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Evaluation of a novel OTEC System composed of Uehara Cycle for power and refrigeration cogeneration

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Abstract

In this paper, a cogeneration system based on Uehara cycle and compression refrigeration cycle is proposed to generate electricity by using temperature difference energy (OTEC). The surface warm seawater of 29℃ is used as the heat source, and the deep cold seawater of 8℃ is used as the cold source. The system can be used to generate electricity and refrigeration for fishing boats, provide fresh-keeping technology for seafood, and can control the refrigeration capacity according to demand. Ammonia and tetrafluoroethane (R134a) are used as the working fluid of Uehara cycle and compression refrigeration cycle, with mass flow rates of 2.06kg/s and 2.7kg/s, respectively. The ASPEN PLUS V11 is used to conduct performance simulation study on co-production cycle system. The results show that the intermediate extraction rate of the steam turbine, the inlet temperature of the steam turbine, the ammonia concentration, and the mass flow rate of R134a all have a certain influence on the exergy efficiency, the primary energy saving rate, the primary energy utilization rate and the Coefficient Of Performance of the refrigeration cycle. From an energy-saving perspective, the system has better energy-saving effects than a single Uehara cycle. From an energy perspective, the primary energy utilization rate is higher than that of a single Uehara cycle.

Key words : Combined power and refrigeration cycle; OTEC; Uehara cycle; Compression refrigeration

1. Introduction

Energy is the basic support for economic development, and also the basis for the survival of human society. With the rapid development of science and technology, while mankind creates material wealth, the demand for energy is increasing. In the past 100 years, fossil energy has always occupied the main part of energy supply, and the problems of energy shortage and environmental pollution have become increasingly serious. With the concept of global carbon neutrality put forward, the global development and application of clean energy using sustainable energy is rapidly increasing. Ocean energy is a clean and renewable energy, with the characteristics of large reserves, stable temperature difference, high density and comprehensive utilization. The surface seawater temperature and the deep seawater temperature change very little, relatively stable, and the energy density is high (Wang et al.,2006), which is a very large amount of energy and makes the ocean the largest energy storage body on the earth. If it can be used, it will bring huge energy benefits to mankind and provide greater impetus for human development.

After D'Arsonval first proposed the concept of ocean thermal energy conversion in 1881, a lot of research work on ocean thermal energy conversion has been carried out (Uehara H and Ikegami Y,1990). In 1981, Kalina proposed the Kalina cycle with ammonia mixture as working fluid to achieve low temperature differential power generation. In the Kalina cycle, the evaporation and condensation temperatures of the mixture are used to improve the cycle thermal efficiency (Matsuda Y et al., 2018). In order to obtain higher thermal efficiency, in 1994, Uehara adopted two-stage expansion and intermediate extraction to improve thermal efficiency on the basis of Kalina cycle. Saga University in Japan established a 4.5KW test power station to test the Uehara cycle (Ikegami et al., 2006) system invented by Professor

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Haruo Uehara. The thermal efficiency of Uehara cycle is 1%-2% higher than that of Kalina cycle (Liu et al., 2012).

Refrigeration is a necessity for human life and the dramatic increase in its use will force the refrigeration sector to continue its efforts towards sustainable development. Based on this basis, this paper combines the Uehara cycle and compression refrigeration, uses the temperature difference energy to generate electricity, and realizes the development and utilization of new energy. At the same time, according to the principle of "temperature matching and step utilization", the power cycle and refrigeration cycle are organically coupled, and the thermal energy is efficiently converted into work and cold, so as to realize the comprehensive utilization of temperature difference energy and improve the thermal efficiency and exergic efficiency. In addition, the compression refrigeration system can be used for the seafood preservation technology on the fishing boat, and can adjust the energy generation and cooling capacity according to the work of the refrigeration compressor, so as to realize the self-sufficiency of the fishing boat in power generation and refrigeration.

