
Capacity/m ³	170000
Main engine power/kw	2.251×10 ⁸
Population type	Diesel engine
Designed speed /kn	19.5
Cargo mix. Pressure /MPa	0.025
LNG booster pressure/MPa	12
Outlet pressure /MPa	5-11
Outlet temperature /°C	10-20
LNG latent heat of vaporization (KJ/kg)	510.25
Quantity of vaporization /(m ³ /h)	1400

2.2. Determine cold energy utilization steps and forms

LNG-FSRU cold energy can be used independently in cold storage, air conditioning and low temperature power generation, which will cause large losses in cooling capacity [2]. Assume that the user system is a heat source and LNG is a cold source, and the amount of cooling is consumed by the entire process based on the conservation of system energy, and then,

$$E_{x,Q_0} = \int_1^2 \left(\frac{T_0}{T} - 1 \right) \delta Q_0 = \left(\frac{T_0}{\bar{T}} - 1 \right) Q_0 \quad (1)$$

In formula (1), T_0 represents the heat source temperature, Q_0 represents the heat load, and \bar{T} represents the average temperature of the LNG in this process. When the heat load is constant, the greater the temperature difference between the LNG temperature and the user's system, the colder exergy are consumed. Therefore, the energy cascade theory is introduced in the design of the cold energy utilization system, and the cold energy of the LNG is divided and used according to the temperature segment which reduces the temperature difference of LNG production and the consumption of cold exergy.

Air separation and dry ice preparation subsystems are set up in the LNG-FSRU cold energy utilization system. On land, the LNG cold energy is used for air separation, but a larger rectification tower device is needed, and the LNG-FSRU is near-shore mooring which is relatively stable compared to other navigation vessels, although the balancing problem of distillation towers still needs to be considered. Air separation requires a lower cold source temperature. Therefore, the air separation is set in the first place of the LNG-FSRU cold energy utilization system. In the subsystem of LNG-FSRU cold energy utilization, dry ice and liquid carbon dioxide are prepared by a low-temperature method. The CO₂ gas source is supplied by land and the products are delivered to onshore industrial users. Due to the convenience of raw material supply and product transportation, the LNG gasification process can be performed, and the amount of released cooling is properly configured to produce dry ice production.

A horizontal two-stage Rankine cycle power generation subsystem is set up on the LNG-FSRU. The output temperature of the liquid LNG from the cargo tank is generally stable within the range of -162°C to -155°C . After the air separation and dry ice preparation device, the total amount of cold energy and cold exergy is large, continuous and stable [3]. This part of cold energy can be considered for low-temperature cold energy power generation. LNG-FSRU cold supply has the following salient features: First, the supply of cooling capacity is very large; second, the range of available temperature (LNG temperature) spans a large range [4]. Horizontal two-stage Rankine cycle power generation is divided into two levels for the use of cold energy, reducing the operating load of single-stage power generation equipment and the investment cost of equipment effectively, while increasing the temperature span of LNG cold energy utilization and increasing the amount of power generation.

The ice making subsystem is set up on the LNG-FSRU. To increase the utilization efficiency of cold energy and combine with market demands and the utilization forms of LNG cold energy, an ice-making system can be added at the last stage of the LNG-FSRU cold energy utilization system. The demand for ice products in summer is relatively large, and it is the opposite in winter. Ice production can be adjusted according to the supply of cold.

