SIMULATION AND OPTIMIZATION OF LIQUEFIED NATURAL GAS COLD ENERGY POWER GENERATION SYSTEM ON FLOATING STORAGE AND REGASIFICATION UNIT

by

Likang XU * **and Guihua LIN**

Marine Design and Research Institute of China, Shanghai, China

Original scientific paper
https://doi.org/10.2298/TSCI200404205X

In this paper, based on the idea of reducing heat exchanger exergy destruction and increasing turbine work, a new three-stage cascade Rankine system and a new four-stage cascade Rankine system is proposed to improve the cold energy utilization rate during liquefied natural gas gasification on liquefied natural gas-floating storage and regasification unit. Then compare them with the original cascade Rankine cycle established under the same conditions. The results show that under the condition of 175 tonne per hour liquefied natural gas flow, the maximum net output power of the new three-stage cascade Rankine cycle system is 4593.31 kW, the exergy efficiency is 20.644%. The maximum net output power of the new four-stage cascade Rankine cycle system is 5013.93 kW, and the exergy efficiency is 22.509%. Compared with the original cascade Rankine cycle system, the maximum net output power of the new three-stage cascade Rankine cycle system and the new four-stage cascade Rankine cycle system is increased by 9.41% and 11.45%, respectively, and the system exergy efficiency is increased by 9.29% and 11.28%, respectively.

Key words: *liquefied natural gas, power generation, exergy analysis, simulation optimization*

Introduction

Natural gas is one of the cleanest fossil fuels. As more and more attention has been paid to environmental problems, natural gas is increasingly used. Natural gas is widely used as a clean fuel, and the liquefied natural gas (LNG) industry has seen phenomenal growth [1]. When pipe-line transportation is not feasible, LNG is the best way to transfer natural gas [2]. The LNG will release a large amount of cold energy during the vaporization process [3], and recovering the remaining cold energy from the regasification process is one of the key challenges of the entire LNG value chain [4]. At present, there are many studies on LNG cold energy utilization systems, including power generation, air separation, desalination, low temperature carbon dioxide capture and natural gas liquid recovery [5]. Power generation is the most important method to make full use of LNG cold energy [6], and has gradually formed various forms of cold energy generation including *direct expansion method*, *secondary media method*, *combined method*, *mixed media method*, *Brayton cycle* and *gas turbine utility method* [7]. Using low temperature organic working fluid to form multi-stage Rankine cycle to maximize the use of LNG cold energy has become the focus of LNG cold energy power generation [8].

* Corresponding author, e-mail: 782940459@qq.com

At present, there are many studies on the use of LNG cold energy for power generation. Yang *et al*. [9-11] proposed a segmentation model for the utilization of LNG cold energy. They then developed horizontal and cascade three-level Rankine cycles that are based on the proposed model. However, the power generation of the horizontal three-level Rankine cycle is low, and the exergy destruction between the heat exchangers during the first and second Rankine cycle is high. Thus, they proposed a two-stage pumping optimization program. Zhixin [12] carried out particle swarm optimization on single-stage Rankine cycle, parallel two-stage Rankine cycle, and cascade two-stage Rankine cycle through, particle swarm algorithm, and compared them to get the optimal configuration of different natural gas distribution. Based on the three-stage condensation Rankine cycle, Junjiang *et al.* [13] optimized the compression and expansion process, optimized the cycle structure and working fluid, and studied the influen ceof LNG gasification pressure. Hao *et al*. [14] introduces the method of screening the working fluid of organic Rankine cycle by using LNG cold energy, and proposes an optimization framework based on simulation compare the performance of twenty-two candidate working fluids, so as to optimize the system performance. Yao *et al*. [15] put forward some improvement ideas for the three-stage condensation Rankine cycle of LNG cold energy utilization, and improved the net output power of the system. Xiu *et al*. [16] proposed a new type of power generation system based on LNG low temperature utilization, which can utilize flue gas waste heat and capture carbon dioxide in flue gas. Chenghao *et al*. [17] proposed and analyzed an improved power generation system using LNG cold energy and low temperature solar energy, which improved the net power output and thermal efficiency of the system. Junjiang *et al*. [18] compared eight different systems by combining single-stage and two-stage condensation Rankine cycles in series and parallel, respectively. Taking the net output power as the objective function, the key parameters and working fluid of eight systems are optimized simultaneously under four different LNG evaporation pressures. Hui *et al*. [19] uses the cold energy of LNG and industrial waste heat to generate electricity, studies the circulation performance under different parameters to compare the performance of working fluid, and optimizes the circulation parameters through genetic algorithm. Lee [20] developed a cold energy recovery and regasification system, which is used to recover and utilize the waste cold energy from the floating storage and regasification unit (FSRU) of LNG, and analyzed its thermal energy, exergy and economic efficiency by using the azeotropic mixture of ethane and propane.