2. Simulation and computation

Figure 2.1 shows the system diagram of the combined cycle, which is the co-generation cycle of the Uehara cycle and the compressed refrigeration cycle. OTEC technology is used to achieve simultaneous power generation and refrigeration. The Uehara cycle adds a heat exchanger coupled to the compression refrigeration cycle, which operates by adding heat exchangers to absorb the heat released by the steam from the turbine in the Uehara cycle.

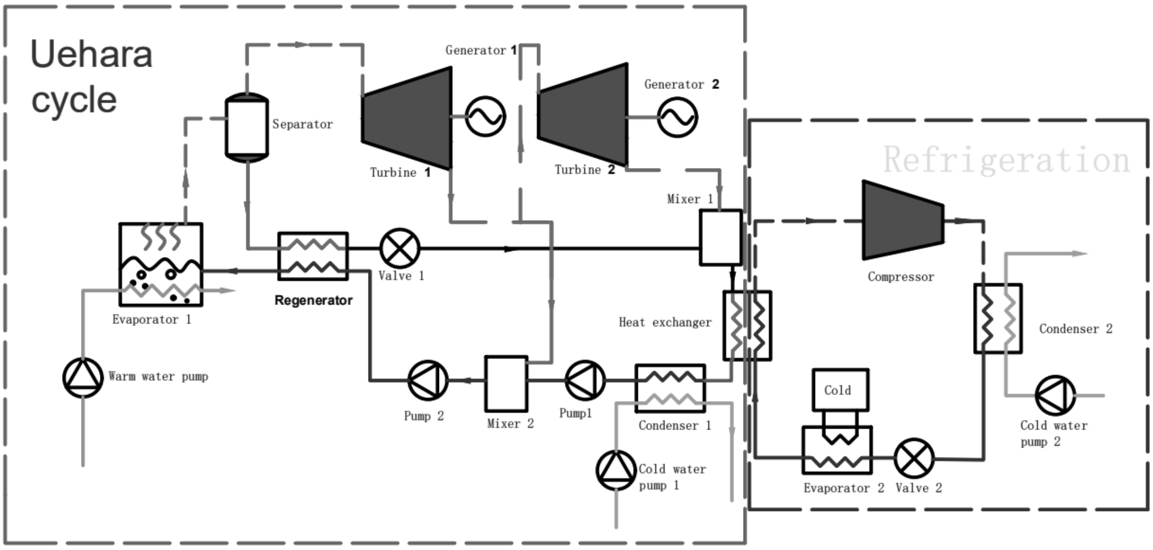

Fig.2.1 System diagram of the union cycle

The Uehara cycle consists of evaporator, condenser, steam turbine, generator, separator, absorber, heat exchanger, pump and so on. Ammonia was chosen as the working fluid in this cycle. The warm seawater is used as the heat source, which is returned after heat release. The ammonia solution is heated by the heat source in evaporator 1 and turns into a gas-liquid mixed stateand enters the separator. The ammonia steam separated from the separator enters the steam turbine 1 to expand and do work. Part of the exhaust steam enters the turbine 2 to expand and do work, and part flows into the mixer 2 to release heat. The unevaporated ammonia solution separated from the separator enters the regenerator to releases heat. After passing through the throttle valve , the ammonia solution is mixed with the lack steam from the steam turbine 2 in the mixer 1. Cold seawater is a cold source, which absorbs heat in condenser 1 and then returns; The basic solution of gas-liquid mixture enters the condenser 1 and is condensed into ammonia solution by cooling water; After the pump 1 pressurized ammonia solution into the mixer 2 to absorb heat, the mixed solution by the pump 2 pressure into regenerator to absorb heat. The heated solution enters evaporator 1 to complete the cycle.

The compressed refrigeration cycle(Huang et al., 2019) , uses less than one throttle valve, but uses evaporative condenser to provide heat for the refrigeration cycle. The cycle consists of condenser 2, heat exchanger, throttle valve 2, compressor and evaporator 2. The circulating working medium is R134a, and the cooling temperature is 5℃. After the refrigerant comes out of the evaporator 2, it is overheated by the heat exchanger, compressed and pressurized by the compressor, then enters the condenser 2 for heat transfer and condensation. Subsequently, the working medium flows into the evaporator 2 to absorb heat after the pressure reduction by throttle valve 2,which provides cold capacity for the cold storage and complete the refrigeration cycle.

