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The Experimental Study of Rankine Cycle in Ocean Thermal Energy Conversion

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Abstract. For the purpose of studying the influence of evaporation temperature on system efficiency and turbine efficiency of ocean thermal energy conversion (OTEC) Rankine cycle in different temperature differences. The 15kW OTEC experiment system has been designed and built. By maintaining hot seawater and turbine parameters, OTEC Rankine cycle has been experimentally studied. The results showed that the system efficiency and turbine efficiency increase with the increase of seawater temperature difference, and when the temperature difference is 19.7°C, matching the design conditions: turbine efficiency is 73%, output power is 15kW. The system efficiency and turbine efficiency show a tendency of rising first and then decreasing with the increase of evaporating temperature at given temperature difference.

1. Introduction

With the rapid development of economy, the international community has increasingly attached importance to environmental issues such as protecting the ecological environment and responding to climate change. Coupled with the depletion of fossil fuels, ocean energy as a clean renewable energy gradually enter people's vision. Accelerating the development and utilization of ocean energy has become a universal consensus and concerted action of coastal countries and regions in the world. Ocean temperature difference energy has attracted the attention of international scholars for its sustainable uninterrupted power generation, huge reserves, clean and pollution-free, etc. [1]. The ocean temperature difference can be converted to an effective head of 197 meters at a temperature difference of 20 ℃ [2]. It has a considerable hydraulic strength and a high energy density.

The cycle mode of ocean thermal power generation can be divided into open cycle, closed cycle and mixed cycle according to the different working fluids and processes. By comparing and analyzing the advantages and disadvantages of various cycle modes, it can be seen that closed cycle can realize miniaturization of device and large scale [3]. Because of its simple structure and reliable operation, the Rankine cycle is still the main circulating form of the existing OTEC system [4]. The cycle system of this experiment is selected as the closed Rankine cycle. In this paper, the test data was analyzed by setting up the 15kW OTEC Rankine cycle system. The operating parameters of the system under different temperature difference were obtained, which provided reference for the study of OTEC Rankine thermodynamic cycle.

2. Experimental system

The low enthalpy difference Rankine cycle has high requirement for thermal physical properties of the working fluid. The main working fluids used in OTEC systems are ammonia and R22, etc. By comparing with the thermodynamic properties of commonly used working fluids in OTEC system, the

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thermodynamic properties of ammonia have been found to be far superior to other working fluids [5]. In addition, ammonia has a low price and it is easy to find out once leaks. As a result of the comprehensive comparison, ammonia was selected as the working fluid of the system. The system is composed of evaporator, separator, turbine, generator, condenser, hot sea water pump, cold sea water pump and working fluid pump. The arrangement of measuring points of 15kW OTEC Rankine cycle test system is shown in figure 1.

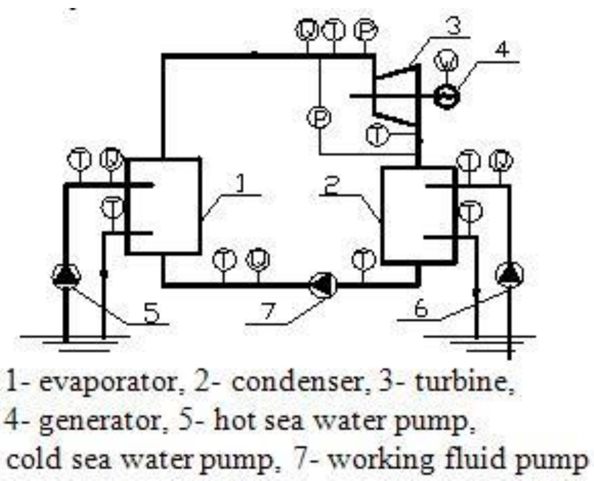

Figure 1. Arrangement of measuring points inOTEC test system.

Agilent 34970A data acquisition system is used in this test data collection. The temperature sensor uses SWB-T armored temperature sensor with an accuracy of 0.5%; The differential pressure sensor uses capacitive sensor G3351DP type model with an accuracy of 0.5%; The seawater flow is measured using an LGD electromagnetic flow meter with a nominal diameter of 200mm and a measurement accuracy of 0.5%; The ammonia flow rate was measured using a model LWYC-50 turbine flow meter with a nominal diameter of 50 mm and a measurement accuracy of 0.5%.

The hot seawater pump power, the cold seawater pump power, the working fluid pump power, and the generator output power in the test are calculated from the effective values of the voltage and current measured during the test. The measurement data in the test are automatically collected and automatically saved by the Agilent 34970A data acquisition system.

