Thermodynamic Analysis and Optimization for Cold Energy Utilization Based on Low Temperature Rankine Cycle Of LNG-FSRU Regasification System

Shouguang YAO1,a*, Hui LIU1,b,Liang TANG1,c,Yong YE2,d, Lianwei ZHANG2,e

1 Jiangsu University of Science and Technology, No.2 Mengxi Road Zhenjiang Jiangsu PRC,202003
2 CSSC Shenghui equipent CO LTD, No.3 Lianjiang Road Zhangjiagang Jiangsu PRC,215600
azjyaosg@126.com b931683499@qq.com

***Abstract* — A LNG cold energy utilization regasification system based on low temperature Rankine cycle for LNG-FSRU is built and reported on in this paper. Comparative thermodynamic analysis of six kinds of working fluid have been done . Studies have shown that seawater as a heat source, R290 is the preferred working fluid, exergy loss occurs mainly in the working fluid condenser. With a lower temperature stage cycle, R170 as the working fluid, exergy loss in the working fluid condenser is reduced, exergy efficiency of the system is increased from 8.1 % to 15.6 %.**

Keywords - LNG-FSRU regasification system, Cold energy utilization, Low temperature, Rankine cycle, Exergy analysis

I. INTRODUCTION

Floating Storage and Regasification Unit is a kind of new type of offshore LNG receiving unit. In recent years, it has rapid development in the world [1-3]. Refasification system as regasification plant of FSRU is the core of dealing with high pressure and low temperature LNG [4]. Intermediate Fluid Vaporize (IFV) is the most commonly type of regasification. It use working medium (R290、R600a etc) [5]for passing heat from seawater to LNG to gasification. It effectively avoid the risk of seawater freezing for LNG directly gasify seawater. figure 1 is the process of IFV system. It include Carburetor, gas heater, intermediate medium evaporator, intermediate medium circulating pump and sea water pump.

LNG is input by high-pressure pump and gasifys gas state through absorbing the heat of seawater in intermediate medium evaporator. Then being cooled as liquid in LNG vaporizer. Then the liquid enter into saving box. The last it is pumped by pump to the evaporator to complete the cycle. It will cost Power consumption about 850 kw h to producing one ton of LNG. And in LNG gasification process, LNG will release cold energy about 830~860kJ/kg[6]. Normally, this part of the cold energy are directly taken by the sea. It not only caused a great deal of energy waste, even damage to natural environment. Reasonable using this cold energy has positive meaning to improve energy efficiency and environmental protection.

LNG cold energy utilization technology has been widely attention in the world. Document [7] developed a technology that combined LNG cold energy with ice storage refrigeration. It plays the role of balance of power load, significantly save electricity of users. Document [8-10]carry out system analysis and optimization design to the technology of LNG cold energy for refrigeration. Document [11]analysis summarized 6 application which has been put into use nowadays.

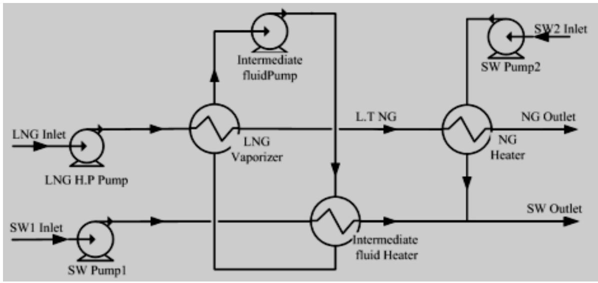


Fig.1 FSRU regasification system diagram

Document [12-13] achieve cold energy cascade utilization by combining LNG cold energy power generation with cooling. We can see that LNG cold energy utilization technology is in a variety of forms, LNG cold energy utilization technology has a bright prospect. At present, Japan's LNG cold energy utilization technology led the world. Cold energy for generating is the most widely application. About 50% of the LNG cold energy is used to generate electricity [14]. However, LNG cold energy utilization mainly revolves around land receiving terminal. By using cold energy of FSRU regasification system generate power. It can become a kind of Marine power station which combine natural gas transmission with power supply.

II. COLD ENERGY UTILIZATION BASED ON LOW TEMPERATURE RANKINE CYCLE OF LNG-FSRU REGASIFICATION SYSTEM

A. System Process

The process of cold energy utilization for Regasification system Of Single stage's Rankine circulation at low temperature is shown in Fig.2, LNG is pressurized by high-pressure pump becoming the high pressure LNG （A1） . Then going through LNG gasification device（HEX2）become the low temperature NG（A2）. Finally in NG thermostat, NG is heated as the demand of transmission state. To meet the demand of long distance gas supply in LNG Regasification system, LNG always vaporised at supercritical pressure [15]. On the other way, in the Working medium evaporator（HEX1）, working medium （C4）absorbs the heat of the sea water to superheated steam condition（C1）then entering the expansion turbine to generate. After that the working medium reduce pressure and temperature as the exhaust gas（C2). the exhaust gas heat transfer with LNG in the LNG gasifier and reduce temperature as subcooled liquid, then being pressurized by pump to go through Working medium evaporator（HEX1）.All of that are the Low-temperature Rankine cycle.