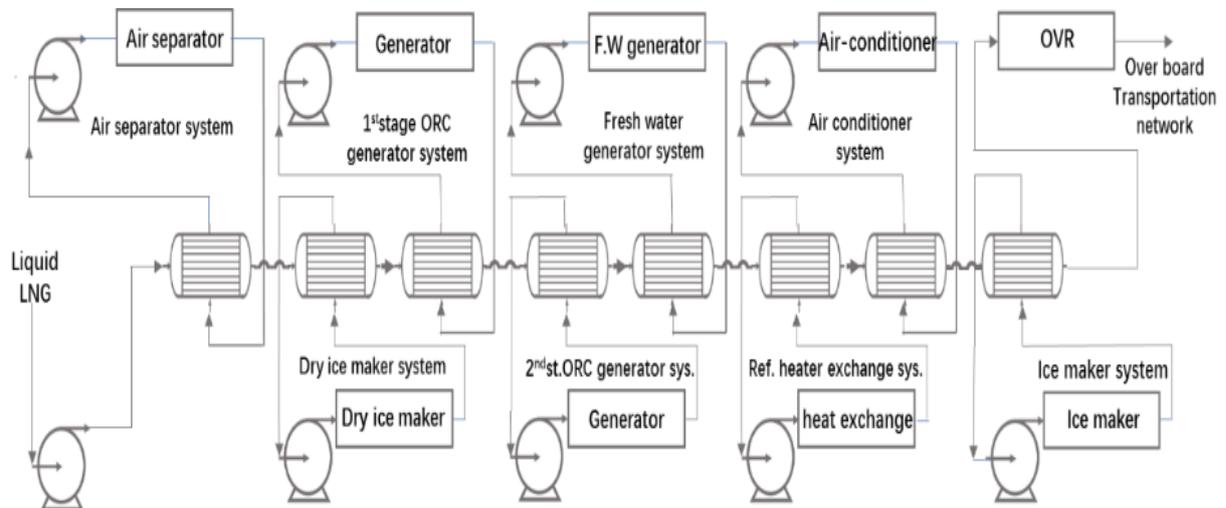


Fig. 1 Overall design of cold energy utilization of LNG FRSU

2.3. Designing a program for Cold Energy Utilization

Based on the above principles and forms of cold energy utilization, it is finally determined that LNG-FSRU's forms of cold energy utilization are air separation, preparation of dry ice, horizontal two-stage Rankine generators, desalination, ship refrigeration, ship air conditioning and ice maker according to the utilization efficiency of cold energy. The overall design scheme is shown in fig.1. Due to sloshing, heat dissipation and other reasons, LNG-FSRU generates a certain amount of BOG in different cargo tanks. During the re-liquefaction process, it needs to consume cryogenic liquid LNG which has a certain impact on the cold energy utilization system. Therefore, the cold energy utilization system should consider this part of the cold energy consumption [5]. After the BOG being mixed with LNG from different cargo tanks, it provides cooling capacity for the above cold energy utilization subsystems in order, and finally it is heated to the outside temperature of the pipeline network through seawater and delivery to land user.

3. Simulation process and determination of operating conditions

3.1. Simulating system workflow based on HYSYS

Taking the summer conditions and the near-empty cargo tank level as an example. Currently, the BOG temperature is relatively high about $-100\text{ }^{\circ}\text{C}$. Simulating the process workflow of comprehensive utilization of the cold energy of the transport ship by using Aspen HYSYS software, and the heat transfer is mainly calculated. The loss of pipeline is ignored. With the effect of resistance, the isentropic efficiency of the pump was set to 85%, and the isentropic efficiency of the expander was 80%. Establishing an LNG-FRCU cold energy simulation flow chart as shown in fig. 2.

3.2. Cold energy utilization system refrigerant selection

The large amount of LNG-FSRU gasification and the direct heat exchange between LNG and FSRU subsystems will not only bring about large potential safety hazards, but also make the maintenance work of each part extremely difficult [6]. Therefore, it is very important to use a reasonable refrigerant medium to bring the LNG cooling capacity out to the various cold energy utilization systems. The selection basis and scheme of the refrigerants in each subsystem are similar. Therefore, the selection process of the refrigerant in the cold energy utilization system is only illustrated by the analysis of the refrigerant selection in the two-stage Rankine cycle power generation system