According to the actual temperature difference between surface seawater and deep seawater, the surface seawater at 20 ℃ is used as cooling water in this test to cool the exhaust gas from the turbine. Relevant studies show that the most reasonable temperature difference between inlet and outlet of seawater in the heat exchanger is 2~4 ℃ [6]. In order to make the working fluid ammonia have sufficient boiling superheat in the evaporator, the hot seawater temperature in this system is reduced by 2 ℃.

During the test, the temperature difference between the hot and cold seawater and the evaporation temperature of the evaporator were adjusted. The following parameters were collected and recorded: Turbine inlet and outlet temperature and pressure, evaporator inlet and outlet working fluid temperature and pressure, and generator output current and voltage. During the test, the temperature of the hot seawater is adjusted according to the temperature of the cold seawater, so that the difference of temperature between hot seawater and cold seawater is 16 ℃, 17 ℃, 18 ℃, 19 ℃ and 20 ℃, respectively. When the hot seawater flow was fixed at 220t/h, the test was conducted with the hot seawater temperature of 40 ℃, 41 ℃, 42 ℃, 43 ℃, and 44 ℃, respectively.

3. Numerical model

The T-S diagram of the OTEC Rankine cycle system is shown in Figure 2. Where T_E is the evaporation temperature, ℃; T_C is the condensing temperature, ℃; T_{wsi} and T_{wso} are the inlet and outlet temperatures of evaporator, ℃; T_{wci} and T_{wco} are the inlet and outlet temperatures of the condenser, ℃;

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Q_E andQ_C are the evaporator and condenser heat load, kW; $W_{P,f}$ is the working pump power, kW; W_T is the turbine output power, kW.

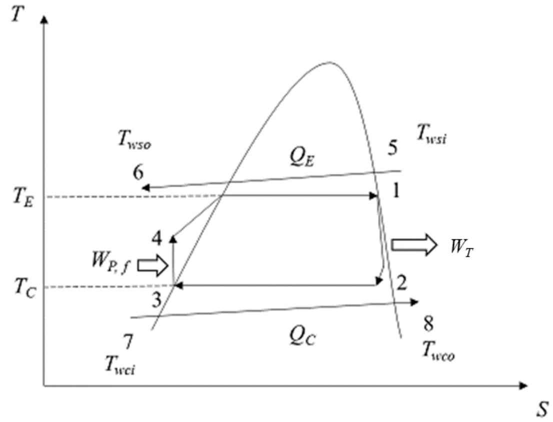

Figure 2. *T-S* diagram of Rankine cycle.

The energy equation of the turbine efficiency:

$$\eta_t = \frac{W_T}{m_f(h_1 - h_2)} \quad (1)$$

where m_f is mass flow rate of working fluid, kg/h; h is specific enthalpy of working fluid, J/kg.

The energy equation of the system efficiency:

$$\eta_s = \frac{W_g}{Q_E} \quad (2)$$

where W_g is the output power of the generator.

4. Analysis of experiment results

During the test, the temperature difference between hot seawater and cold seawater is 16 ℃, 17 ℃, 18 ℃, 19 ℃ and 20 ℃ respectively. The ammonia turbine performance and generator output power parameters are shown in Table 1.

Table 1. Ammonia turbine and generator parameters.

The temperature difference between hot and cold seawater(℃)	Turbine efficiency (%)	Generator output power (kW)
16	24.2	3.42
17	30.1	4.13
18	40.1	6.23
19	55.3	10.01
20	73.2	15.27

The output power of the turbine varies with the temperature difference as shown in Figure 3. With the increase of temperature difference between cold and hot water, the power of the generator increases continuously. When the temperature difference is 19.7 ℃, the turbine output power reaches the rated power of 15kW. The relationship between turbine efficiency and temperature difference is shown in Figure 4. With the temperature of hot seawater rises, the efficiency of turbines continues to increase. From the curve change law, It can be seen that when the turbine reaches the rated power of 15kW, the efficiency is close to the highest point, which is 73%.

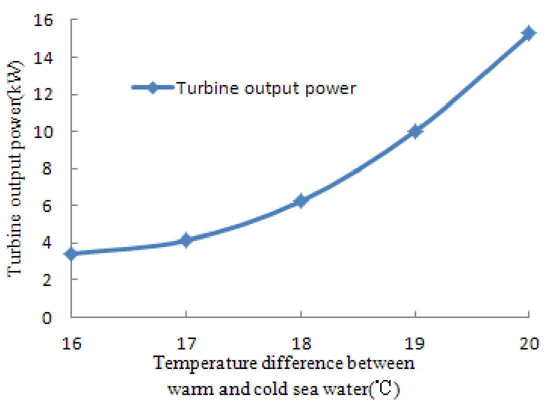

Figure 3. The variation of turbine output power with temperature difference.