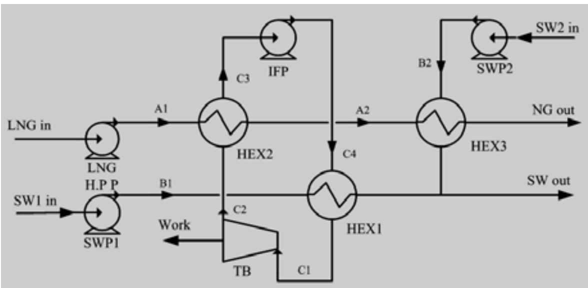


Fig.2 Single-stage low-temperature Rankine cycle cold energy utilization regasification system diagram

B. The Analysis of System Thermodynamics

Fig.3 Low-temperature Rankine cycle T-S diagram

The equal entropy efficiency of the turbine expander is η_T. So the Actual output work is

$$W_T = q_m(h_1 - h_{2'}) = q_m \eta_T (h_1 - h_2) \qquad (1)$$

Pump efficiency is η_P, so the actual power consumption of pump is:

$$W_P = q_m(h_{4'} - h_3) = q_m(h_4 - h_3)/\eta_P \qquad (2)$$

Assume that the heat exchanger were no heat loss. By the first law of thermodynamics

$$Q = q_{mH}(h_{H,in} - h_{H,out}) = q_{mC}(h_{C,out} - h_{C,in}) \qquad (3)$$

The net output power of system is:

$$W_{net} = \sum_i W_{T,i} - \sum_j W_{P,j} \qquad (4)$$

For heat source water input heat to the system for Q, the thermal efficiency of system is:

$$\eta = \frac{W_{net}}{Q} \qquad (5)$$

The exergy of fluid each state point is:

$$Ex = q_m[(h - h_0) - T_0(s - s_0)] \qquad (6)$$

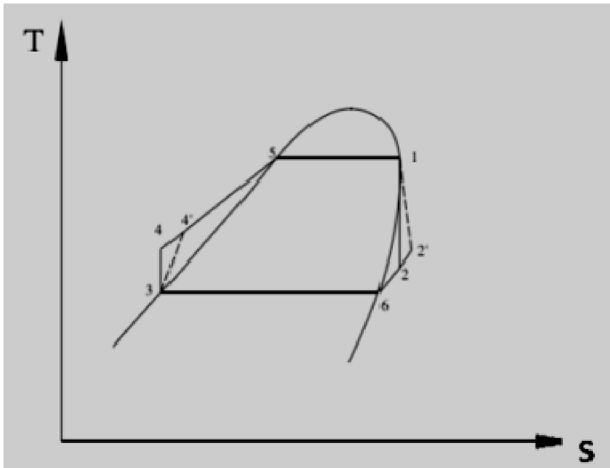


Fig. 3 is the Low-temperature Rankine cycle T-S diagram

.

The exergy efficiency of system is:

$$\eta_{ex} = \frac{W_{net}}{Ex_{LNG} + Ex_{SW}} \qquad (7)$$

The way of The cost exergy, Earnings exergy, exergy efficiency calculation method is shown in table 1. [16].

TABLE 1 CALCULATION METHOD

equipment	cost exergy	Earnings exergy	exergy efficiency
pump	WP	Qm (exout-exin)	Qm (exout-exin)/WP
Turbine expander	Qm (exin-exout)	WT	WT/ [qm(exin-exout)]
heat exchanger	qm1(ex1in-ex1out)	qm2(ex2out-ex2in)	qm1(ex1in-ex1out)/qm2(ex2out-ex2in)

DOI 10.5013/IJSSST.a.17.30.35

ISSN: 1473-804x online, 1473-8031 print

C. The Cycle Working Medium

In this paper, we simplify the composition of LNG, only considering Methane, ethane, and propane, and take the mole fraction of 95%, 3% and 2% respectively of LNG as the research object. The critical temperature Tr is -68.16, the critical pressure Pr is 5.74MPa, which is found by REFPROP8.0. For the convenience of comparison. The amount of LNG gasification is 1kg/h. LNG is from the initial state (0.5MPa, -162 C) into the system, vaporization on Supercritical pressure (8MPa). Heated it to over heated gas (8MPa, 5) output. And ignore the pressure drop of the heat exchanger. The working medium condensing pressure is 0.11MPa, Degree of supercooling of the HEX2 outlet is 2°Cand the inlet working medium of the turbine expander is saturated. Terminal difference of the heat exchanger is 5℃ [17]. ηT=80%, ηP=75%. The parameters of heat source water and LNG is shown in Table 2.