In order to simplify the calculation of the system model, the following assumptions are made for the Uehara-compression refrigeration cycle:

1. Ignoring pressure drop and heat loss in heat exchangers and pipes;
2. Ignore the pump power consumption of cold sea water pump and warm sea water pump;
3. The equipment of the combined generation circulation system is in a stable state;
4. The working process of the working medium in the throttle valve is an isentropic process;
5. The working medium at the outlet of the gas-liquid separator is saturated;
6. The working medium flowing out of the condenser is in the saturated liquid state;
7. The working medium flowed out of the evaporator is in the condition of saturated steam.
8. The working medium temperature of the heat exchanger outflow is 5℃;
9. The isentropic efficiency of the pump is 98%, and the isentropic efficiency and mechanical efficiency of the turbine and compressor are 87% and 96%, respectively.

Table 1 Input date for the combined cycle.

Parameter	Number
Inlet temperature of warm seawater/°C	29
Mass flow rate of the warm seawater/kg s-1	80
Mass flow rate of ammonia-water to evaporator 1/kg s-1	2.06
Basic solution concentration of ammonia-water/%	95
Cold sea water temperature/°C	8
Mass flow rate of the cold seawater/kg s-1	50
Inlet temperature of the turbine 1/°C	27.26
Inlet pressure of the turbine 1/MPa	0.9
Outlet pressure of the turbine 1/MPa	0.78
Inlet pressure of the turbine 2/MPa	0.78
Outlet pressure of the turbine 2/MPa	0.63
Inlet temperature of evaporator 2 /°C	0
Outlet pressure of evaporator 2/MPa	0.35
Outlet temperature of heat source of condenser 2/℃	10
Outlet pressure of valve 1(MPa)	0.201
Mass flow rate of R134a/kg s-1	2.7

To evaluate the overall performance of the combined cycle, some key evaluation indicators are defined as follows:

The performance of the separate Uehara cycle is evaluated in terms of its thermal efficiency which can be defined as:

$$\eta = W_{net}/Q_{g1} \tag{1}$$

$$W_{net} = W_T - W_p \tag{2}$$

where W_T represents the total output power of the turbine 1 and turbine 2, W_p represents the total input power of the pump 1 and pump 2, and Q_{g1} represents the heat exchange in the generator 1.

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

$$COP = (Q_{ref} + W_{net})/Q_{g1} \tag{3}$$

where Q_{ref} represents the total heat exchange through evaporator 2.

The exergy efficiency is given as:

$$\eta_{ex} = (W_{net} + E_{x,ref})/E_{x,in} \tag{4}$$

where $E_{x,ref}$ denotes the refrigeration exergy and $E_{x,in}$ stands for the exergy of the heat source fluid.

It is not quite proper to use the thermal efficiency here to measure a combined cycle (Han Yuan et al, 2015) since it is usually used to evaluate a single thermodynamic cycle. However, analog to its definition, a primary energy ratio and a primary energy saving ratio are proposed in the current study. PER is defined as the total energy output to the heat input and it represents the energy utilization ratio as:

$$PER = (W_T + Q_{ref})/Q_{g1} \tag{5}$$

Primary energy saving ratio ($PESR$) (Alelyani SM et al., 2015) is an indicator of the combined cooling and power production system. It reflects the energy saved in the combined system compared with the energy consumption of the referred separate systems from the energy saving perspective. It is defined as:

$$PESR = (Q' - Q_{g1})/Q_{g1} \tag{6}$$

$$Q' = (W_T + Q_{ref}/3)/\eta \tag{7}$$

where, Q' is the primary energy consumption in conventional separate systems, Uehara cycle and a conventional compression chiller system, under the same energy output as the combined system. Take the calculation of Q' in the compression chiller (COP=3) of the refrigeration cycle for example.

