Thermodynamic Analysis of Rankine Cycle in Ocean Thermal Energy Conversion

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***Abstract* — The thermodynamic cycle efficiency is low because the temperature difference is very small in the ocean thermal energy conversion (OTEC) system, so it is particularly important to increase the cycle efficiency when the OTEC is developed and utilized. In this paper the cycle efficiency calculation method of the ocean thermal energy conversion (OTEC) is obtained through the theoretical analysis and model establishment of the equipment in the OTEC system according to the first and second law of thermodynamics for Rankine cycle, and also the influence of turbine inlet pressure, warm and cold seawater temperature on the thermal and exergy efficiency are obtained. At last the development and utilization direction of OTEC system is proposed. This research will guide the thermodynamic cycle selection and operating parameters optimization of the low grade energy utilization.**

Keywords - ocean thermal energy conversion, Rankine cycle, thermodynamic efficiency, exergy efficiency, terminal temperature difference

I. INTRODUCTION

Ocean thermal energy is large reserves, renewable, no fluctuation with day and night and no pollution. Besides used to generate electricity the ocean thermal energy can also be air conditioning refrigeration, deep seawater products, marine chemical, desalination and other accessory development. So the ocean thermal energy is generally considered to be the most potential of development and utilization value by the international society. Development of ocean thermal energy can not only can reduce the pressure on our energy, adjust the energy structure, but also to be beneficial to environmental protection of our country [1].

Although ocean thermal energy is high energy density in the ocean energy, the temperature difference is very small, so the thermodynamic cycle efficiency of OTEC is relatively low. When the warm seawater temperature is 25 ℃ and cold seawater is 5℃, ideal Carnot cycle efficiency is only about 6.7%. So it is extremely important to study the thermodynamic calculation of the OTEC cycle. In this paper, it is calculated for Rankine cycle according to the laws of thermodynamics.

II. MATERIALS AND METHODS

A. Principle of Rankine cycle

Rankine cycle is a thermodynamic cycle of steam power machine. Adopted by the modern large-scale thermal power plant is developed on the basis of the Rankine cycle, and also Rankine cycle is the basic cycle of the waste heat recovery, geothermal and solar power device. The earliest Rankine cycle uses water as working medium, and now most of waste heat power generations prefer to use organic Rankine cycle with low boiling point organic working medium [2]. Pure ammonia is mostly used as working medium in OTEC [3].

In the OTEC the principle of Rankine cycle is showed in Fig.1. First the working fluid is pumped into the evaporator where it is vaporized and then drives a turbine. The turbine exhaust is condensed by the cold seawater and then into the pump. In this paper, thermal properties of working medium of the equipment before and after are calculated, and operation parameters of cycle are determined. Also the thermodynamic efficient is analyzed.

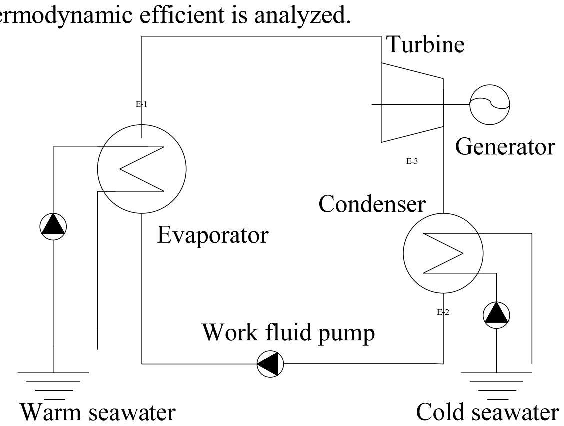

Figure 1: Principle of Rankine cycle

B. Thermal progress of cycle

The T-S diagram of Rankine cycle is showed in Fig.2. In the T-S diagram 1-2 is the progress of turbine doing work, 2-3 is condensed in the condenser of working medium, 3-4 is the process of working medium through the pump, 4-1 is the evaporation of working medium in the evaporator.