The LNG-FSRU system is usually moored in the offshore area. At present, most of the gasification process of LNG on LNG-FSRU is directly heated by sea water, which takes away all the cold energy of LNG and does not make use of the cold energy of LNG. In order to transport natural gas to the land for a long distance, the transmission pressure should be over 7 MPa [21], at this time, LNG is in a supercritical state. In this paper, IFV regasification system on LNG-FSRU is taken as the object, and seawater is taken as the heat source. Based on the three-stage cascade Rankine cycle [9], the idea of reducing LNG heat exchanger exergy destruction and improving the turbine work is adopted in this paper. Through optimization and improvement, a new three-stage cascaded Rankine cycle system (NTCRS) and a new four-stage cascaded Rankine cycle system (NFCRS) are proposed. On this basis, the best matching parameters and the best working fluid are selected, and the thermodynamic comparison and analysis are carried out for different schemes.

New system principle

In this paper, the molar composition of LNG is 95% methane, 3% ethane, 2% propane, and the gasification pressure is 8 MPa.

The way to reduce LNG heat exchanger exergy destruction: add a stream of working fluid which is in the system to the LNG heat exchanger and the inlet temperature of the working fluid is between that of the two streams of the original heat exchanger.

The way to improve the turbine work: increase the inlet temperature of working fluid before entering the turbine.

See fig. 1 for the NTCRS and fig. 2 for the NFCRS. The red part is process optimization.

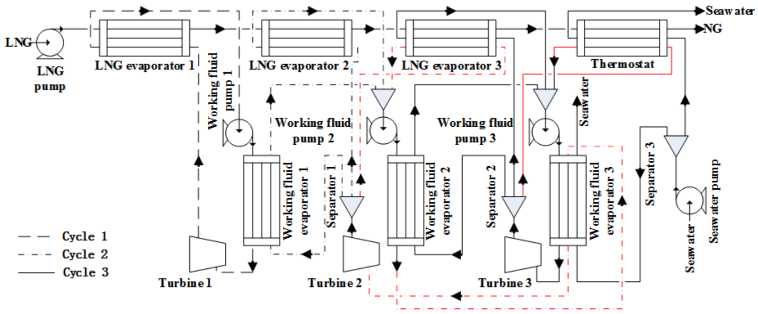

Figure 1. The NTCRS diagram

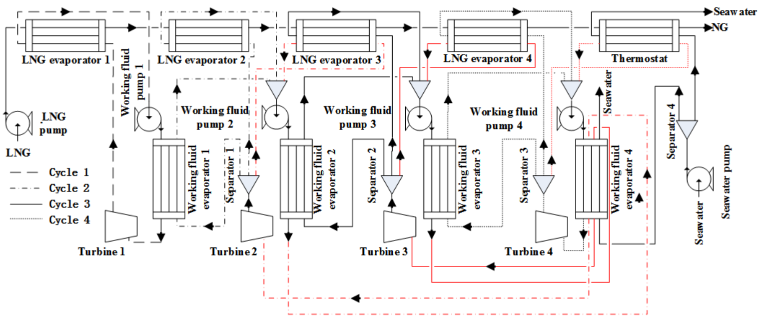

Figure 2. The NFCRS diagram

The NTCRS: The two-stage working fluid separated by Separator 1 is divided into one more stream and introduced into LNG Evaporator 3. The three-stage working fluid separated by Separator 2 is divided into one more stream and introduced into the thermostat. The two-stage working fluid vaporized by the working fluid Evaporator 2 is introduced into the working fluid Evaporator 3 for heating. Thus, the exergy destruction of LNG Evaporator 3 and thermostat can be reduced, and the work of Turbine 2 can be increased.

The NFCRS: The two-stage working fluid separated by Separator 1 is divided into one more stream and introduced into LNG Evaporator 3. The three-stage working fluid separated by Separator 2 is divided into one more stream and introduced into LNG Evaporator 4. The four-stage working fluid separated by Separator 3 is divided into one more stream and introduced into the thermostat. The two-stage working fluid vaporized by the working fluid Evaporator 2 and the three-stage working fluid vaporized by the working fluid Evaporator 3 are introduced into the working fluid Evaporator 4 for heating. Thus, the exergy destruction of LNG Evaporator 3, LNG Evaporator 4 and thermostat can be reduced, and the work of Turbine 2 and Turbine 3 can be increased.

Determination of the best working fluid combination and parameter matching of the system

The working fluid combination and parameters of the system have a great influence on the performance of the system.

Selection of system parameters

For simulation calculations and analysis, the flow of LNG is assumed to be 175 tonne per hour. The simulation calculation was conducted with the following settings:

- The condensation pressure of circulating working fluid is 110 kPa.
- The temperature of seawater, which is the heat source, is 20 °C, the ambient temperature is 25 °C, and the natural gas outlet temperature is 5 °C.
- The minimum end difference of all heat exchangers is 5 °C.
- In all heat exchangers, the subcooling degree of hot fluid outlet is taken as 2 °C. If the working fluid newly introduced into the heat exchanger fails to meet the requirement of subcooling 2 °C, the outlet temperature shall be taken as the limit temperature.
- The turbine efficiency is 80% and the pump efficiency is 75%.
- Ignore the losses in the pressure and heat of each heat exchangers and pipes
- The working fluid at the inlet of the turbine expander is in saturated gas state.
- The model calculation process is a steady-state process.