3 Results and discussion

In order to study the combined cycle under different working conditions, this paper established the Uehara cycle compression refrigeration co-generation system with reference to the data of references (Aphornratana S and Sriveerakul T,1984) and (Goto S et al., 2011). ASPEN PLUS V11 software was used to simulate the co-generation cycle system. The state parameters of ammonia and R134a were provided in ASPEN PLUS database, and PENG-ROB was selected as the physical property method. The flow rate of warm sea water is 80 kg/s and the temperature is 29℃. The flow rate of cold sea water is 50kg/s and the temperature is 8℃. Basic solution concentration of ammonia-water is 95%, and the flow rate is 2.06kg/s. Based on the input parameters, this paper analyzes the influence on the thermodynamic performance of the cogeneration system by changing the intermediate pumping rate of the turbine, the concentration of ammonia-water, mass flow rate of refrigerant (R134a) and the inlet temperature of turbine 1. The results are shown in Figure 3.1-3.4.

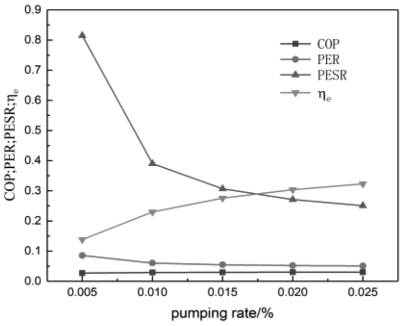

Fig.3.1 Relationship between PER, COP, $PESR$, η_{ex} and pumping rate

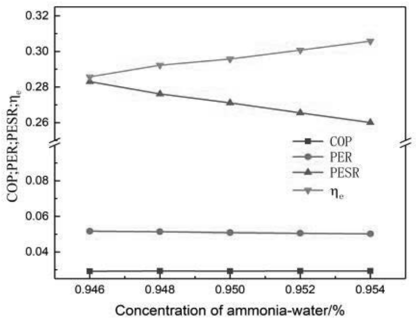

Fig.3.2 Relationship between PER, COP, $PESR$, η_{ex} and concentration of ammonia-water