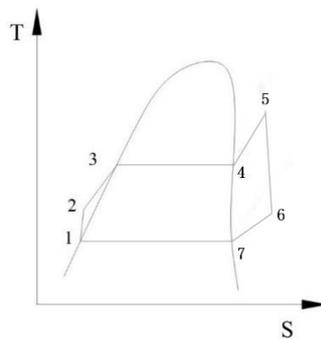


Fig. 3 Rankine Cycle Power Generation Process T-S Diagram

Single-stage Rankine cycle power generation system has low cold exergy efficiency, which is mainly caused by excessive heat exchange temperature difference. This article proposes a system of a two-stage Rankine cycle power plant with horizontal "parallel" in order to improve the process as shown in fig.2. Compared to a single-stage Rankine cycle system, two-stage system has added a cryogenic stage cycle in order to improve the matching of the working fluid condensing curve and the LNG temperature rise curve, making full use of LNG cryogenic range cold capacity exergy to reduce exergy damage and improve system exergy efficiency. mainly through technical means. The low-temperature Rankine cycle power generation process of this system is shown in fig. 3. The low-pressure gaseous refrigerant is condensed into the liquid state point 1 and exchanges heat with the low-temperature LNG in the heat exchanger HEX-3, then pressurized to the supercooled state by the high-pressure pump to reach the state point 2, then enter the heat exchanger HEX-3-1 and be heated by seawater to the state point 5, then enters the expander to do work and changes to the low-pressure gas state point 6. At last, the refrigerant enters the heat exchanger HEX-3 to exchange with the low temperature LNG Heat, to complete a Rankine cycle power generation process.

In order to realize the above process, the first-stage low-temperature Rankine cycle refrigerant should be condensed into liquid by low-temperature LNG, and the LNG temperature should not fall below $-112\text{ }^{\circ}\text{C}$ to meet the demand for subsequent seawater desalination, low-temperature cold storage, high-temperature cold storage, and air-conditioning cooling energy. At the same time, considering that the heat transfer issues the heat exchange efficiency of the heat exchanger, the condensing temperature of the first Rankine cycle must be higher than $-92\text{ }^{\circ}\text{C}$ when the exhaust pressure of expansion less than or equal to 100 kPa. The second-stage high-temperature Rankine cycle refrigerant in the exhaust gas and other heat source temperature (About $200\text{ }^{\circ}\text{C}$) should be evaporated to a gas state. Considering the heat transfer temperature difference of the heat exchanger, the evaporation temperature (saturation temperature) of the high-temperature circulating refrigerant should be lower than $180\text{ }^{\circ}\text{C}$ after the high-pressure pump is pressurized (the pressure is about 3 MPa). To reduce the difficulty of regasification system construction and the reliability of system operation and maintenance, LNG needs to be kept at the HEX-3 exit. At the same time, in addition to the Rankine cycle power generation system, the refrigerant should be kept as liquid as possible to

facilitate the circulation of the system to avoid the control difficulties and high costs brought about by the phase change of the refrigerant.

It is assumed that the inlet of the turboexpander is in the saturated gas state, and the pressure and heat loss of the heat exchanger in the system are ignored. The minimum end difference of the working substance evaporator and the working fluid condenser is 5°C , and the efficiency of the turboexpander is 80%, and the efficiency of the pressurized pump is taken as 75%, and the performance of each refrigerant in the system at different evaporation temperatures is simulated and calculated using HYSYS software.

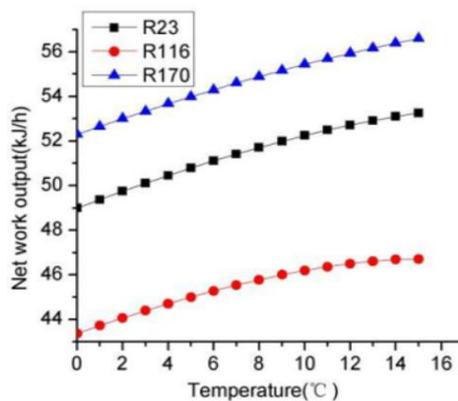


Fig. 4 Effect of 1st evaporation temperature on net work

Fig.4 shows the effect of evaporation temperature on the net output work of the system. When the outlet pressure of the turboexpander is constant, the higher the evaporation temperature of the working fluid, the greater the inlet pressure and the greater the output power. Due to the relatively low operating pressure, the R116 also has a small net output. When the R170 evaporation temperature is 15°C , the net output power of the system reaches 56.6kJ/h , which indicates that R170 performs good expansion.