Screening of working fluid combinations and parameter matching

The condensation temperature of common working fluid under 110 kPa is shown in tab. 1.

Table 1. Condensation temperature of common working fluid under 110 kPa

Working fluid	R1150	R170	R23	R1270	R290	R717	R152a	R600a
Condensation temperature [°C]	–102.64	–87.22	–80.53	–46.16	–40.55	–31.44	–22.61	–9.93

For NTCRS: According to the principle of cold capacity cascade utilization, the one-stage working fluid may be R1150, R170, R23, the two-stage working fluid may be R170, R23, R1270, R290, and the three-stage working fluid may be R1270, R290, R717, R152a, and R600a. There are a total of 36 combinations.

For NFCRS: The one-stage working fluid is R1150, the two-stage working fluid may be R170 and R23, the three-stage working fluid may be R1270, R290, and R717, and four-stage working fluid may be R717, R152a, and R600a. There are a total of 16 combinations.

The HYSYS was used to simulate the system and Peng-Robinson was used as the fluid property package.

Working fluid screening and parameter matching for NTCRS

The order of parameter configuration is:

- Given the inlet temperature of working fluid entering Turbine 2 (hereinafter referred to as: inlet Temperature 1).
- Given the ratio of two-stage working fluid in Separator 1 entering into working fluid Evaporator 1 (hereinafter referred to as: Ratio 1);
- Given the ratio of three-stage working fluid in Separator 2 entering into working fluid Evaporator 2 (hereinafter referred to as: Ratio 2).

Next, take R1150, R23 and R290 as examples to show how to match the best parameters of the system.

The inlet Temperature 1 cannot be heated to the inlet temperature (15.05 °C) of the three-stage working fluid entering the turbine 3. When the inlet Temperature 1 is higher, the temperature of the two-stage working fluid is higher after the Turbine 2 works, resulting in the higher temperature of the one-stage working fluid. As a result, the temperature of LNG Evaporator 1 is crossed. When the working fluid combination is R1150, R23, and R290, the temperature range of inlet Temperature 1 is –45.55~–16 °C. In this paper, the temperature range is divided by 5 °C.

Table 2 shows the ranges of Ratio 1 and Ratio 2 that make the system process work at different inlet Temperature 1.

Table 2. Inlet Temperature 1 and corresponding Ratio 1 and Ratio 2

Inlet temperature 1 [°C]	Ratio 1	Ratio 2	Inlet temperature 1 [°C]	Ratio 1	Ratio 2
–16	0.6195	0.555-0.575	–21	0.620	0.550-0.570
	0.6196	0.555-0.575		0.630	0.540-0.565
	0.6197	0.555-0.575		0.640	0.535-0.555
	0.6198	0.555-0.575		0.65	0.525-0.545
	0.6199	0.555-0.575		0.66	0.515-0.540
–26	0.620	0.550-0.575	–31	0.620	0.555-0.580
	0.630	0.545-0.565		0.630	0.545-0.570
	0.640	0.535-0.560		0.640	0.540-0.560
	0.65	0.530-0.550		0.65	0.530-0.550
	0.66	0.520-0.540		0.66	0.525-0.545
–36	0.620	0.560-0.580	–41	0.620	0.560-0.585
	0.630	0.550-0.570		0.630	0.555-0.575
	0.640	0.540-0.565		0.640	0.545-0.565
	0.65	0.535-0.555		0.65	0.535-0.560
	0.66	0.525-0.545		0.66	0.530-0.550

Reasons for the upper limit of Ratio 1: When the outlet Temperature 1 is given, the flow rate of the two-stage working fluid entering the working fluid Evaporator 1 and the LNG Evaporator 2 in the Separator 1 has been determined. If there is no third branch, the Ratio 1 has been determined, so the Ratio 1 cannot exceed the Ratio 1 that was determined when the third branch was not included, otherwise the flow rate of the third branch is negative. Reasons for the lower limit of Ratio 1: The decrease in the Ratio 1 indicates that the flow rate of the two-stage working fluid entering the LNG Evaporator 3 increases, which takes away more cold energy of the LNG in the LNG Evaporator 3. The cold energy of the LNG passing through the LNG Evaporator 3 is constant. At this time, the remaining cold energy of the LNG cannot cool the three-stage working fluid in the LNG Evaporator 3 to a subcooling degree of 2 °C. In other cases, the reasons for the upper and lower limits of the ratio are the same.

