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Explore the influence of intermediate extraction on thermodynamic performance and economy of Uehara cycle

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Abstract

The South China Sea contains abundant ocean thermal energy. This paper simulates an OTEC system based on Uehara cycle and considers the actual situation in the South China Sea. The extra middle steam extraction segment is examined to check its influences on the circulating thermal efficiency, the consumption of cold and hot seawater and the circulating exergy efficiency. The results show that in the Uehara cycle Ocean Thermal Energy Conversion System under the working condition of this paper, for the circulating thermal efficiency and the circulating exergy efficiency, there is the best intermediate steam extraction capacity. Different pressures have different optimum values. Concurrently, the circulating exergy efficiency is much greater than thermal efficiency. With the increase of intermediate steam extraction, the consumption of cold and hot seawater both decreased and there is a certain upper limit for steam extraction. The cost of equipment foundation increases with the increase of additional intermediate steam extraction rate, and is mainly concentrated in the heat exchanger. With other conditions unchanged, increasing the working fluid flow can effectively reduce Levelized Cost of Energy (LCOE). When building an ocean thermoelectric power plant, the appropriate intermediate extraction pressure and extraction rate shall be selected according to the specific working conditions.

Key words : OTEC；low-temperature heat；Uehara cycle；economic analysis；Aspen plus

1. Introduction

The ocean thermal energy is the ocean thermal energy stored in the form of the water temperature difference between the surface hot sea water and the deep cold sea water, whose reserves are huge and is almost unaffected by time. 71% of the earth's surface area is the ocean, which is also the largest solar storage device on the earth. At the current technical level, about 10000YWh/a of ocean temperature difference energy can be converted into electricity[1].

In 1881, the concept of ocean thermal energy conversion was first proposed by French scientist Arsened Arsonva[2]. In 1930, Claude successfully used ocean thermal energy to generate electricity in the offshore of Cuba, proving the practical feasibility of ocean thermal energy conversion theory[3]. In 1998, Professor Uehara H of Saga University in Japan first proposed the Uehara cycle, and through analyzing the physical properties of ammonia working fluid and comparing it with Kalina cycle, it was proved that it can greatly improve the thermal efficiency of the cycle. Later, the feasibility and rationality of the system were analyzed through experiments, and the system was evaluated [4-5].

In this paper, based on the Uehara cycle, 95.6% ammonia water mixture is used as the working fluid, and the initial parameters are determined according to the geographical information and climatic conditions of the South China Sea. Adjust the extra intermediate air extraction rate of Uehara cycle, observe the thermal performance change of its cycle and conduct economic analysis, so as to provide a theoretical basis for the development of ocean thermal power generation technology applied in the South China Sea region in the future.

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2. Circulation process and control equation

2.1 Systemic circulation process

Figure 1 shows the flow diagram of Uehara cycle. The ocean surface warm seawater is recycled as the heat source, and the deep cold seawater is used as the cold source. The ammonia solution is partially heated by the warm sea water in evaporator and evaporated into a gas-liquid mixed state. It is separated into rich ammonia steam and lean ammonia solution through separator. Among them, the ammonia rich steam enters turbine 1 for expansion and work, and then enters turbine 2 to continue expansion with the liquid phase part extracted through the separator. After the lean ammonia solution enters regenerator 1 for heat release, the pressure is adjusted by the throttle valve to be consistent with the outlet pressure of turbine 2, and then it is mixed with the rich ammonia steam in mixer. The mixed working medium is condensed into liquid phase by cold sea water in the condenser, pressurized to the initial pressure by pump 1, and heat exchange with the extracted liquid phase in regenerator 2. The extracted liquid passes through regenerator 2 and tank, is pressurized by pump 2 to the initial pressure, and then mixed with the ammonia solution.