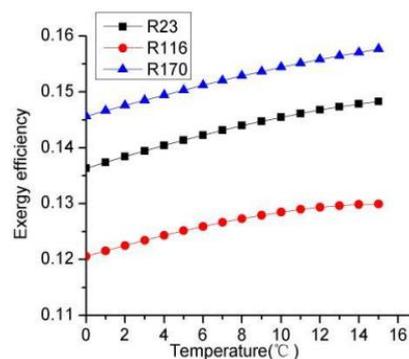


Fig. 5 Effect of 1st evaporation temperature on net work

Figure 5 shows the effect of low temperature evaporation temperature on the system efficiency. The higher the evaporation temperature is, the higher the system efficiency is, and we can find that the highest efficiency is R170 according to the figure. Therefore, the best choice of low-temperature Rankine cycle refrigerant is R170.

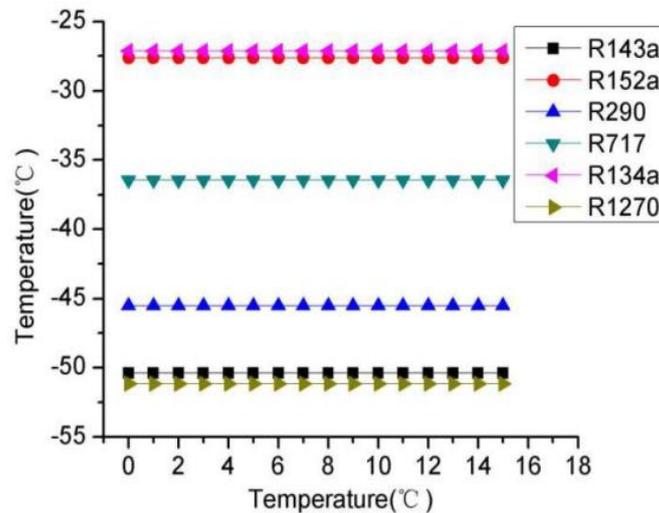


Fig. 6 Corresponding NG temperature of each fluid

Fig. 6 shows the temperature of HEX2 outlet NG at different evaporation temperatures for each cycle of the working fluid. In the evaporation temperature range of 0°C - 15°C , the NG temperature corresponding to each working medium is constant, and the NG temperature of R1270 is the lowest. It is conducive to the renewal of the refrigerant following the desalination of seawater, the cold storage of ships, the air conditioning of ships, and the production of ice.

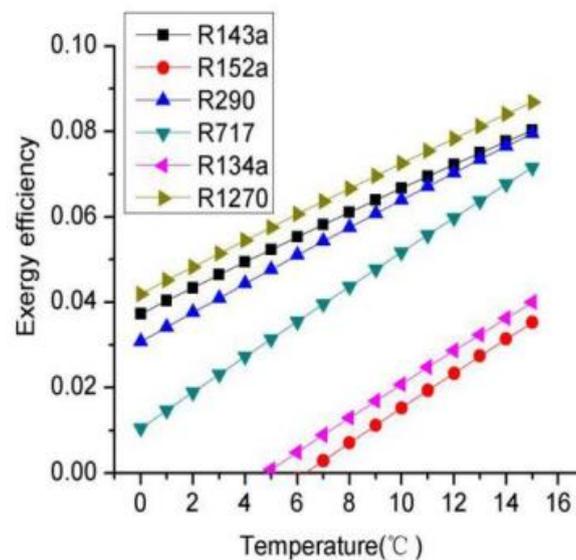


Fig. 7 Effect of 2nd evaporation temperature on exergy efficiency

Fig. 7 shows the effect of the evaporation temperature of the circulating working medium on exergy efficiency of the system. The higher the evaporation temperature, the higher the system efficiency. Among them, the net power output by the R1270 is the largest, and its cycle efficiency is the highest. Therefore, the best refrigerant for the second stage high-temperature Rankine cycle is R1270.