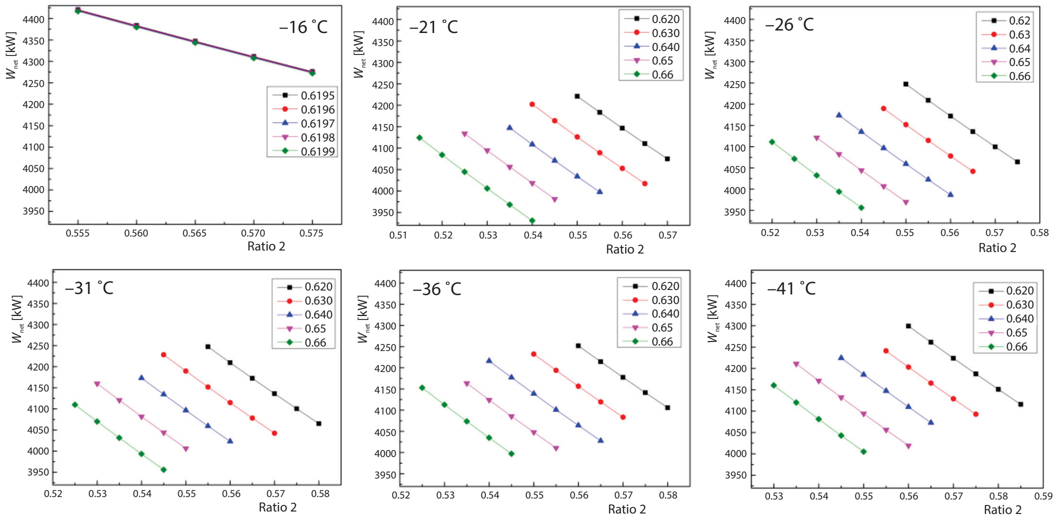

Figure 3. Net output power of the NTCRS (R1150, R23, R290)

Ratio 2 is divided by 0.005. Figure 3 shows the net output power of the NTCRS at Ratio 1 and Ratio 2 corresponding to different inlet Temperature 1.

When the outlet temperature 1 is –16 °C, the situation is special. At this time, it is the situation described in hypothesis (5), that is, in the LNG Evaporator 3, the outlet temperature of the two-stage working fluid cannot take the subcooling degree of 2 °C. It is equal to the inlet temperature of LNG in the LNG Evaporator 3. At other inlet Temperatures 1, the outlet temperature of the two-stage working fluid in the LNG Evaporator 3 can be taken the subcooling degree of 2 °C. It can be seen from fig. 3 that at the same inlet Temperature 1 and the same Ratio 1, the smaller the Ratio 2 is, the larger the net output power of the system is. At the same inlet Temperature 1 and the same Ratio 2, the smaller the Ratio 1 is, the larger the net output power of the system is. Moreover, at the same inlet Temperature 1, the smaller the Ratio 2 is, the larger the maximum net output power of the system obtained by adjusting the Ratio 1 is. In addition, when the outlet Temperature 1 is the highest, the net output power of the system is the largest. Therefore, it can be concluded that when the outlet Temperature 1 takes the maximum value and the Ratio 1 and the Ratio 2 take the minimum value, the net output power of the system is the largest. This can also be understood from the reasons for the upper and lower limits of the ratio.

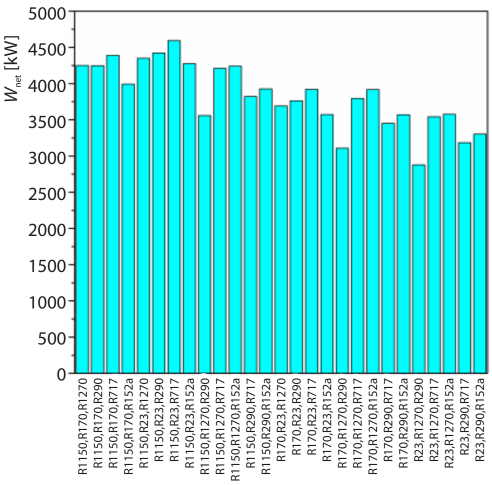

Figure 4. Net output power of the NTCRS under different working fluid combination

To calculate the maximum net output power of the NTCRS under different working fluid combinations, this paper uses the minimum Ratio 1 corresponding to the maximum outlet temperature 1 and the minimum Ratio 2 corresponding to the minimum Ratio 1 to calculate. It is found in the simulation that when the three-stage working fluid is R600a, the process cannot be established.