Figure 2 is the schematic diagram of the improved Uehara cycle system. The rich ammonia solution passing through separator 2 does not directly enter steam turbine 2, but passes through the middle extraction, and then the remaining part enters steam turbine 2 for expansion and work. The extracted solution is mixed with stream 7 and then enters regenerator 2 for heat release. After condensation, the ammonia working medium is pressurized by pump 1 to the outlet pressure of turbine 1 after passing through the liquid storage tank. It is mixed with stream 16 in the buffer tank after passing through the regenerator 2 and outputs pure liquid stream 17. Pressurize to the initial pressure through pump 2, and then absorb heat in regenerator 1 to complete the whole cycle. Compared with the normal Uehara cycle, the improved model increases the intermediate extraction, makes full use of the total heat of the extracted part, and improves the thermal efficiency of the cycle.

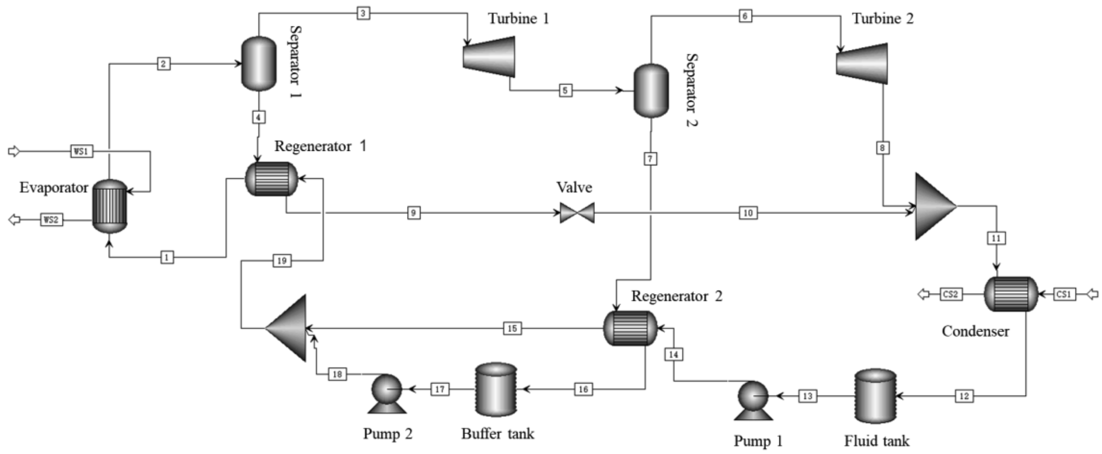

Fig. 1 System flow chart of the Uehara cycle.

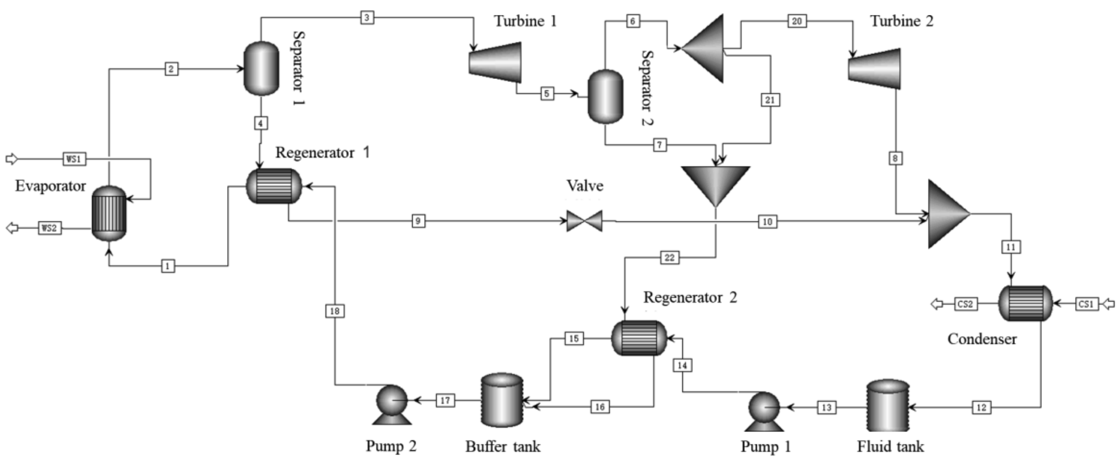

Fig. 2 System flow chart of the modified Uehara cycle.

