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A Combined Cooling and Power System Based on Guohai Cycle

Yutong ZHANG, Yongning BIAN

School of Ocean Science and Technology, Dalian University of Technology
Panjin, Liaoning, 124211, P.R. China

Abstract

In this study, a combined cooling and power system is constructed based on the Guohai Cycle, and the cooling and power output performance of the cycle is analyzed by numerical simulation. In the scope of this study, it can be clearly seen that the improvement of thermal efficiency and primary energy rate in the combined cooling and power system. In addition, the effects of operating conditions on the cycle performance were also investigated. The results show that the inlet temperature of seawater and the pressure of the expander inlet have obvious effects on the cycle performance.

Keywords: OTEC, Guohai Cycle, a combined cooling and power system

1. Introduction

Coal, petroleum and natural gas and other traditional fossil fuels are non-renewableenergies, which will eventually be exhausted due to human exploitation. The continuous consumption of fossil energy has been causing serious problems including global temperature rise, air pollution and changes of ecological system. Therefore ocean energy as an renewable, abundant energy source is expected to become a suitable alternative, which also has advantages such as non-polluting, recyclable and so on.(Junxiu Pan,2020)

The thermal energy resources in China are mainly concentrated in the South China Sea, and the flux density of thermal energy is also increasing. It is expected that the generation of thermal energy using the temperature difference between sea surface and deep sea to become a broad prospective in the future.(Jisheng Zhang,et al.,2019)

In south China, the high temperature lasts throughout the year has generated a high demand of air conditioning for daily life as well as the storage requirement of fishery industry. Currently, the energy consumption of seafood refrigeration is very high, thus reducing the energy consumption of storage systembecomes an important task of energy-saving.

The concept of ocean thermal energy was first proposed by D'Arsonval in 1881, and Anderson first proposed the concept of a closed cycle system for ocean thermal energy in 1964. In 1979, Hawaii built the world's first truly closed cycle OTEC device "MINI-OTEC" For the study of OTEC, scholars also proposed other improvement schemes.(Weimin Liu,2012) Kalina proposed a Kalina Cycle using non-azeotropic mixtures to reduce the irreversible loss during heat exchange. Uehara et al. also proposed the Uehara Cycle for the low efficiency of the condenser when using non-azeotropic refrigerants. The Guohai Cycle of the First Institute of Oceanography of China and the new cycle of Ocean University of China have also built new cycles based on the Kalina cycle, and prototype tests have verified that they have higher thermal efficiency than the Kalina Cycle.(Haifeng Xue et al.,2018)

Recently, the research direction of OTEC is more popular, which is the combined cooling and power system. A combination of power cycle system and refrigeration cycle system is used to improve the energy utilization efficiency of the cycle system, and generate electricity and cooling capacity. Bian et al. proposed a combined cooling and power cycle system combining Kalina Cycle and ejection refrigeration cycle. (Yongning Bian et al.2019) The cycle system mainly uses the waste heat of exhaust

* Received Date: 2021.10.17
E-mail: 1219847620@qq.com

steam discharged from the steam turbine to vaporize the working medium in the jet refrigeration cycle, so that the jet refrigeration cycle can operate and output cooling. Yunjie Yang proposed the combined cooling and power system of Rankine Cycle.(Yunjie Yang,2021) Some of the working fluids outflowed from the condenser were transported to the refrigeration cycle through the shunt for refrigeration and then entered the compressor. The working fluids outflowed from the compressor were mixed with another working fluid in the mixer and entered the power generation cycle, so as to realize the full utilization of energy.

In this paper, the absorption refrigeration cycle driven by low-grade heat source (Xiaoyang Hui,2014) is analyzed. Based on the Guohai Cycle, the absorption refrigeration with ammonia-water as working fluid is combined to improve the energy utilization of the cycle system without affecting the power generation performance.