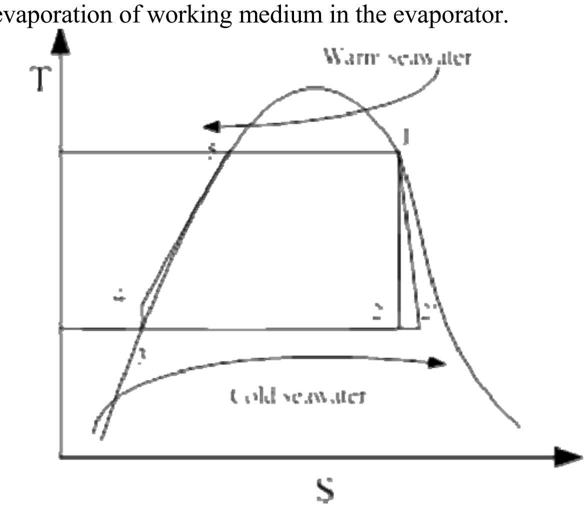

Figure 2: The T-S diagram of Rankine cycle

C. Thermodynamic model of equipment

(1) Evaporator

The thermal equilibrium equation of evaporator

$$Q_E = m\ (h_1 - h_4) \tag{1}$$

Q_E — heat transfer of the evaporator, kW; m —mass-flow rate of work fluid, kg/s; h_n —enthalpy of n, kJ/kg.

(2) The thermal equilibrium equation of condenser

$$Q_C = m(h_2 - h_3) \tag{2}$$

Q_C —heat transfer of the condenser, kW;

(3) Power generation of turbine

$$W_t = m(h_1 - h_2) \tag{3}$$

W_t —power generation of turbine, kW;

(4) Work fluid pump

$$W_P = m(h_4 - h_3) \tag{4}$$

(5) Thermodynamic cycle efficiency

$$\eta_t = \frac{(h_1 - h_2) - (h_5 - h_4)}{h_1 - h_4} \tag{5}$$

(6) Net work of output

$$W = W_t - W_p \tag{6}$$

D. The calculation condition

The research shows temperature difference between the import and export of the heat exchanger is about 2~ 4℃. In order to make the ammonia boil in the evaporator and condense in the condenser, in this paper 2℃ is selected of the terminal temperature in the heat exchanger. At the same time in the process of calculation thermodynamic cycle is simplified as follows:

(1) Gas expending in the turbine is simplified as isentropic expansion

(2) Ignore the pressure loss of the heat exchanger and pipe.

III. RESULTS

E. The influence of the warm temperature change on the system

When the inlet temperature of warm seawater is 27℃, 28 ℃, 29℃, 30 ℃, 31℃, and cold seawater temperature is 4℃, and also the mass-flow rate of work fluid is constant, obtain a series of data of the Rankine cycle by the program.

F. Relationship between net output work and terminal temperature difference of heat exchanger

Thermodynamic cycle efficiency and net output work of the generator should be considered when comparing the advantages and disadvantages of different working conditions. With the increasing of generator output mass-flow of warm seawater and work fluid increases, and the consumed work of warm/cold seawater pump and work fluid pump also increase accordingly. So the net output work of the system should be considered.

The effect of terminal temperature difference on net output of system is showed as Fig3. It can be seen when mass-flow of working fluid is constant, with the increase of terminal temperature difference of evaporator, in other words, the temperature difference between outlet of working fluid and inlet of warm seawater in evaporator is larger, and the net output work is smaller. Because the terminal temperature difference increases, and the steam temperature of turbine inlet decrease, work capacity is reduced accordingly, net output work of the system decreases. If terminal temperature difference is under the same conditions, the inlet temperature of warm seawater is higher; and the net output work is larger. Because with the increasing of warm seawater temperature, the available temperature difference of system increases, also the steam temperature of turbine inlet and work capacity increase, the net output work of system increases.