TABLE 2 PARAMETERS OF SINGLE STAGE SYSTEM

Project & logistics	The temperature (℃)	Pressure (KPa)	gas phase fraction	Flow (kg/h)
LNG in	-162	500	0	1
A1	-158	8000	0	1
A2	----	8000	1	1
NG out	5	8000	1	1
SW1 in/SW2 in	20	150	0	----
B1/B2	20.05	750	0	----
SW out	15	750	0	----

In the supercritical pressure, LNG gasify As temperatures rise directly to complete gasification at the superheated steam zone. In this paper, the author studies on LNG, the critical temperature is 68.16 ℃, critical pressure is 5.74 MPa, and meet the demand that Terminal difference of the heat exchanger is 5℃.our work medium is that at the 0.11MPA,the saturation temperature is greater than 68.16 ℃.So that Ensure the LNG gasification in HEX2 and NG thermal control at the HEX3.According to the requirements, we Preliminary select R143a, R152a, R290 and R717, R1270 six kinds of working medium.

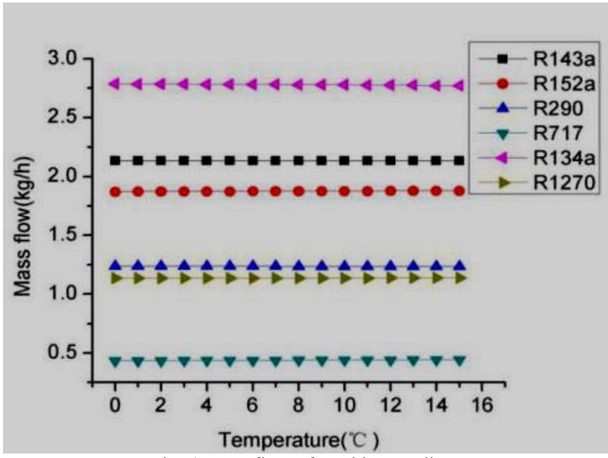


Fig. 4 Mass flow of working medium

Fig.4 is on different evaporation temperature condition the mass flow of the working medium. In HEX2 the import and export pressure and temperature of the working medium have been identified, so the evaporation temperature basicly has no effect on the mass flow rate.mass flow rate of the R134a is 2.8 kg/h, being 7 times of R717.the mass flow rate of R290 and R1270 are close, which is about 1.2kg/h.

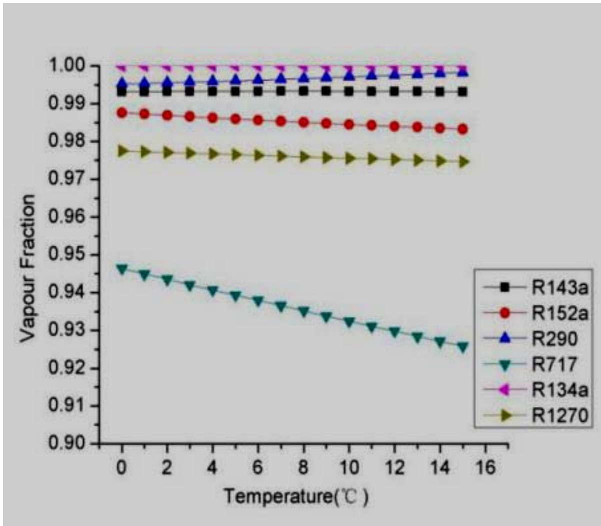


Fig.5 Vapour fraction of working medium

That caused by two aspects reasons. On the one hand when working medium is R134a HEX2 export NG is at higher temperature,HEX2 thermal load is bigger. On the other hand the latent heat of vaporization of working medium is different.Fig.5 shows , on different evaporating temperature, Turbine expander export gas phase fractions of each working medium. With the increase of evaporation temperature. At the Turbine expander export ,gas phase fraction of the R717 decreases from 0.945 to 0.925.The other five kinds of working medium gas phase fractions are above 0.975,and Under the influence of evaporation temperature is smaller.