In LNG-FRCU, air separation, dry ice making, seawater desalination, ship refrigerated storage, ship air conditioning, and ice making subsystems are similar, and according to the above refrigerant determination method, refrigerants from other subsystems can be obtained, as shown in Table III.

Tab. 3 Refrigerant choice & characteristic of LNG-FSRU cold energy utilization system

Cold Energy Utilization System	Ref. Choice	Refrigerant Characteristic			
		Critical Pre. (kPa)	Critical Temp. (°C)	Boiling Point (°C)	Freeze Point (°C)
Air Separator	R1150	5040	9.2	-104	
Dry Ice Maker	Ref. Mixture	4.26	96.8	-42	-187
1 st Stage RC Generator	R170	2979	19.65	-78.2	-100.7
2 nd Stage RC Generator	R1270	4618	91.8	-51.1	-185
Fresh Water Generator	R601a	3330	187.8	27.8	
Low-temp. Ref. storeroom	R600	3790	151.9	-0.5	
High-Temp. Ref. storeroom	R600	3790	151.9	-0.5	
Air Conditioner	R601	3860	196.6	36	

4. Parameter optimization and cold EXERGY analysis

4.1. System parameter optimization

Taking exergy efficiency as the objective function, Aspen HYSYS software simulation system was used to calculate the impact of various parameters on the objective function [8]. At the same time, considering the specific working conditions and related limitations of LNG-FRCU, the parameters of each part are optimized. Taking the determination of NG-2 temperature in Fig. 2 as an example, the main parameters of the cold energy utilization system are analyzed and optimized, and the optimal parameter settings are finally determined [9]. After the liquid LNG fuel is output from the cargo tank through an air separation and dry ice preparation device, it is suitable for two-stage Rankine cycle power generation. It is required that the liquid LNG is still in the low temperature range, the released cold exergy is relatively large and stable, and the LNG and BOG after Rankine recycling are used at the same time. To meet the requirements of subsequent Rankine cycle, seawater desalination, ship refrigerated storage, ship air conditioning and ice making systems for cold energy, the temperature change range of NG-2 section should not exceed -90°C. The total system exergy efficiency and Rankine cycle exergy efficiency with NG-2 temperature changes are shown in Fig.8 through the HYSYS simulation.

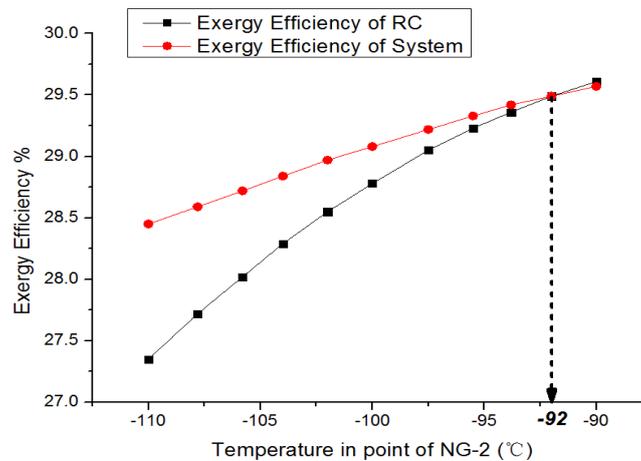


Fig. 8 Effect of Temperature of NG-2 on system performance

Due to the increase of NG-2 temperature, the cold exergy released by the liquid LNG is more used for cold power generation and meets all levels of utilization. Cold exergy increases the temperature of NG-2, and the overall system efficiency and Rankine cycle tend to increase linearly. As shown in Fig. 8, the optimal temperature of NG-2 is generally set at approximately -92°C which Guarantee the rationality of cold energy design and simulation.

Similarly, the other optimized key parameters of the cold energy utilization system can be determined in same method, and the other optimized key parameters is shown in Table 4.