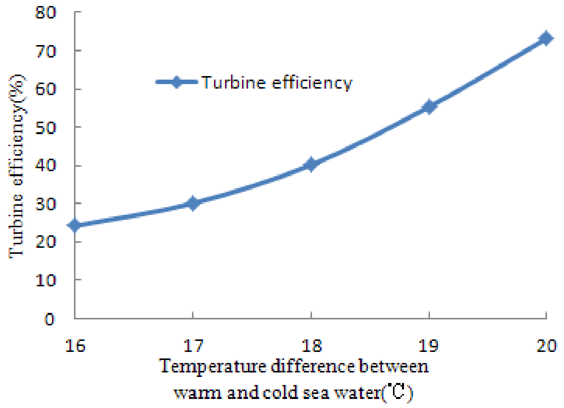

Figure 4. The variation of turbine efficiency with temperature difference.

The system operating parameters were fixed at the cold seawater temperature of the system is 20 ℃, the condensing temperature is 24 ℃ and the temperature sea water flow is 220t/h. The hot seawater temperature is adjusted to 40 ℃, 41 ℃, 42 ℃, 43 ℃ and 44 ℃, respectively. The variation of system efficiency with evaporation temperature is shown in Figure 5. When the temperature of seawater flow and the inlet temperature are constant, with the increase of evaporation temperature, the efficiency of the system rises first and then decreases, and there is a maximum point. Because the cold seawater temperature and condensation temperature are constant, Rankine cycle efficiency increases with the temperature of the hot seawater rising, and basically changes linearly with the temperature of the hot seawater. On the other hand, turbine efficiency is related to ammonia mass flow. Under the combined effect of turbine efficiency and Rankine cycle system efficiency, the system efficiency increases first and then decreases. In Figure 6, when the inlet temperature of hot seawater are 40 ℃, 41 ℃, 42 ℃, 43 ℃ and 44 ℃, respectively, the evaporation temperatures corresponding to the maximum points of the generator output power are 37 ℃, 38 ℃, 39 ℃, 40 ℃ and 41 ℃, respectively. With the inlet temperature of hot seawater increases, the maximum value of the generator output power increases, and the evaporation temperature corresponding to the maximum point of the generator output power also increases.

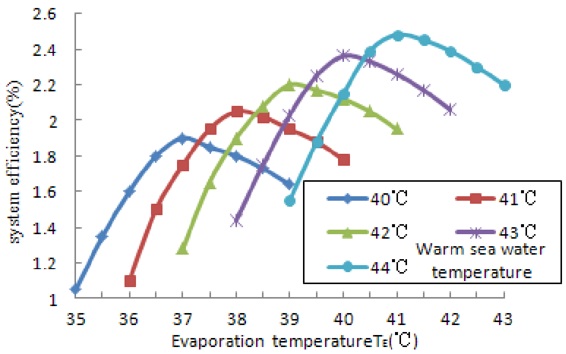

Figure 5. System efficiency varies with evaporation temperature.

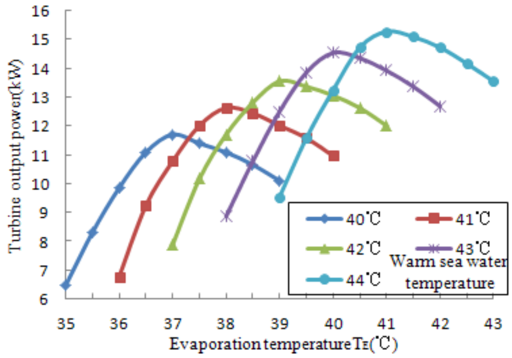

Figure 6. Generator power varies with evaporation temperature.

5. Conclusion

This paper selects the Rankine cycle system as the studied system through analysis and comparison. The closed OTEC Rankine cycle demonstration plant was designed and built to experimentally study its performance with the help of temperature and pressure readings before and after each component. By changing the operating conditions of the system, the influence of various parameters of the system on the OTEC Rankine cycle system performance is analyzed. The following conclusions were obtained through calculation and analysis:

(1) Turbine efficiency is positively correlated with the temperature difference between cold and hot seawater. When the temperature difference is 19.7℃, it matching the design conditions: turbine efficiency is 73%, output power is 15kW.

(2) With the increase of evaporation temperature, the changes in system efficiency, generator power and net output power are basically the same as first increasing and then decreasing, and there are maximum points. With the evaporation temperature increases, the maximum values of system power, generator power, and net output power increase.

6. Acknowledgements

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