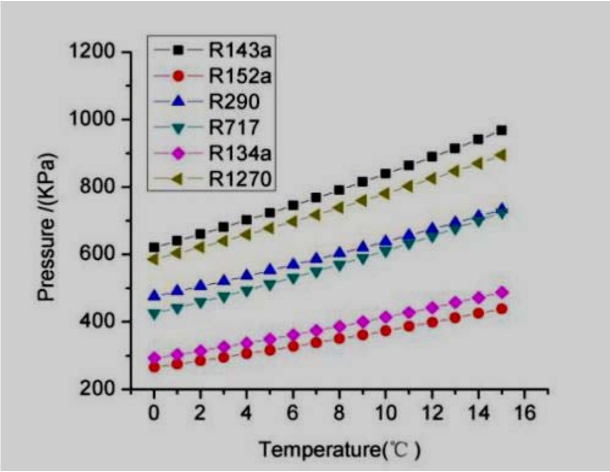


Fig.6 Pressure of working medium

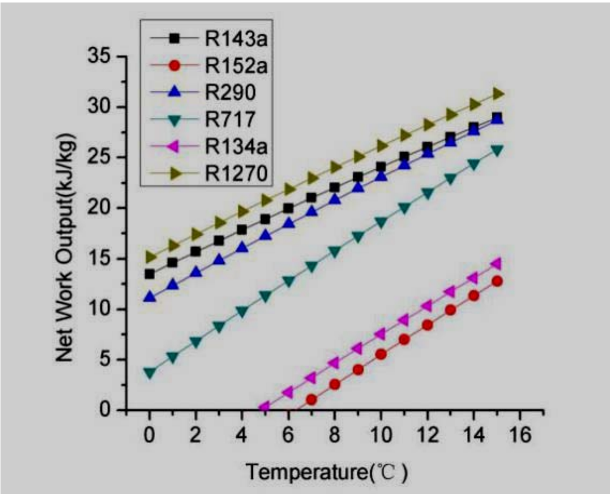
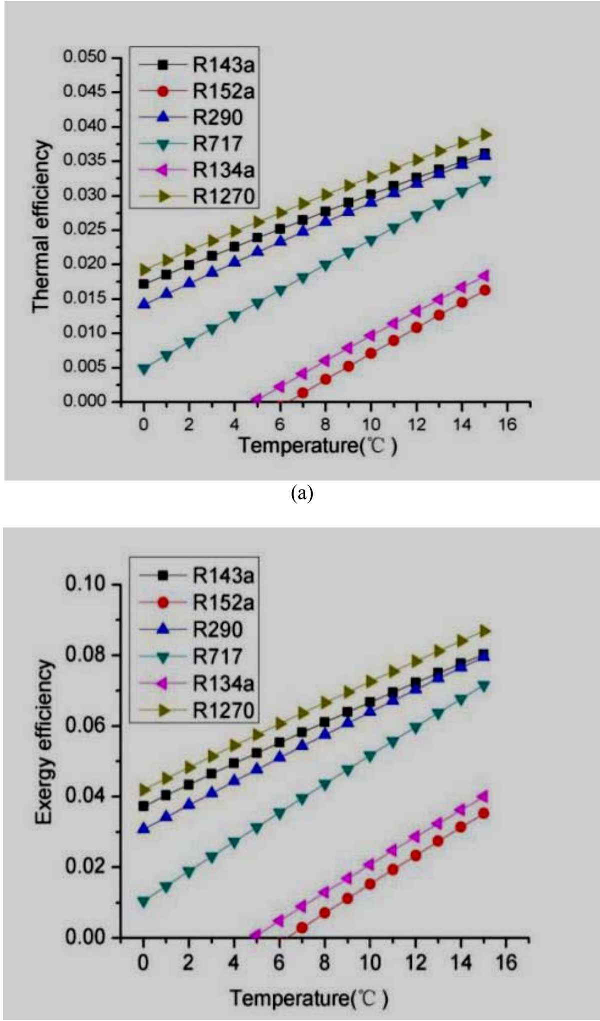


Fig.7 Net work output

Fig.6 shows that on different evaporation temperatures the turbine expander inlet working medium pressure and evaporation temperature correspond to the saturation pressure working medium can be divided into three groups, R143a and R1270 evaporating pressure is relatively high, R290 and R717 are the second group,R134a and R152a is relatively low. When the evaporation temperature is 15 ℃, pressure of R143a is 0.96 MPa, pressure of R134a is 0.48MPa, pressure of R152a is 0.43MPa.Fig.7 show that the more evaporation temperature is, the greater the net output power of the system is, so The higher heat source temperature, the more advantageous to the LNG cold energy utilization. With the increase of evaporation temperature, the output work of using R290、R717 is faster growing. When the evaporation temperature is more than 5,only using R134a、R152a can system have the net output power. This means that under the condition of low temperature of seawater in winter system cannot "compensation" power consumption of each pump.



(b)
Fig.8 Efficiency of the system

Fig.8 shows that working medium evaporation temperature has influence on the efficiency of the system. the higher Evaporation temperature is, The higher the efficiency of system is. When R134a and R152a is working medium the efficiency is low. When the evaporation temperature is 15 ℃. exergy efficienc of R1270 is the highest 8.7%. exergy efficienc of R290 and R143 both are 8.1%,In the six working medium shows good cold energy utilization.

The above six kinds of working medium , R143a cycle efficiency has good performance, But the GWP value is high. The system of using R134a、R152a net work and efficiency is low. turbine expander export gas phase fraction of R717 is relatively low.so superheating temperature is higher.R1270 in net output power and efficiency is slightly better than R290. But in export pressure and dryness of export turbine expander ,R1270 is worse than R290.Overall considerations ,we choose the R290.

D. The Analysis of Exergy Loss

With R290 being working medium, according to the calculation method of table 1 and we can figure out the results. Analysis the proportion of each equipment's exergy. We can see the results in Table 3.