Table 3. Outlet temperature range and ratio range of the NTCRS

Working fluid combination Cycle 1, 2, 3	Outlet temperature 1 [°C]	Ratio 1	Ratio 2
R1150, R170, R1270	–51.16 ~ –29	0.6859~0.6961	0.525~0.555
R1150, R170, R290	–45.55 ~ –22	0.6848~0.7019	0.500~0.520
R1150, R170, R717	–36.44 ~ –10	0.6843~0.7017	0.470~0.480
R1150, R170, R152a	–27.62~2	0.6851~0.6947	0.440~0.450
R1150, R23, R1270	–51.16 ~ –25	0.6192~0.6216	0.585~0.615
R1150, R23, R290	–45.55 ~ –16	0.6195~0.6199	0.555~0.575
R1150, R23, R717	–36.44 ~ –3	0.6183~0.6279	0.520~0.530
R1150, R23, R152a	–27.62~10	0.6181~0.6286	0.490~0.500
R1150, R1270, R290	–45.55 ~ –41	0.3772~0.3796	0.945~0.990
R1150, R1270, R717	–36.44 ~ –29	0.3774~0.3781	0.885~0.910
R1150, R1270, R152a	–27.62 ~ –19	0.3781~0.3804	0.840~0.860
R1150, R290, R717	–36.44 ~ –31	0.3596~0.3600	0.935~0.965
R1150, R290, R152a	–27.62 ~ –22	0.3593~0.3617	0.890~0.910
R170, R23, R1270	–51.16 ~ –25	0.6760~0.6787	0.575~0.610
R170, R23, R290	–45.55 ~ –16	0.6762~0.6768	0.545~0.565
R170, R23, R717	–36.44~–3	0.6750~0.6859	0.510~0.525
R170, R23, R152a	–27.62~10	0.6748~0.6867	0.485~0.495
R170, R1270, R290	–45.55 ~ –41	0.4069~0.4095	0.955~0.990
R170, R1270, R717	–36.44 ~ –29	0.4073~0.4080	0.885~0.910
R170, R1270, R152a	–27.62 ~ –18	0.4067~0.4096	0.840~0.860
R170, R290, R717	–36.44 ~ –31	0.3881~0.3885	0.935~0.965
R170, R290, R152a	–27.62 ~ 22	0.3878~0.3901	0.885~0.905
R23, R1270, R290	–45.55 ~ –41	0.4015~0.4034	0.945~0.990
R23, R1270, R717	–36.44 ~ –29	0.4018~0.4026	0.880~0.910
R23, R1270, R152a	–27.62 ~ –19	0.4016~0.4038	0.835~0.855
R23, R290, R717	–36.44 ~ –31	0.3829~0.3831	0.935~0.965
R23, R290, R152a	–27.62 ~ –22	0.3825~0.3851	0.885~0.905

Under different working fluid combinations, the temperature range of the outlet Temperature 1, the Ratio 1 range corresponding to the maximum outlet Temperature 1, and the Ratio 2 range corresponding to the minimum Ratio 1 are shown in tab. 3.

For different working fluid combination, the net output power of the NTCRS is shown in fig. 4.

It can be seen from fig. 4 that the working fluid combination is R1150, R23, R717, and the system's net output power is the largest, which is 4533.31 kW.

In summary, the best working fluid combination for the NTCRS is R1150, R23, and R717. The best matching parameters include: outlet Temperature 1 is –3 °C, Ratio 1 is 0.6183, and Ratio 2 is 0.520.

Working fluid screening and parameter matching for NFCRS

It was found in the simulation that when the four-stage working fluid was R600a, the process could not be established.

The order of parameter configuration is:

– Given the outlet temperature of the three-stage working fluid in the working fluid Evaporator 4 (hereinafter referred to as : outlet Temperature 3);
– Given the outlet temperature of the two-stage working fluid in the working fluid Evaporator 4 (hereinafter referred to as: outlet Temperature 2);
– Given the ratio of two-stage working fluid in Separator 1 entering into the working fluid Evaporator 1 (hereinafter referred to as: Ratio 3);
– Given the ratio of three-stage working fluid in Separator 2 entering into the working fluid Evaporator 2 (hereinafter referred to as: Ratio 4);
– Given the ratio of four-stage working fluid in Separator 3 entering into the working fluid Evaporator 3 (hereinafter referred to as: Ratio 5).

Table 4 shows the temperature range of outlet Temperature 3, outlet Temperature 2, Ratio 3, Ratio 4, and Ratio 5 of the NFCRS under different working fluid combinations. The corresponding range in the table is determined by the parameter configuration order. When determining the range of outlet Temperature 2, take the maximum outlet Temperature 3. When determining the range of Ratio 3, take the maximum outlet Temperature 3 and outlet Temperature 2. When determining the range of Ratio 4, take the maximum outlet Temperature 3, maximum outlet Temperature 2 and minimum Ratio 3. and so on.

Table 4. Outlet temperature range and ratio range of the NFCRS

Working fluid combination Cycle 1, 2, 3,4	Outlet temperature 3 [°C]	Outlet temperature 2 [°C]	Ratio 3	Ratio 4	Ratio 5
R1150, R170 R1270, R717	–36.44~–30	–47.34~–25	0.6833~0.7080	0.5250~0.5322	0.885~0.910
R1150, R170 R1270, R152a	–27.62~–19	–47.34~–24	0.6851~0.7029	0.5246~0.5287	0.840~0.860
R1150, R170 R290, R717	–36.44~–32	–41.68~–17	0.6837~0.7031	0.4997~0.5032	0.930~0.960
R1150, R170 R290, R152a	–27.62~–22	–41.32~–17	0.6832~0.6999	0.4996~0.5009	0.885~0.905
R1150, R170 R717, R152a	–27.62~–18	–32.14~–5	0.6831~0.7075	0.4672~0.4691	0.950~0.975
R1150, R23 R1270, R717	–36.44~–30	–47.34~–20	0.6175~0.6302	0.5826~0.5907	0.885~0.910
R1150, R23 R1270, R152a	–27.62~–19	–46.93~–20	0.6169~0.6349	0.5829~0.5880	0.840~0.860
R1150, R23 R290, R717	–36.44~–32	–41.68~–12	0.6167~0.6372	0.5522~0.5580	0.935~0.965
R1150, R23 R290, R152a	–27.62~–22	–41.32~–11	0.6171~0.6330	0.5526~0.5561	0.885~0.905
R1150, R23 R717, R152a	–27.62~–18	–32.14~3	0.6172~0.6312	0.5166~0.5188	0.950~0.970

The reason for the upper and lower limits of the ratio is the same as that for the range of the ratio in the NTCRS.