Tab. 4 Lng-Fsru Relevant Parameter

Point No.	material composition	Tem p. (°C)	Pressu re (kPa)	Flow ($\text{kg}\cdot\text{h}^{-1}$)
1	LNG	-160.98	210	2620
NG-1	NG	-122.43	300	5247
NG-2	NG	-92.0	300	5247
NG-3	NG	-44.09	300	5247
E-2-2	R1150	-151.97	1200	3530
E-21	Ref.Mixture	-101.93	100	4003
A-2	R116	-77.95	110	3766
A-5	R116	-76.11	1320	3766
A-2-3	R1270	-51.96	120	4081
A-3-3	R1270	-49.75	3500	4081

4.2. System cold exergy utilization analysis

The Peng-Robinson equation calculation method was used to establish a mathematical model for the cold exergy utilization of the LNG-FRCU cold energy utilization system based on Aspen HYSYS [10]. Assume that e_x is the physical mass of unit mass fluid, G_j represents the mass flow of refrigerant j, and E_x represents the total system exergy, then

$$e_x = h - h_0 - t_0(S - S_0) \quad (2)$$

$$E_x = \sum_{j=1}^n (G_j \cdot e_{x,j}) \quad (3)$$

In formula (2), t_0 is the ambient temperature, h and S are the enthalpy and entropy of the refrigerant in the corresponding state, and $e_{x,i}$ represents the cold exergy released by the evaporation of refrigerant j per unit mass flow.

Since the system is designed with a two-stage Rankine cycle power generation device, it is assumed that W_i is based on the energy conservation law. The energy equation of the power equipment of the Rankine cycle power generation system is:

$$W_i = G_{i,in} | h_{i,out} - h_{i,in} | \quad (4)$$

The network of the power system working medium in the Rankine loop is W_{net} :

$$W_{net} = W_{HT} - W_{Ph} \quad (5)$$

According to the law of conservation of energy, the mathematical model of the utilization efficiency of LNG-FSCU cold energy utilization system by the formula (2)-(4) is η_{cold} .

$$\eta_{cold} = \frac{E_{x,out} + W_{net}}{E_{x,in}} \quad (6)$$

$$= \frac{\sum_i (G_{R,i} e_{x,R,i}) + \sum_i W_{net,i}}{G_{LNG} e_{x,LNG}} \quad (7)$$

In the formula, $G_{i,in}$ is the flow rate of the power generation material entering the power plant of i, and $h_{i,out}$ and $h_{i,in}$ are the power generation fluids flowing out and input to the power plant of i. The value of $W_{net,i}$ is the net work performed by the Rankine cycle for the working medium of the power generation system of i. $W_{HT,i}$ and $W_{Ph,i}$ are the power consumed by the high-pressure expander output work and the high-pressure pump of i respectively.

It is assumed that the components of LNG are all methane. data in Table I ~IV and the parameters obtained from process simulation based on HYSYS are substituted into the η_{cold} cold hydrazine utilization formula (6), and the LNG-FSCU cold energy utilization after optimization parameters can be calculated. The result of the optimized system cold exergy utilization efficiency η_{cold} is 29.57%.

5. conclusion

- Taking LNG-FSRU as the research object, designing the system for comprehensive utilization of LNG-FSRU cold energy which was based on energy cascade theory and conservation theory. This system includes air separation, preparation of dry ice, horizontal two-stage Rankine cycle power generation, seawater desalination, ship refrigerated storage, ship air-conditioning, and ice-

making.

- The system of comprehensive utilization of LNG-FSRU cold energy and research results provide theoretical guidance and technical support for the comprehensive utilization of ship cooling energy, which is conducive to energy saving and emission reduction of ships and is in line with the development trend of green shipping.

- Using Aspen HYSYS for system simulation calculation and parameter optimization, determining the types of system refrigerant and the optimization values of the main parameters. A mathematical model of cold exergy utilization efficiency was established based on the Peng-Robinson equation calculation method.

- The exergy utilization efficiency of the optimized cold energy utilization system reaches 29.57% which proves the rationality and reliability of the system.

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