TABLE 3 EXERGY ANALYSIS OF SINGLE STAGE SYSTEM

Equipment	Cost Exergy (KJ/h)	Earnings Exergy (KJ/h)	Exergy loss (KJ/h)	Exergy Efficiency	Proportion of Exergy
HEX1	39.706	15.211	24.495	38.3%	7.3%
HEX2	370.371	147.017	223.354	39.7%	67.3%
HEX3	38.933	5.014	33.919	12.6%	10.2%
TB	108.395	82.099	26.296	75.7%	7.9%
LNGPP	22.532	2.635	19.897	11.7%	6%
IFPP	1.764	1.084	0.68	61.5%	0.2%
SWPP1	21.896	19.452	2.444	88.8%	0.7%
SWPP2	7.218	6.412	0.806	88.8%	0.2%
Sum	610.815	278.924	331.891	------	100%

The most proportion of exergy is working medium cooler. It is 67.3%. It is caused by the loss of irreversible of heat transfer is too large because wide thermal difference between heat fluid and cold fluid, and part of the phase state is not stable.

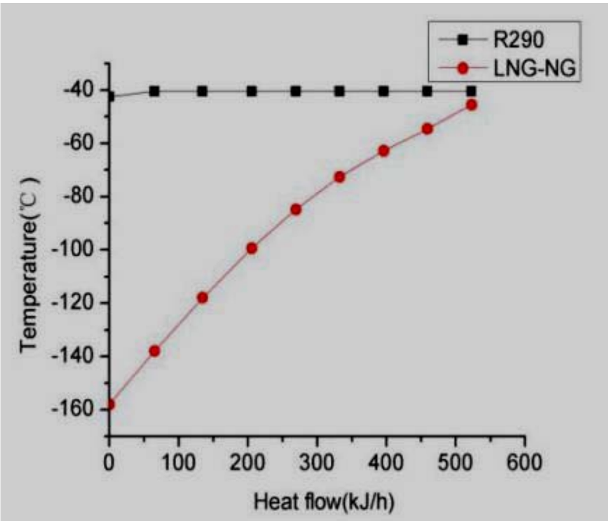


Fig.9 Temperatures in HEX2

Logarithmic mean temperature difference of hex1 is 3.66℃, logarithmic mean temperature difference of hex2 is 35.25℃.Fig.9 shows the relationship of the temperature and Heat flow. Obviously temperature variation curve matching of the 3 heat exchanger is not good.

III. SYSTEM IMPROVEMENT.

A. Introduction of System Process

As shown in Fig.10 for two stage's circulation cold energy utilization system in low temperature. Compared with the single stage circulation system, it add the low temperature cycle. LNG is heated by working medium in hex2,and then it is gasificated in hex4.

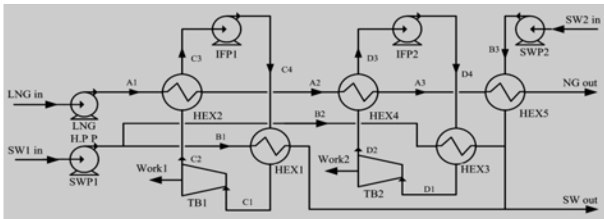


Fig.10 Double-stage low-temperature Rankine cycle cold energy utilization regasification system diagram

B. The Choose of Working Medium of High and Low Temperature Cycle

We use the R290 as the high temperature level cyclic working substance. Temperature of NG2 at HEX4 export is -45.55 ℃.

For ensuring LNG is still in a liquid state at HEX2 exit, we choose the working medium which the saturated temperature is lower than -68.16 ℃ in 0.11MPa. R23、R116 、 R170 is our initial separation as the low temperature level cyclic working substance. The corresponding LNG temperature of LNG at HEX2 export respectively is - 87.02 ℃, -83.09 ℃, -83.09 ℃.