2.2 Model assumptions and initial parameters

To simplify the system model calculation, the following assumptions are made for Uehara cycle: (1) The system is an adiabatic system. (2) Ignore the pressure drop and heat loss in the pipeline and heat exchanger. (3) The system operates stably, and the parameters at each point do not change with time. (4) Heat transfer end difference of heat exchanger is 2℃. The parameters of each point of the cycle are shown in Table 1:

Table 1 Initial parameters of the circulatory system modle.

Parameter	Number
Surface temperature sea water inlet temperature WS_1/℃	29
Surface temperature sea water return temperature WS_2/℃	27
Deep cold sea water inlet temperature CS_1/℃	5
Deep cold sea water return temperature CS_2/℃	7
Mass fraction of ammonia working medium/%	95.6
Working medium pressure of evaporator/kPa	900
Turbine 1 outlet pressure/kPa	780
Turbine 2 outlet pressure/kPa	630
Isentropic efficiency of steam turbine/%	87
Mechanical efficiency of steam turbine/%	96
Mechanical efficiency of pump/%	98
Working medium mass flow/kg·s	2.06
Ambient temperature T_0/℃	25
Ambient pressure P_0/kPa	101

2.3 Governing equation

The Uehara circulation system is composed of evaporator, steam turbine, condenser, pump and other equipment. The model control equations involved are as follows: [m* is the mass flow of ammonia water, kg/s; h* is the enthalpy of ammonia, kJ/kg; s* is the entropy of ammonia.]

Heat absorption of ammonia working medium in evaporator:

$$Q_e = m_1 \left(h_2 - h_1 \right) \tag{1}$$

Ammonia mass conservation:

$$m_2 x_2 = m_3 x_3 + m_4 x_4 \tag{2}$$

$$m_5 x_5 = m_6 x_6 + m_7 x_7 \tag{3}$$

$$m_6 x_6 = m_{20} x_{20} + m_{21} x_{21} \tag{4}$$

Heat release of ammonia working medium in condenser:

$$Q_c = m_{11} \left(h_{11} - h_{12} \right) \tag{5}$$

Heat exchange in regenerator 1:

$$Q_{h_1} = m_4 \left(h_4 - h_9 \right) = m_1 \left(h_1 - h_{18} \right) \tag{6}$$

Heat exchange in regenerator 2:

$$Q_{h_2} = m_{22} \left(h_{22} - h_{16} \right) = m_{14} \left(h_{15} - h_{14} \right) \tag{7}$$

Output power of turbine 1:

$$W_{t_1} = m_3 \left(h_3 - h_5 \right) \tag{8}$$

Output power of turbine 2:

$$W_{t_2} = m_{20} \left(h_{20} - h_8 \right) \tag{9}$$

Input power of pump 1:

$$W_{p_1}=m_{13}\left(h_{14}-h_{13}\right) \tag{10}$$

Input power of pump 2:

$$W_{p_2}=m_{17}\left(h_{18}-h_{17}\right) \tag{11}$$

Net output work:

$$W_{net}=\left(W_{t_1}+W_{t_2}\right)-\left(W_{p_1}+W_{p_2}\right) \tag{12}$$

Cycle thermal efficiency:

$$\eta_{I}=\frac{W_{net}}{Q_e} \tag{13}$$

Input heat exergy:

$$E_e=m_{ws}\left[\left(h_{ws_1}-h_{ws_2}\right)-T_0\left(s_{ws_1}-s_{ws_2}\right)\right] \tag{14}$$

Input cold exergy:

$$E_c=m_{cs}\left[\left(h_{cs_1}-h_{cs_2}\right)-T_0\left(s_{cs_1}-s_{cs_2}\right)\right] \tag{15}$$

Cycle exergy efficiency:

$$\eta_{II}=\frac{W_{net}}{E_e+E_c} \tag{16}$$

Investment cost calculation formula:

$$\log_{10} C_p=K_1+K_2\log_{10}A_*+K_3\left(\log_{10} A_*\right)^2 \tag{17}$$

In the formula, A_* represents the measurement parameter of equipment investment cost, and the subscript $*$ represents the corresponding equipment: For the heat exchanger, it is the effective heat exchange area(m^2). For the turbine, it is the output work(kW). For pumps, it is the input work(kW).