In this paper, the maximum value of each outlet temperature and the minimum value of each ratio are used for calculation. The net output work of the NFCRS under different working fluid combinations is shown in fig. 5.

As can be seen from fig. 5, when the working fluid combination is R1150, R23, R1270, and R152a, the system's net output power is the largest at 5013.93 kW.

In summary, the best working fluid combination for the NFCRS is R1150, R23, R1270, and R152a. The best matching parameters include: outlet Temperature 3 is –19 °C, and outlet Temperature 2 is –20 °C, Ratio 3 is 0.6169, Ratio 4 is 0.5829, and Ratio 5 is 0.840.

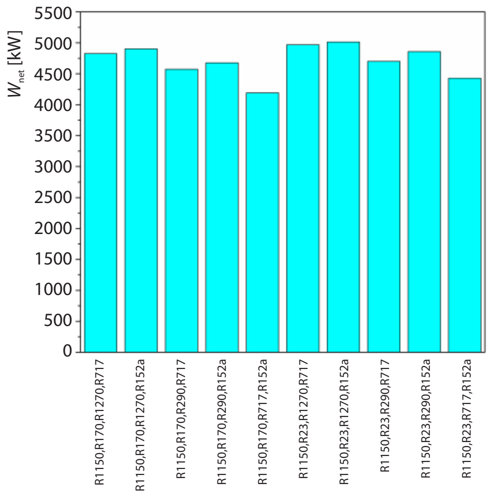

Figure 5. Net output power of the NFCRS under different working fluid combination

Thermodynamic analysis and comparison of new systems

The analysis of the defined exergy destruction and exergy efficiency in this paper is shown in tab. 5.

Table 5. Definition of exergy destruction and exergy efficiency

Equipment	Consumption exergy	Income exergy	Exergy destruction	Exergy efficiency
Heat exchanger	$m(ex_{1,\text{in}} - ex_{1,\text{out}})$	$m(ex_{2,\text{out}} - ex_{2,\text{in}})$	Consumption exergy / income exergy	Consumption exergy / income exergy

The total efficiency of the system is specified:

$$\eta_{nx} = \frac{W_{\text{net}}}{Ex_{\text{LNG}} + Ex_{\text{seawater}}} \tag{1}$$

where W_{net} is the net output work of the system, that is, the difference between the output work of the turbine and the work of all pumps. The Ex_{LNG} is the difference between LNG import exergy and LNG export exergy in the system. The Ex_{seawater} is the difference between the sea water export exergy and the sea water import exergy in the system.

The calculation results are shown in tab. 6.

It can be seen from tab. 6 that the exergy efficiency of the improved LNG evaporator and thermostat in the improved NTCRS and the NFCRS has been improved. Compared with the original three-stage cascade Rankine cycle system (TCRS), the system efficiency of NTCRS has been increased by 9.29%. Compared with the original four-stage cascade Rankine cycle system (FCRS), the system efficiency of the NFCRS has been improved by 11.28%. The TCRS is the three-stage cascade Rankine cycle system in reference [9]. The construction idea of FCRS and TCRS is the same, but one has four Rankine cycles and the other has three Rankine cycles.

Table 6. Exergy analysis and comparison

System		LNG Evaporator 3	LNG Evaporator 4	Thermostat	Exergy efficiency of system
TCRS	Exergy destruction [kW]	2573.02		1032.09	18.889%
	Exergy efficiency	57.45%		15.38%	
NTCRS	Exergy destruction [kW]	2178.52		861.65	20.644%
	Exergy efficiency	60.40%		29.35%	
FCRS	Exergy destruction [kW]	1425.01	565.88	637.70	20.227%
	Exergy efficiency	70.12%	67.12%	17.96%	
NFCRS	Exergy destruction [kW]	1152.79	338.10	502.13	22.509%
	Exergy efficiency	76.05%	73.02%	35.40%	

Turbine work and net output work of system are shown in tab. 7.

Table 7. Turbine work and net output work of system

Output work [kW]	TCRS	NTCRS	FCRS	NFCRS
Turbin 1	635.25	776.09	634.58	743.98
Turbin 2	2097.91	2401.48	1476.94	1882.90
Turbin 3	4156.47	4124.13	1570.83	1645.18
Turbin 4			3531.25	3482.41
System [kW]	4198.29	4593.31	4499.39	5013.93
Working fluid combination	R1150, R23, R717	R1150, R23, R717	R1150, R23, R1270, R152a	R1150, R23, R1270, R152a

It can be seen from tab. 7 that increasing the temperature of the working fluid entering the turbine increases the output power of the turbine, and also increases the output power of the turbine in the previous Rankine cycle. Compared with the TCRS, the net output power of the NTCRS has been increased by 9.41%. Compared with the original FCRS, the net output power of the NFCRS has increased by 11.45%. Combining tabs. 6 and 7, it can be seen that, compared to the NTCRS, the NFCRS has significantly improved exergy efficiency and net output work of system.