2. Cycle description

2.1 Guohai Cycle

Wu Haoyu et al. from the first Institute of Oceanography has put forward a new thermodynamic circulation mode for ocean thermal energy cycle, Guohai circulation, as shown in Fig.1. Compared with Rankine Cycle, the power generation performance of Guohai Cycle is improved by 31.7%, and the cycle thermal efficiency and turbine net output are significantly improved.(Haoyu Wu,2020)

According to their research of workflow, the surface warm seawater is used as a heat source of the non-azeotropic mixed working medium (ammonia water solution)in the evaporator, while the ammonia water solution enters the separator (process1), the separated gaseous ammonia working medium enters the two-stage turbine to expand and do work, then the lean ammonia solution from the separator enters the Regenerator1(Process3) to preheat the ammonia solution from the working fluid pump, and the steam from the outlet of the first stage turbine is drawn out into the Regenerator2(process4). The remaining steam goes into the second stage turbine to do work, and the steam outlet after work goes into the absorber (process5). In the absorber, there is the steam from the two stage turbine, and the preheat regenerator1 comes out through the throttle valve with a lean ammonia solution (process12), and the working medium from the Regenerator2(process10), entering the condenser and the cold sea water together for heat exchange (process6), being condensed into a liquid solution into the ammonia tank (process7), entering the Regenerator1(process8)and Regenerator2(process12)in turn through the pressure of the pump; Finally enters the evaporator to absorb heat, completes the cycle (process11).

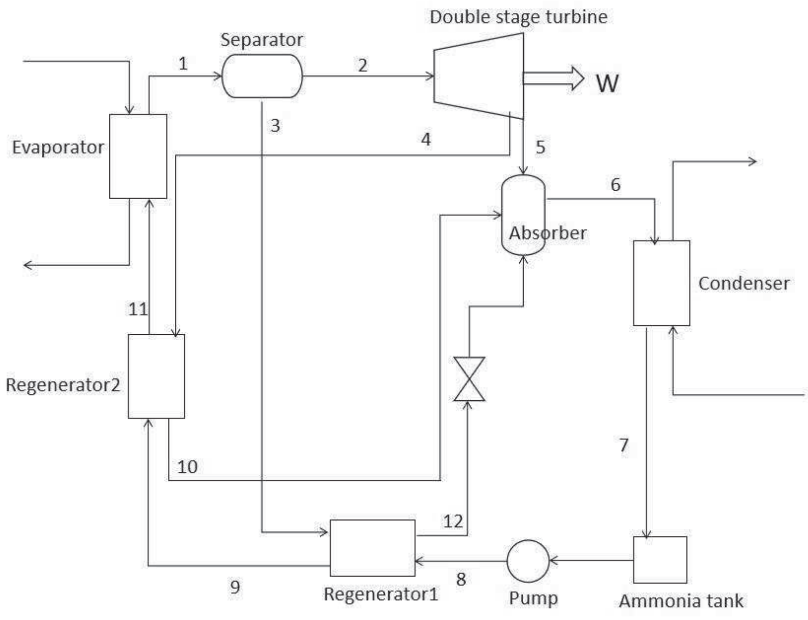

Fig. 1 Guohai Cycle

2.2 A combined cooling and power system based on Guohai Cycle

Based on the existing research of Guohai Cycle, the absorption refrigeration cycle is added. The cooling capacity is produced simultaneously on the basis of power generation. The combined cooling and power system is shown in Fig. 2. A stream of lean ammonia solution is separated from the Separator and fed into the refrigeration cycle by absorption refrigeration. The cooling capacity is released from the Evaporator and returned to the Regenerator1.