Effective heat exchange area of heat exchanger:

$$A=\frac{Q}{U\cdot LMTD} \tag{18}$$

Where LMTD is the average logarithmic temperature difference:

$$LMTD=\frac{\left(T_{hot}^{"}-T_{cold}^{'}\right)-\left(T_{hot}^{'}-T_{cold}^{"}\right)}{\ln\frac{T_{hot}^{"}-T_{cold}^{'}}{T_{hot}^{'}-T_{cold}^{"}}} \tag{19}$$

Investment cost after correction of material and pressure environment:

$$C_{BM}=C_P F_{BM}=C_P\left(B_1+B_2F_MF_P\right) \tag{20}$$

In order to simplify the calculation, all heat exchangers adopt plate heat exchangers from the heat transfer coefficient $U=3100\ W\cdot m^{-2}\cdot K^{-1}$. The calculation coefficients are listed in Table 2 according to literature [6].

Table 2 Parameters of cost calculation.

Parameter	Heat exchanger /regenerator	Turbine	Pump
K_1	4.6656	2.7051	3.8696
K_2	-0.1557	1.4398	0.3161
K_3	0.1557	-0.1776	0.1220
B_1	0.96	\	1.89
B_2	1.21	\	1.35
F_M	1.4/1	\	2.2
F_{BM}	calculation	3.5	calculation

2.4 Economic evaluation index

In this paper, the system performance is analyzed from the perspective of thermal economy, and the Leveled Cost of Energy (LCOE) is taken as the system economic index.

Investment recovery factor:

$$CRF=\frac{i\left(i+1\right)^{N}}{\left(i+1\right)^{N}-1} \tag{21}$$

Leveled Cost of Energy:

$$LCOE=\frac{C\cdot CRF+\Phi}{W_{net}\cdot n} \tag{22}$$

In the formula, i is the interest rate, the service life of the equipment N=20, the operation and maintenance cost Φ is 3% of the total investment cost, and the annual operation time n=8000h.

3. Result analysis and discussion

3.1 Thermal analysis

In Uehara cycle, the change of intermediate extraction volume will affect the mass flow of working medium entering turbine 2, reducing the output work of turbine 2. At the same time, the working medium extracted is used to heat the condensed working medium, improve the temperature of the working medium at the evaporator inlet, reduce the heat absorption of the evaporator, and thus increase the circulating thermal efficiency. In Fig.3, with the increase of additional extraction, the cycle thermal efficiency shows a trend of increasing first and then decreasing. When the extra middle steam extraction is small, because the isentropic efficiency of the turbine is less than 1, the working medium cannot fully expand. This part of heat is taken away by the cold seawater in the condenser and cannot be used. The extracted part does not pass through the condenser, and the heat utilization rate is 100%. When the extra middle steam extraction reaches a certain limit, continuous extraction will reduce the flow of working medium in turbine 2, resulting in a decrease in output work.

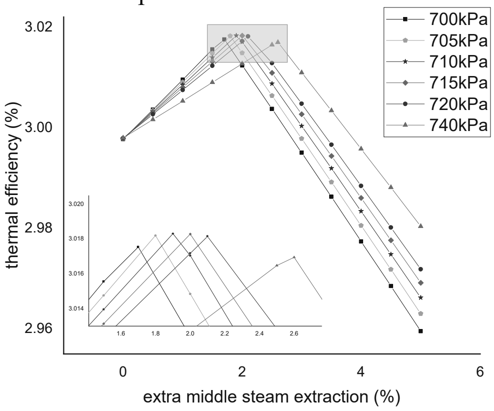

Fig. 3 Effect of extra middle steam extraction on the circulating thermal efficiency.

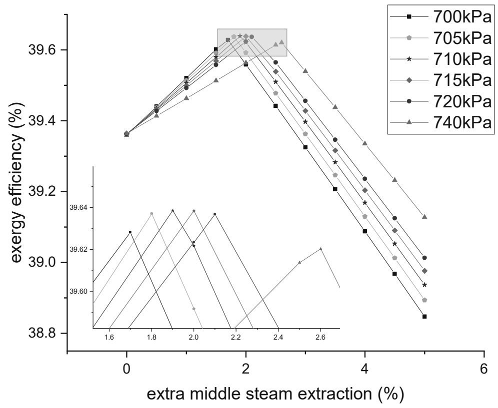

Fig. 4 Effect of extra middle steam extraction on the circulating exergy efficiency.