The tables in the *Appendix* show the key process parameters for the NTCRS and the NFCRS to obtain the maximum net output work.

Conclusions

In order to reduce the exergy destruction of heat exchanger and improve the performance of turbine, a new three-stage cascade Rankine cycle system and a new four-stage cascade Rankine cycle system are proposed in this paper by adding a stream of working fluid to the heat exchanger and increasing the inlet temperature of the working fluid before entering the turbine. This paper makes a comparative analysis with the existing cascaded Rankine cycle, and gives the optimal working fluid and matching parameter of two new cascaded Rankine cycle system. The specific conclusions are as follows.

- A new three-stage cascade Rankine cycle system and a new four-stage cascade Rankine cycle system are proposed to reduce the heat exchanger exergy destruction, improve the turbine work, increase the net output power of the system, and improve the utilization rate of LNG cold energy.
- The maximum net output power and the system exergy efficiency of the new three-stage cascade Rankine cycle system are 4593.31 kW and 20.644%, respectively. Compared with the original three-stage cascade Rankine cycle system, the system exergy efficiency and net output power of the new three-stage cascade Rankine cycle system are increased by 9.29% and 9.41%, respectively.
- The maximum net output power and the system exergy efficiency of the new four-stage cascade Rankine cycle system are 5013.93 kW and 22.509%, respectively. Compared with the original three-stage cascade Rankine cycle system, the system exergy efficiency and net output power of the new four-stage cascade Rankine cycle system are increased by 11.28% and 11.45%, respectively.

References

[1] Baris, B., *et al.*, Cold Utilization Systems of LNG: A Review, *Renewable and Sustainable Energy Reviews*, 79 (2017), Nov., pp. 1171-1188
[2] Tianbiao, H., *et al*., A Novel Conceptual Design of Hydrate Based Desalination (HyDesal) Process by Utilizing LNG Cold Energy, *Applied Energy*, *222* (2018), July, pp. 13-24
[3] Wensheng, L., *et al*., A Seawater Freeze Desalination Prototype System Utilizing LNG Cold Energy, *International Journal of Hydrogen Energy*, *42* (2017), 29, pp. 18691-18698
[4] Inkyu, L., *et al*., A Novel Cryogenic Energy Storage System with LNG Direct Expansion Regasification: Design, Energy Optimization, and Exergy Analysis, *Energy*, *173* (2019), Apr., pp. 691-705
[5] Tianbiao, H., *et al.*, The LNG Cold Energy Utilization: Prospects and Challenges, *Energy*, *170* (2019), Mar., pp. 557-568
[6] Guoguang, M., *et al*., Multi-Stage Rankine Cycle (MSRC) Model for LNG Cold-Energy Power Generation System, *Energy*, *165* (2018), Part B, pp. 673-688
[7] Wang, K., *et al.*, Analysis of LNG Cold Energy Utilization Technology (in Chinese), *Cryogenics*, *1* (2005), pp. 53-58
[8] Yanni, L., *et al*., Benefit Analysis of LNG Cold Energy Power Generation (in Chinese), *Cryogenics and Superconductivity*, *38* (2010), 02, pp.13-17
[9] Yang, H., Optimization of Cold Energy Power Generation System for Liquefied Natural Gas (LNG) (in Chinese), M. Sc. thesis, Beijing University of Technology, Beijing, China, 2010
[10] Yang, H., *et al*., Analysis of Low Temperature Power Cycle Based on LNG Gasification Segmentation Model (in Chinese), *Natural Gas Industry*, *30* (2010), 7, pp. 98-102
[11] Yang, H., *et al*., Optimization of LNG Cold Energy Cascade Utilization System (in Chinese), *Renewable Energy Resources*, *29* (2011), 1, pp. 72-75
[12] Zhixin, S., *et al*., Comparative Study of Rankine Cycle Configurations Utilizing LNG Cold Energy under Different NG Distribution Pressures, *Energy*, *139* (2017), Aug., pp. 380-393
[13] Junjiang, B., *et al*., Simultaneous Optimization of System Structure and Working Fluid for the Three-stage Condensation Rankine Cycle Utilizing LNG Cold Energy, *Applied Thermal Engineering*, *140* (2018), July, pp.120-130
[14] Hao, S., *et al*., A Study of Working Fluids for Organic Rankine Cycles (ORC) Operating Across and below Ambient Temperature to Utilize Liquefied Natural Gas (LNG) Cold Energy, *Energy*, *167* (2019), pp. 730-739
[15] Yao, S., *et al*., New Cold-Level Utilization Scheme for Cascade Three-Level Rankine Cycle Using the Cold Energy of Liquefied Natural Gas, *Thermal Science*, *23* (2019), 6B, pp. 3865-3875
[16] Xiu, W., *et al*., A Novel Combined System for LNG Cold Energy Utilization Capture Carbon Dioxide in the Flue Gas from the Magnesite Processing Industry, *Energy*, *187* (2019), Nov., 115963
[17] Chenghao, L., *et al.*, Performance Analysis of an Improved Power Generation System Utilizing the Cold Energy of LNG and Solar Energy, *Applied Thermal Engineering*, *159* (2019), Aug., 113937
[18] Junjiang, B., *et al.*, Comparative Study of Liquefied Natural Gas (LNG) Cold Energy Power Generation Systems in Series and Parallel, *Energy Conversion and Management*, *184* (2019), 2, pp. 107-126