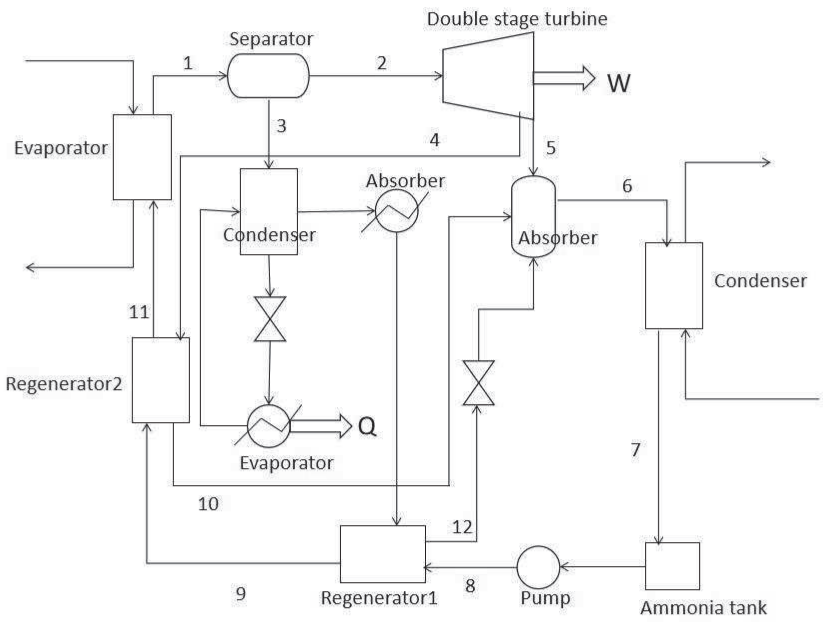

Fig. 2 Combined cooling and power system based on Guohai Cycle

3. Thermodynamic modeling of systems

3.1 System assumption

Aspen Plus, which has been used for decades, is generally considered to have the most suitable and complete physical system for industry. This paper uses the modules of heat exchanger, separator and pressure transmission equipment in Aspen Plus V11 to build the cycle simulation and explore the performance of the cycle system by changing different parameters. The state parameters of ammonia-water are available in Aspen Plus database, and their thermodynamic properties are determined by Peng-Robinson cubic equation. In order to simplify the calculation of the system model, following assumptions are made for the simulation of the combined cooling and power system by Aspen Plus:

(1) Ignore the heat loss of pipe fittings and parts;

(2) The steam turbine and the working fluid pump are both isentropic processes

(3) Ignore the power consumption of warm seawater supply pump and cold seawater supply pump;

(4) The efficiency of the pump and turbine is an ideal value given.

In order to obtain better cold output performance, this study envisages the introduction of auxiliary heating means (such as the use of solar energy, hot seawater salt pool, etc.) to increase the heat source temperature.

The initial parameters of the Guohai circulation system are shown in Table 1.

Table 1 The initial parameters of the model

Parameters	Value
Inlet temperature of warm seawater/°C	99
Mass flow rate of the warm seawater/kg·s^{-1}	89
Inlet temperature of cold seawater/°C	5
Basic solution concentration of ammonia-water/%	89
Inlet pressure of the turbine/MPa	2.2
Isentropic efficiency of the turbine/%	87
Mechanical efficiency/%	98
Pressure losses in heat exchanger/MPa	0.1

3.2 Computing formula

Based on the first and second law of thermodynamics, the mathematical model of the proposed cycle is expressed as follows.

$$\sum_{in}^{out} m_i = 0 \tag{3.1}$$

where m is the mass flow of working medium in the system, and i = 1, 2, 3... are the state points at different positions of the system.

The evaporator and condenser, the core equipment in the system, are simulated by the HeatX model in Aspen Plus.

The surface warm seawater exchanges heat with the working medium in the evaporator. The warm seawater releases heat. The ammonia-water absorbed heat which is the system heat absorption. According to the law of energy conservation, the system heat absorption is:

$$Q_e = m_1(h_1 - h_{11}) \tag{3.2}$$

where h represents the specific enthalpy of the working medium.

The deep cold seawater absorbs heat to cool the working medium in the condenser. The heat is released is the system heat release, which can be calculated as:

$$Q_c = m_6(h_6 - h_7) \tag{3.3}$$

The heat of the condenser in absorption refrigeration cycle can be calculated as follows:

$$Q_g = m_{17}\ (\mathrm{h}_{17} - h_{16}) \tag{3.4}$$

The cooling capacity released by the evaporator in the system which can be calculated as:

$$Q_{ref} = m_{16}(h_{15} - h_{16}) \tag{3.5}$$

The double stage turbine in Guohai cycle is simulated by using two compr modules and flash module. The output work of the steam turbine can be calculated as follows:

$$W_t = m_2(h_2 - h_4) + m_4(h_4 - h_5) \tag{3.6}$$

The working medium pump is simulated by the pump module, and the input work of the working medium pump can be calculated as:

$$W_p = m_7(h_8 - h_7) \tag{3.7}$$

After obtaining the output work W_1 and W_P , the net output work of the system can be calculated. In this system, the net output work is the output work in the steam turbine minus the input work of the working medium pump, which is:

$$W_{net} = W_t - W_p \tag{3.8}$$

Thermal efficiency is an important index to measure the performance of marine thermal energy cycle system. The thermal efficiency of Guohai Cycle can be calculated as:

$$\eta = \frac{W_{net}}{Q_e} \tag{3.9}$$

The Coefficient Of Performance (COP) is usually used to evaluate the performance of the refrigeration cycle which is defined as:

$$\mathrm{COP} = \frac{Q_{ref}}{Q_g} \tag{3.10}$$

Primary energy rate (per) can be used to evaluate the Guohai Cycle combined cooling and power system. PER is defined as the total energy output to the heat input and it represents the energy utilization ratio as:

$$\mathrm{PER} = \frac{W_{net}+Q_{ref}}{Q_e} \tag{3.11}$$

During the simulation, the built-in PENG-ROB method of Aspen Plus is employed to calculate the thermodynamic properties of working fluids. The standard Peng-Robinson cubic equation of state is expressed by:

$$\mathrm{P} = \frac{\mathrm{RT}}{\mathrm{V-b}} - \frac{\mathrm{a}}{[\mathrm{V(V+b)+b(V-b)}]} \tag{3.12}$$

where R is the gas constant, a and b can be calculated as follows:

$$\mathrm{a} = \sum_i \sum_j x_i x_j \left(a_i a_j\right)^{0.5} \left(1 - k_{ij}\right) \tag{3.13}$$

$$\mathrm{b} = \sum_i x_i b_i \tag{3.14}$$

the a_i, b_i are:

$$a_i = \frac{\alpha_i(T) \cdot 0.45724 R^2 T_{ci}^2}{P_{ci}} \tag{3.15}$$

$$b_i = 0.0778 R T_{ci} / P_{ci} \tag{3.16}$$

where the α_i is given by:

$$\alpha_i(T) = [1 + m_i(1 - T_r^{0.5})]^2 \tag{3.17}$$

where x is the mole fraction of component, T_r is the reduced temperature which is defined as:

$$T_r = \frac{T}{T_c} \tag{3.18}$$

The subscript i, j and c represent component i, j and critical state respectively. k_{ij} is binary interaction coefficient between the component i and j in a mixture, whose value is set to zero in this study. mi is a constant characteristic of each substance and it could be correlated against acentric factors ω, resulting in:

$$m_i = 0.37464 + 1.54226\omega_i - 0.26996\omega_i^2 \tag{3.19}$$

where ω is the acentric factor, calculated according to:

$$\omega_i = -\log_{10}\left(\frac{P^*}{P_{ci}}\right) - 1.0 \tag{3.20}$$

where P^* is the vapor pressure calculated at a reduced temperature $\mathrm{T} = T_C \times 0.7$

4. Model validation

4.1 Calculation results

According to the calculation formula, the results of the Guohai cycle combined cooling and power system in this paper are shown in Table 2.

Under the same conditions, the primary energy rate of single Guohai Cycle is the thermal efficiency which is 2.60%. According to the calculation table, the thermal efficiency of Guohai cycle combined cooling and power system is 2.57%, the primary energy rate is 55.11%. It is proved that the new system greatly improves the energy rate.

4.2 Analysis and discussion

After the simulation experiment, this section selects to change the thermodynamic state parameters

Table 2 Simulated results

Parameters	Value
Q_e/kJ	4471.51
Q_g/kJ	780.58
Q_{ref}/kJ	2349.54
W_t/kW	170.50
W_p/kW	55.76
W_{net}/kW	114.74
η/%	2.57
COP	3.01
PER	55.11

such as inlet temperature of warm seawater and stream pressure to analyze and explore the best performance of the system.

Fig.3 shows net output work under different inlet temperatures at 2.2MPa. Fig.4 shows the refrigeration capacity by changing different inlet temperatures at 2.2MPa.