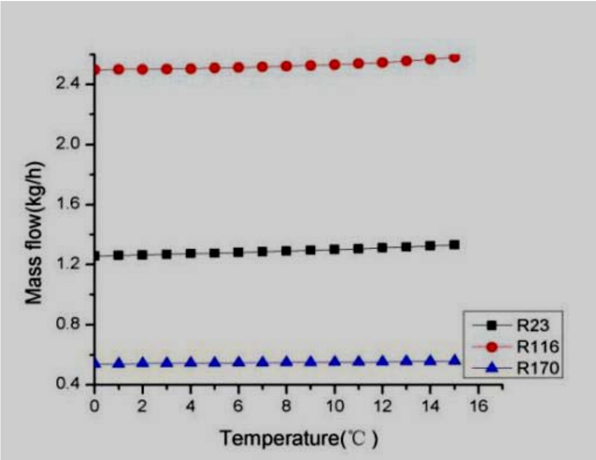


Fig.11 Mass flow of LT working medium

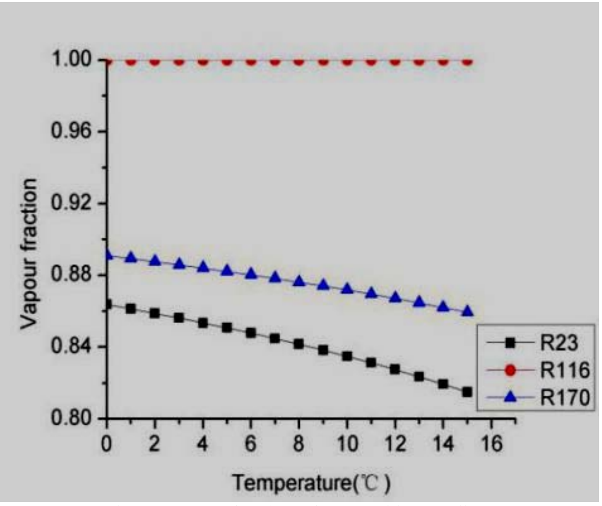


Fig.12 Vapour fraction of LT working medium

Fig.11 shows that grade low temperature cycle working medium mass flow increases with evaporation temperature rise slightly. Evaporation temperature under the condition of same quality of three kinds of working medium flow rate differences, the mass flow of R116 is about 5.5 times of R170, This is mainly determined by the working medium of the latent heat of bigger difference. Fig.12 shows the different evaporation temperature in the low temperature stage to the dry degree of each working fluid of the turbine expander. On the whole, the dry degree of R23 and R170 decreased with the increase of evaporation temperature, When the evaporation temperature is 15 ℃, the outlet of R23 is 0.81,Under the same conditions, the export of R170 is more than R23;R116 for dry working medium, The dryness of the outlet is not affected by the evaporation temperature.

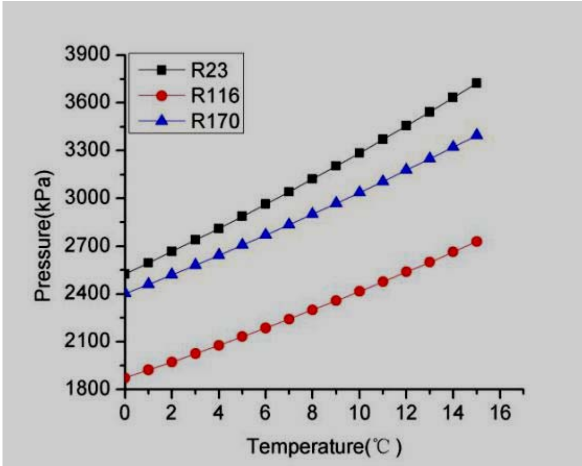


Fig.13 Pressure of LT working medium

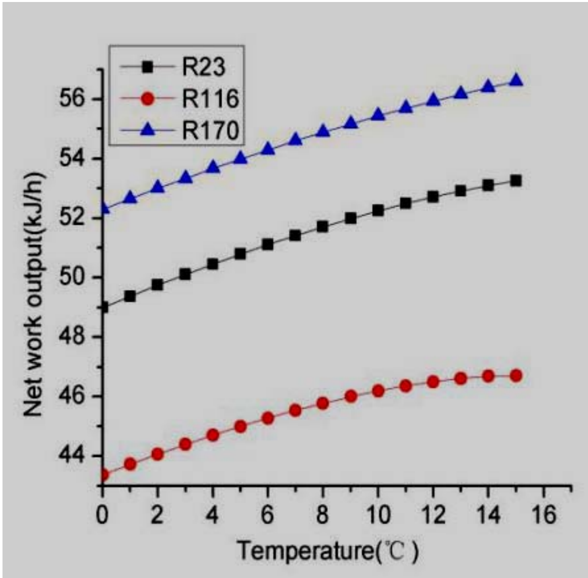
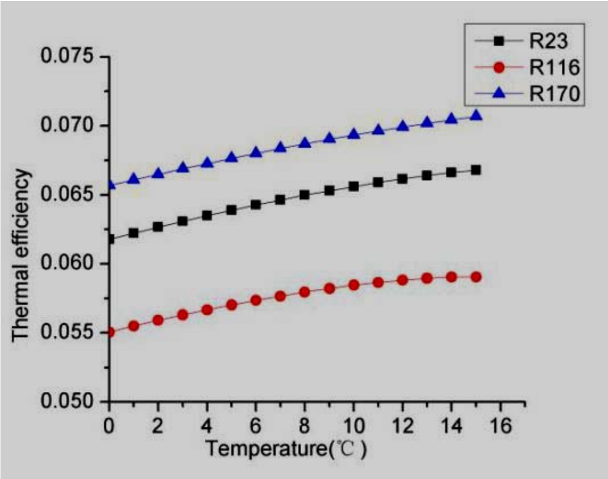


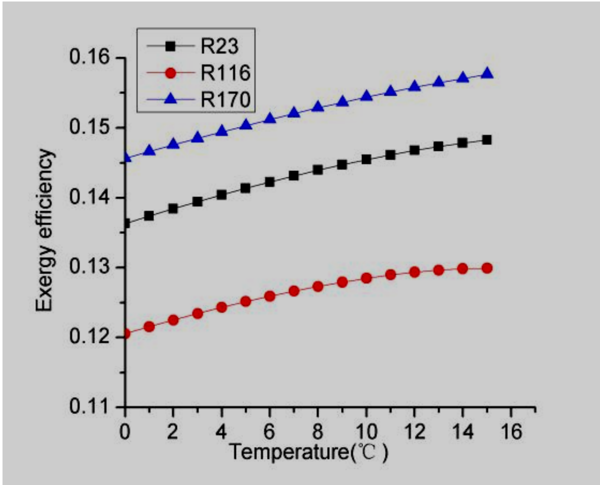
Fig.14 Net work output of double-stage system