Exergy refers to the part of energy that can be converted into any other energy form theoretically when the system changes reversibly from any state to a state in equilibrium with the given environment. The relationship curve between the cycle execution efficiency of Uehara cycle system and extra middle steam extraction is shown in Fig.4. In the cycle, the main exergy loss is concentrated in the evaporator and condenser. With the increase of extraction, the heat exchange in these two places decreases, and the corresponding exergy loss is also decreasing. At the beginning, the decrease of the input exergy is greater than the decrease of the output work, and it reverses after reaching the limit.

3.2 Economic analysis

Take the extract pressure of 710kPa as an example, with the increase of additional intermediate air extraction rate, the equipment cost increases slowly at first, and then the cost increases faster when it exceeds the limit. As shown in Fig.8, the main cost is concentrated on the heat exchanger. With the increase of extraction, the working medium flowing through the condenser decreases, the heat exchange area required by the condenser decreases, and the cost of the condenser decreases. Meanwhile, after heat recovery, the working medium temperature at the evaporator inlet increases, the logarithmic average temperature difference of the evaporator decreases, the required heat exchange area increases, and the cost of the evaporator increases. When the cycle output power is increased by increasing the working fluid flow, the LCOE decreases sharply first and then slowly, as shown in Fig.6.

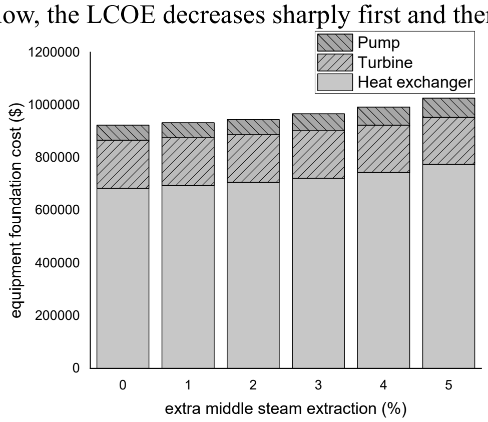

Fig. 5 Effect of extra middle steam extraction on equipment foundation cost.

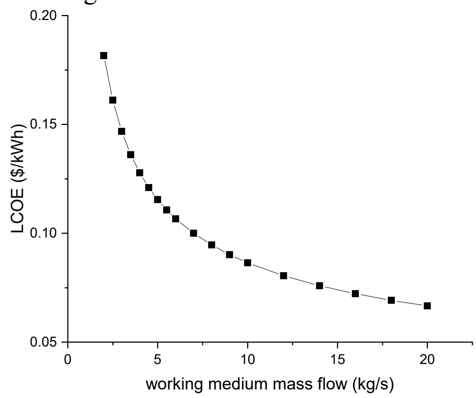

Fig. 6 Effect of working medium flow on Levelized Cost of Energy.

4. Conclusion

Based on Uehara cycle, this paper uses ammonia water mixture as working fluid, and Aspen Plus to simulate the cycle system. By changing a series of thermodynamic parameters and economic parameters obtained from extra middle steam extraction and analyzing and comparing them, the following conclusions are drawn:

(1) Compared with the approximate Karina cycle, the cycle thermal efficiency of the Uehara cycle has been significantly improved. The maximum thermal efficiency of 3.0183% is obtained when the ammonia mass fraction is 95.6%, the surface temperature of sea water is 29℃, and the deep cold sea water is 5℃, the extract pressure is 710kPa, and the extra middle extraction is 1.9%.

(2) Considering the utilization of effective energy, there is an optimal value for extraction to maximize the exergy efficiency. And because the ocean temperature difference energy is a low-grade heat source with less efficiency, the exergy efficiency is far greater than the thermal efficiency.

(3) The equipment cost is mainly concentrated in the heat exchanger cost. Large scale can effectively reduce costs.

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