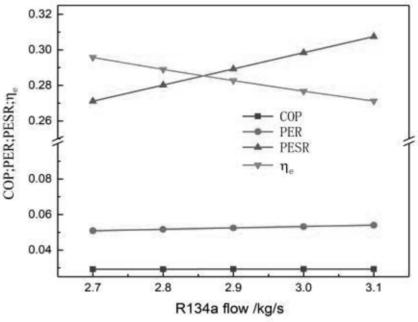

Fig.3.3 Relationship between PER, COP, $PESR$, η_{ex}

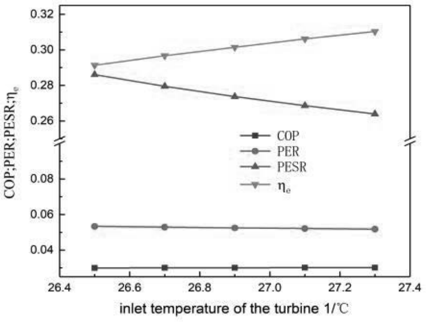

Fig.3.4 Relationship between PER, COP, $PESR$, η_{ex}

and R134a flow and inlet temperature

As can be seen in FIG. 3.1, exergy efficiency (η_{ex}), primary energy saving rate ($PESR$), primary energy rate (PER) and the Coefficient Of Performance (COP) versus the pumping rate. When the extraction rate of the original cycle is 0, turbines 1 and 2 are considered as a whole, and the regenerator 2 has no heat input and cannot work, which is equivalent to a Kalina cycle. It is clearly demonstrated that the gas extraction increases with the increase of the pumping rate. Therefore, the steam entering turbine 2 decreases, the output power of turbine 2 decreases, and the total output work of turbines 1 and 2 decreases. At the same time, the working fluid entering the condenser is reduced, and the heat exchange of evaporator 1 is reduced. The total input power of pump 1 and 2 decreases slightly, while the input power of the compressor remains unchanged. The decrease of the total output power of turbine 1 and 2 is larger than that of pump 1 and 2. According to Eq. (2), the net output power of the system (W_{net}) decreases. According to Eq (3), the decrease of W_{net} is much smaller than that of evaporator 1 heat exchange, so the COP increases. According to Eq (2), the reduction of the sum of the total output work of turbines 1 and 2 and the cooling capacity of the cold storage is less than the reduction of the heat exchange of evaporator 1, so the PER increases. The $PESR$ is bigger than 0 and gradually increases, indicating that compared with the single generation cycle or refrigeration cycle, the performance of the union cycle is better and has certain energy saving. With the increase of pumping rate, the performance of the union cycle becomes better and better. As the η_{ex} gradually decreased, the qualitative pumping rate of the system was about 2%.

Figure 3.2 shows that the relationship between η_{ex}, $PESR$, PER, COP and the concentration of ammonia-water. With the increase of concentration, the mass flow rate of ammonia-rich steam separated from the separator, W_T, W_{net}, Q_{g1} all increase with the concentration of ammonia-water. Besides, the increase range is much larger than W_T. According to Eq. (3), COP decreases gradually. $E_{x,ref}$ remained unchanged and W_{net} was greater than that of overall $E_{x,in}$. As per Eq. (4), the exergy efficiency η_{ex} gradually increased. The $PESR$, is greater than 0. According to Eq. (5), although the system shows certain energy saving performance, the PER gradually decreases, indicating that the ammonia concentration is not good if it is too high or too low, but reaches the best value at 95%.

Figure 3.3 illustrates the effect of the R134a flow on $PER, COP, PESR, \eta_{ex}$. The total heat exchange through evaporator 2 (Q_{ref}) and the net output power of the compressor (W_{com}) increases as the mass flow rate of R134a increases. It is noted that as the heat exchange of evaporator 2 increases the heat exchange of condenser 1 and W_{net} declines significantly. According to Eq. (3), Q_{g1} remains unchanged, and COP gradually increases. According to Eq. (5), W_T remains unchanged, and PER gradually increases. Since $PESR$ which is greater than 0 gradually increases, the energy saving performance of the system gradually becomes better. According to Eq. (4), the decrease of W_{net} was larger than the increase of $E_{x,ref}$, as a consequence, η_{ex} gradually decreased. As a result, there is a certain limit to the R134a flow rate.

Figure 3.4 describes the effect of the inlet temperature of the turbine 1 on $PER, COP, PESR, \eta_{ex}$. It is easily deduced that as inlet temperature of the turbine 1 increases, the specific enthalpy difference between inlet and outlet of the turbine rises accordingly. Therefore, these result in the increase of W_T and Q_{g1}. It is also found that W_p decreased slightly. Based on Eq. (3) and Eq. (4), COP increases slightly accordingly and so does W_{net}, which together lead to mildly increase of η_{ex} as observed in Fig. 5.4. $PESR$ is greater than 0, which means the system has energy saving property; According to Eq. (2), PER decreases gradually. The above results show that the inlet temperature of the turbine reaches the optimum at 26.9℃.

The results show that under the condition of the same input parameters, compared with the power generation system which uses the Uehara cycle, the input heat is reduced by 0.7%, outlet power of the turbine is increased by 4.6%. At the same time, the cooling output of 3502KW is increased, the net output power is increased by 4%, and the thermal efficiency is increased by 5%. When the parameters are changed, COP is almost unchanged and $PESR$ is positive. It means that this system has certain energy saving effect. However, as ammonia concentration and inlet temperature increased, η_{ex} increases and yet PER decreases. As pumping rate and R134a flow increase, η_{ex} decreases while PER increases. The research results provide a useful reference for further optimizing the performance and comprehensive utilization of thermal power generation system.

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