Fig.13 shows that the temperature of the low temperature circulating refrigerant is corresponding to the inlet pressure of the turbine expander, the working medium saturation pressure. The higher evaporation temperature corresponds to the higher saturation pressure. When the evaporating temperature is 15 ℃,The pressure of the three working fluids were 3.7MPa, 3.4MPa, 2.7MPa.Fig.14 shows the effect of evaporation temperature on the net output power of the system, In general, the outlet pressure of the turbine expansion machine is at a certain time, The higher the working fluid temperature is, the higher the inlet pressure is, The output power is larger. The working pressure of R116 is lower, Net output of the system is smaller. The working pressure of R170 is less than R23, as shown in Fig.13, and the mass flow rate is less than R23,The system is bigger than the net output power R23;When the evaporation temperature of 15 ℃,net output of the system to achieve 56.6kJ/h.



(a)
Fig.15 Efficiency of double-stage system

Fig.15 shows the influence of Low temperature stage evaporation temperature to the system thermal efficiency and exergy effects. We find that the higher evaporating temperature is, there is higher system efficiency. Under the condition that R290 is the high temperature level cyclic working substance, that using R170 for The low temperature level cyclic working substance is the most efficiency, the second is R23. The R116 is the worst choose. When the evaporation temperature is 15 ℃, we use r290 as high temperature level cyclic working substance and R170 as the low temperature level cyclic working substance, the exergy efficiency of system can be 15.6%.But on the same heat source ,Single-stage cycle of R290 only has 8.1%.



(b)
Fig.15 Efficiency of double-stage system

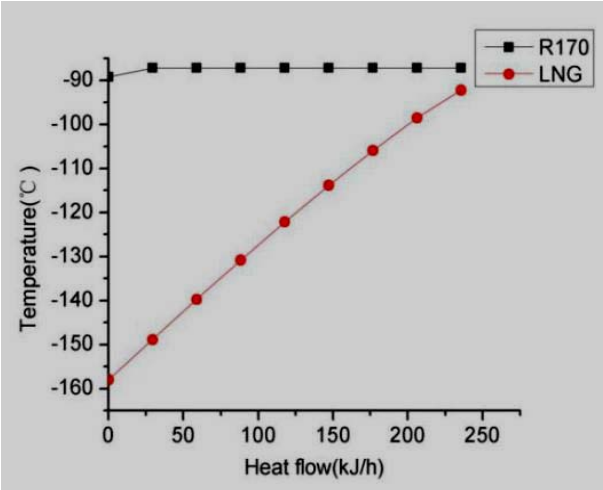
C. Analysis of the Exergy Loss of Double-Stage System

We use R290 as high temperature level cyclic working substance and R170 as the low temperature level cyclic working substance. The other parameter can be find in Table 2 and Table 1, Table 4 shows the result

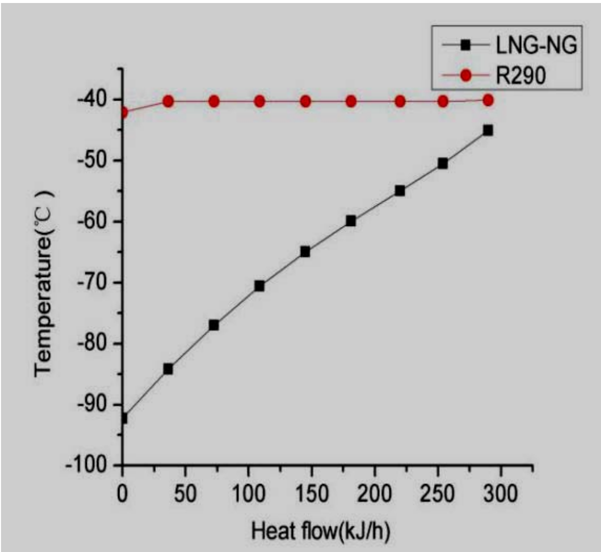
TABLE 4. EXERGY ANALYSIS OF DOUBLE-STAGE SYSTEM

Equipment	Cost Exergy (KJ/h)	Earnings Exergy (KJ/h)	Exergy Loss (KJ/h)	Exergy Efficiency	The Proportion Of Exergy
HEX1	46.945	7.580	39.365	16.1%	13%
HEX2	241.576	142.013	99.563	58.8%	32.9%
HEX3	21.924	8.432	13.492	38.4%	4.4%
HEX4	129.657	81.138	48.519	64.06%	16.1%
HEX5	38.071	4.944	33.919	12.6%	11.2%
TB1	97.294	69.462	27.832	71.4%	9.2%
TB2	59.809	45.317	14.492	75.8%	4.8%
LNGPP	22.532	2.635	19.897	11.7%	6.6%
IFPP1	4.518	2.226	2.292	49.3%	0.7%
IFPP2	0.968	0.594	0.374	58.3%	0.1%
SWPP1	21.896	19.452	2.444	88.8%	0.8%
SWPP2	7.218	6.412	0.806	88.8%	0.2%
Sum	692.408	390.205	302.203	------	100%