[19] Hui, H., *et al*, The Study of a Novel Two-Stage Combined Rankine Cycle Utilizing Cold Energy of Liquefied Natural Gas, *Energy*, *189* (2019), Dec., 116290
[20] Lee, Y., The LNG-FSRU Cold Energy Recovery Regasification Using a Zeotropic Mixture of Ethane and Propane, *Energy*, *173* (2019), Apr., pp. 857-869
[21] Hongming, H., *et al.*, The LNG Physical Radon and Its Recycling (in Chinese), *Cryogenics*, *6* (2006), pp. 58-61 + 66

Appendix

Appendix 1. Key process parameters for the NTCRS

Working fluid	LNG				
Equipment export	LNG pump	LNG Evaporator 1	LNG Evaporator 2	LNG Evaporator 3	Thermostat
Pressure [kPa]	8000.00				
Temperature [°C]	–157.99	–107.64	–81.44	–36.44	5

Working fluid	One-stage working fluid (R1150)		
Equipment export	LNG Evaporator 1	Working fluid Evaporator 1	Turbine 1
Pressure [kPa]	110.00	320.43	110.00
Temperature [°C]	–104.64	–81.44	-–102.64

Working fluid	Two-stage working fluid (R23)					
Equipment export	LNG Evaporator 2	Working fluid Evaporator 2	Working fluid Evaporator 3	Turbine 2	LNG Evaporator 3	Working fluid Evaporator 1
Pressure [kPa]	110.00	808.09	808.09	110.00	110.00	110.00
Temperature [°C]	–82.53	–36.44	–3.00	–76.44	–81.44	–82.53

Working fluid	Three-stage working fluid (R717)				
Equipment export	LNG Evaporator 3	Working fluid Evaporator 3	Turbine 3	Thermostat	Working fluid Evaporator 2
Pressure [kPa]	110.00	726.10	110.00	110.00	110.00
Temperature [°C]	–33.44	15.05	–31.44	–33.44	–33.44

Working fluid	Seawater		
Equipment export	Seawater pump	LNG Evaporator 3	Thermostat
Pressure [kPa]	750.00		
Temperature [°C]	20.05	15.00	15.00

Appendix 2. Key process parameters for the NFCRS

Working fluid	LNG					
Equipment export	LNG pump	LNG Evaporator 1	LNG Evaporator 2	LNG Evaporator 3	LNG Evaporator 4	Ther-mostat
Pressure [kPa]	8000.00					
Temperature [°C]	–157.99	–107.64	–82.36	–46.93	–27.62	5

Working fluid	One-stage working fluid (R1150)		
Equipment export	LNG Evaporator 1	Working fluid Evaporator 1	Turbine 1
Pressure [kPa]	110.00	307.49	110.00
Temperature [°C]	–104.64	–82.36	–102.64

Working fluid	Two-stage working fluid (R23)					
Equipment export	LNG Evaporator 2	Working fluid Evaporator 2	Working fluid Evaporator 4	Turbine 2	LNG Evaporator 3	Working fluid Evaporator 1
Pressure [kPa]	110.00	542.85	542.85	110.00	110.00	110.00
Temperature [°C]	–82.53	–46.93	–20.00	–77.36	–82.36	–82.53

Working fluid	Three-stage working fluid (R1270)				
Equipment export	LNG Evaporator 3	Working fluid Evaporator 3	Turbine 3	LNG Evaporator 4	Working fluid Evaporator 2
Pressure [kPa]	110.00	233.48	110.00	110.00	110.00
Temperature [°C]	–48.16	–27.62	–19.00	–46.93	–48.16

Working fluid	Four-stage working fluid (R152a)				
Equipment export	LNG Evaporator 4	Working fluid Evaporator 4	Turbine 4	Thermostat	Working fluid Evaporator 3
Pressure [kPa]	110.00	440.07	110.00	110.00	110.00
Temperature [°C]	–24.61	15.05	–22.62	–24.61	–24.61

Working fluid	Seawater		
Equipment export	Seawater pump	Working fluid Evaporator 4	Thermostat
Pressure [kPa]	750.00		
Temperature [°C]	20.05	15.00	15.00

Paper submitted: April 24, 20200
Paper revised: June 22, 2020
Paper accepted: June 30, 2020