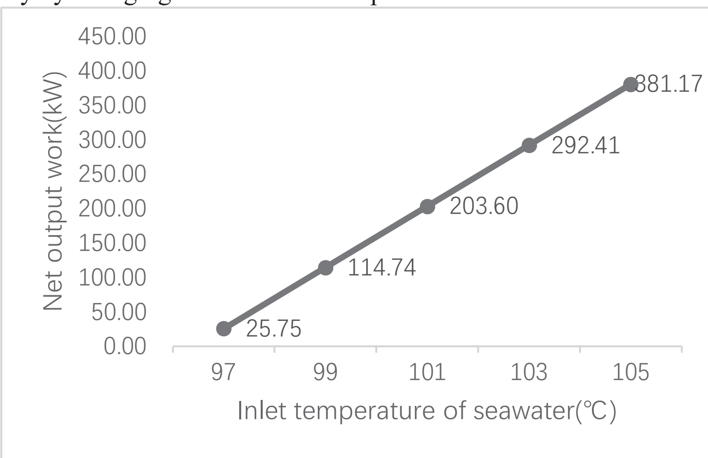

Fig. 3 Effect of inlet temperature of seawater on net output work

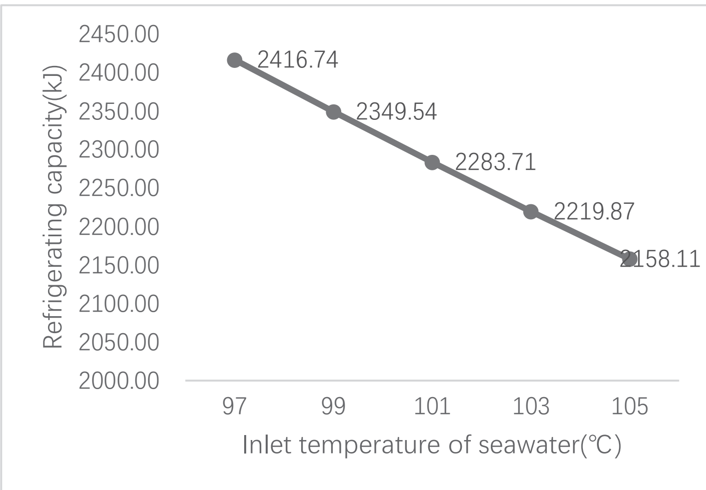

Fig. 4 Effect of inlet temperature of seawater on refrigerating capacity

It can be analyzed from the data that under the same pressure, when the inlet temperature is higher, the more net output work system obtains and the less refrigeration capacity it obtains. The working medium enters the separator, after that the gaseous ammonia enters the double stage turbine, and the lean ammonia solution enters the condenser of refrigeration cycle. When the temperature of the heat source rises, the mass flow of gaseous ammonia entering the double stage turbine increases and the mass flow of lean ammonia solution decreases. So the work of the steam turbine increases and the refrigeration capacity in the refrigeration cycle decreases.

Under this condition, the primary energy rate (per) can be obtained, as shown in Fig.5:

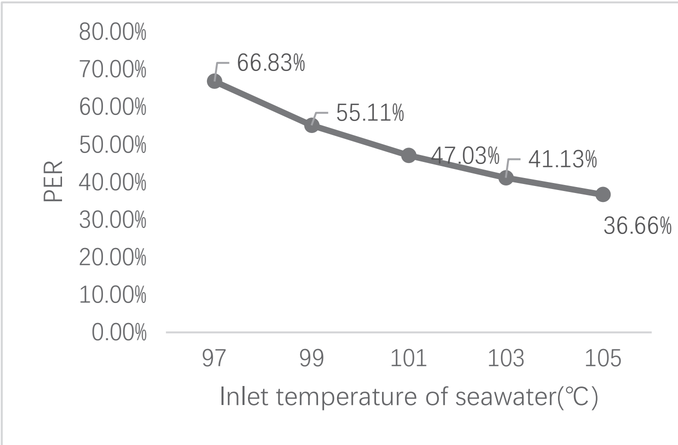

Fig. 5 Effect of inlet temperature of seawater on PER

By analyzing Fig.5, the primary energy rate decreases with the increase of heat source temperature under the condition of constant working fluid flow pressure. When the heat source temperature is 97 ℃, the primary energy rate is the highest. Therefore, the flow pressure of working medium was changed at 97 ℃ for data analysis.

Fig.6 shows the net output work by changing the stream pressure at 97 ℃. Fig. 7 shows the refrigerating capacity by changing the stream pressure at 97 ℃.

It can be analyzed from the data that under the same heat source temperature, when the flow pressure is greater, the net output work is less and the refrigeration capacity is more. When the working medium stream pressure increases, the mass flow of gaseous ammonia entering the double stage turbine decreases and the mass flow of lean ammonia solution increases. So the turbine work decreases and the refrigeration capacity increases.