In the Two cycle system working medium, condensers HEX2 and HEX4 efficiency of exergy were about 60%, the total exergy loss respectively is 32.9%, 16.1%. Two low-temperature Rankine cycle using working medium condenser significantly reduce exergy loss, so exergy efficiency of the system can be improved. Logarithmic mean temperature of HEX 2 is 23.28 ℃. Logarithmic mean temperature of HEX 2 is 18.51 ℃, were lower than the single-stage system. From Figure 16, each heat transfer temperature, we can see contrast to a single circuit units, two cycle system working medium in the condenser temperature have been greatly improved, which is the key of system exergy to improve.



(a)



(b)

Figure 16 Temperatures in HEX2 and HEX4 of double-stage system.

IV. SUMMARY

In this paper, using the method for achieving low temperature Rankine cycle LNG-FSRU regasification system of cold energy utilization, for single stage low temperature Rankine cycle system cold energy utilization regasification system, R143a, R152a, R290, R717, R134a, R1270 six kinds of working fluid, we can Come to the following conclusions whiche is come from the working medium circulation amount of system net power output, system of exergy efficiency, analysis cycle performance comparison:

1) With the seawater as high-temperature heat source , using R290 as working medium.,we can get the highest net system output power and exergy efficiency

2) The system of energy loss mainly occurs in the working medium condenser (LING gasifier).

3) Compared with the single stage system, with R290 and R170 respectively for high and low temperature working medium construct two low-temperature Rankine cycle cold energy utilization re gasification system, system of net output power and efficiency of energy has greatly improved.

REFERENCES

[1] STEPHEN BILLIOT. AnOffshore Solution for Califomia[J]. LNG Joumal,2004,4（5）:1-4.

[2] Jianguo Hou， Qun Huang， Liang Chu technology and application of Floating LNG receiving terminal[J]. Sun Yatsen University Forum,2007,2(2):47-54.

[3] The statistics of global LNG receiving station, International Petroleum Economics[J]. 2014,34(6):86-89.

[4] Wei Song, Hongliang Yuan,Bin Duan difficulty analysis and countermeasure research of The LNG floating AnZhan terminal design, [J]. Ship and ocean engineering, 2015，32（3）:1-6.

[5] yongdong Chen， Xuedong Chen. exchanger key of technical analysis of LNG plant heat exchanger [J].natural gas industry, 2010，30（1):96-100.

[6] Fang Wang，Yike Fu，Xiaowei Fu，The research of LNG cold energy utilize.[J].Progress in Chemical Engineering，2016， 35（3）：748-753. The research of LNG cold energy utilize

[7] Chen qiuxiong ， Xu wendong,Chen ming. Technology development of LNG cold energy and ice storage air conditioning[J].Gas & Heat，2012，32（8）：6-9.

[8] Yang chun ， Xu wendong ， Zhang hui,etc.Technology development of LNG cold energy used for cold storage and cold water[J]. Gas & Heat，2012， 32（12）：4-7.

[9] Xiao fang ,Shen chenghua ,Xu hong ,etc . Cold analysis of cold storage technology in LNG gasification[J].Natural gas technology and the economy，2014，8（4）：45-47，79.

[10] LA ROCCA Vincenzo. Cold recovery during regasification of LNG part two ： applications in food industry and a hypermarket[J].Energy，2011，36：4897-4908.

[11] Liqing Chen，Peiling Xu，Lei Sun，etc.actuality analysis of the LNG cold energy power generation Technology[J].Natural gas and oil，2013，31（6）：8-9，39-44.

[12] Lei He，Lei Zhang，Wei Gao，etc. technology research on LNG cold energy cascade utilization combining Power with cooling[J].Cryogenics and Superconductivity，2015，43（5）：22-27.

[13] Nannan Sun，Hongbo Tan，Yang Zhang，etc. LNG cold energy utilization technology of power fishing boats[J]. Journal of chemical engineering，2015,66（2）：50-55.

[14] Dun Liu. parameters optimization of LNG cold energy generation and cooling composite scheme[J].Energy and Energ,（4）:172-175,2015.

[15] Hongchang Yang.Liquefied natural gas (LNG) optimization and research of LNG cold energy power systems [D].Beijing：Beijing University of Chemical Technology，2010.

[16] Qinsheng Fu.Thermodynamic analysis method of energy system [M]. Xi'an Jiaotong University Press, Xian.2005.

[17] Yanni Liu，Kaihua Guo. Efficiency analysis of Liquefied natural gas (LNG) cold energy power generation [J]. cryogenic technology,38（2）：13-17,2010.