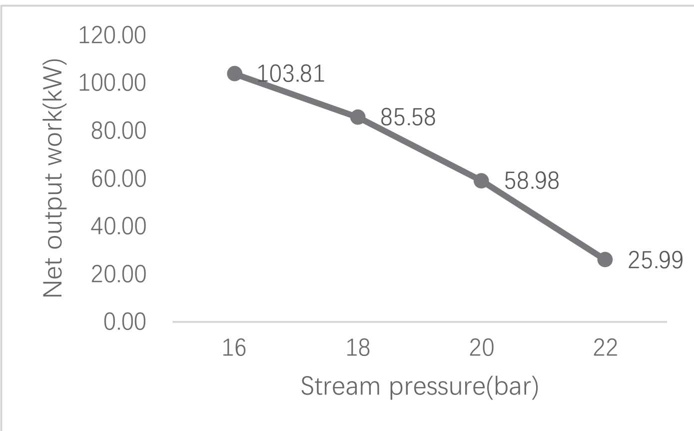

Fig. 6 Effect of stream pressure on net output work

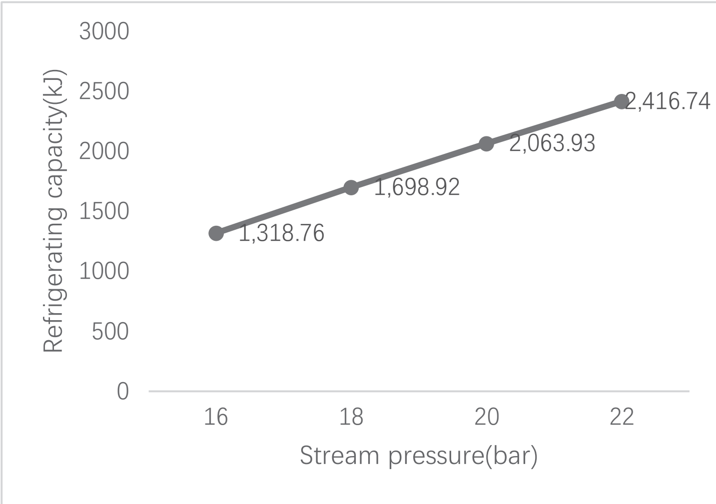

Fig. 7 Effect of stream pressure on refrigerating capacity

Under this condition, the f primary energy rate (per) can be obtained, as shown in Fig.8:

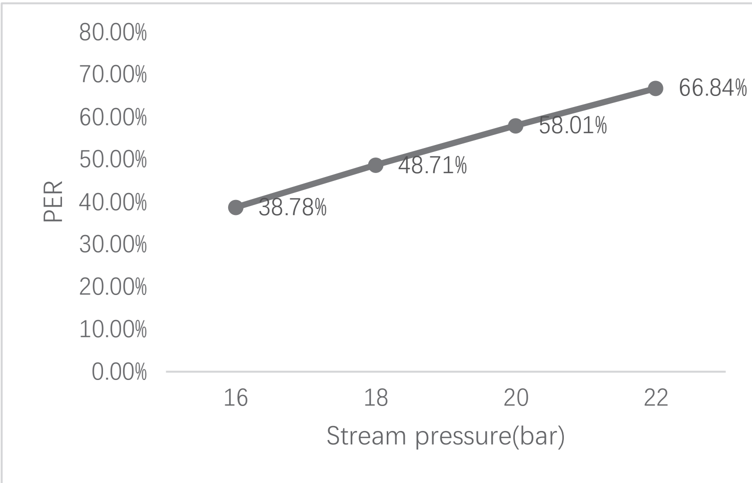

Fig. 8 Effect of stream pressure on PER

According to the analysis of Fig.8, under the condition of constant heat source temperature, the primary energy rate increases with the increase of working medium flow pressure. When the flow pressure is 22bar, the primary energy rate is the highest. Therefore, according to the current calculation and analysis, the primary energy utilization rate is the highest under the conditions of heat source temperature of 97℃ and working medium flow pressure of 22bar. However, the thermal efficiency is very low at 97℃, it can not meet the expected power generation, so 99℃ is the most appropriate heat source temperature.

5. Conclusion

In this paper, on the basis of the latest national sea cycle proposed by the ocean thermal energy cycle, a combined cooling and power supply system for the Guohai Cycle is established. The absorption refrigeration cycle is added to Guohai Cycle, and the output of cooling capacity is increased without affecting the output of electricity.The new cycle is simulated by Aspen Plus, and the system performance is analyzed by changing key thermal parameters. The main conclusions are as follows:

(1) Under the same conditions, the thermal efficiency of the Guohai Cycle is 2.60 %, and the primary energy rate is thermal efficiency, which is 2.60 %. The calculation table shows that the thermal efficiency of the combined cooling and power system is 2.57 %, and the primary energy rate is 55.11 %, which proves that the combined cooling and power system greatly improves the energy utilization rate.

(2) The net output net work, refrigerating capacity and primary energy rate of the new system vary with the change of heat source temperature and working medium pressure.

(3) According to the current simulation calculation, the results of Guohai cycle combined cooling and power system are more remarkable at 99 ℃ and 2.2MPa.

Acknowledgments

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