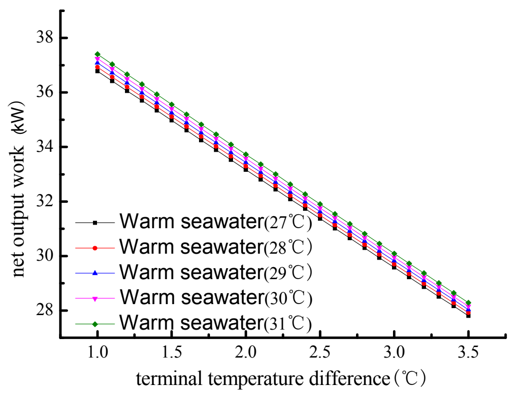

Figure 3: Effect of terminal temperature difference on net output work of the system

The relationship between cycle efficiency and terminal temperature difference is showed as Fig.4. It is found that when mass-flow of working fluid is constant and the inlet temperature of the warm seawater is determined, cycle efficiency decreases and the heat of the work fluid absorbed from evaporator reduce with the terminal temperature difference increasing.

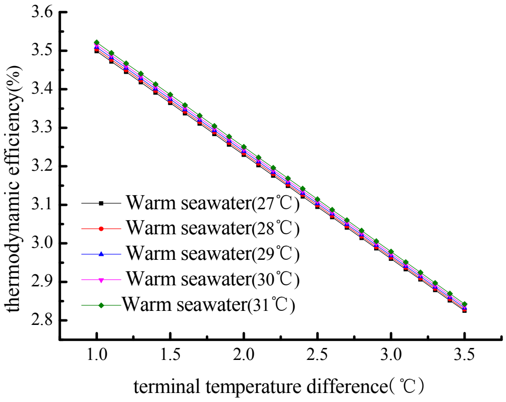

Figure 4: relationship between thermodynamic efficiency and terminal temperature difference

When the terminal temperature difference is constant, the cycle efficiency increases with the inlet temperature of warm seawater increasing. When the temperature of warm seawater rises from 27℃ to 31℃, cycle efficiency increases from 3.228% to 3.250%. Because with the increasing of warm seawater temperature, the available temperature difference of system increases, according to the formula of efficiency the cycle efficiency increases.

Figure 5 shows the exergy efficiency of system changes with terminal temperature difference. It can be seen when mass-flow of working fluid is constant, the exergy efficiency decreases with the terminal temperature difference increasing. Because with the terminal temperature difference increasing, the absorption curve of the working fluid in the evaporator matches with the exothermic curve of the warm seawater worse, and the irreversible heat transfer losses increase. Under the same terminal temperature difference, the warm inlet temperature is higher; the system cycle exergy efficiency is lower. When the warm rise from 27℃ to 31℃, cycle exergy efficiency decreases from 15.42% to 15.38%.

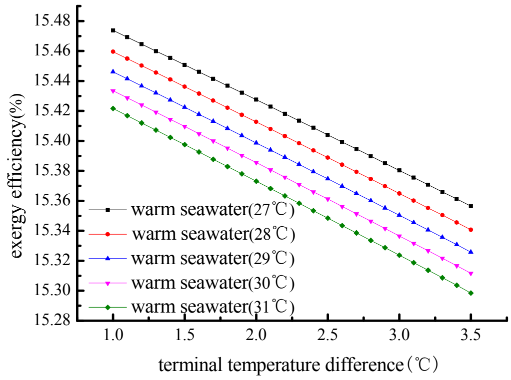

Figure 5: Relationship between exergy efficiency and terminal temperature difference

G. *The influence of cold water temperature on the system*

The relationship between cold seawater temperature and net output work is shown in figure 6.The output work decreases with the increase of cold seawater temperature. Because if the inlet temperature of cold seawater increases, the backpressure of turbine increases, and also the enthalpy drop of working fluid in the turbine decreases. So the output work of turbine decreases.

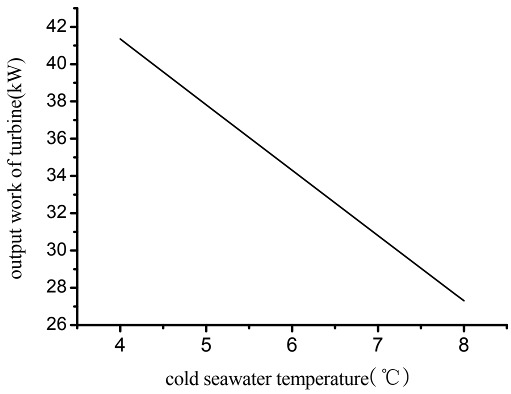

Figure 6: Relationship between cold seawater temperature and net output work of the system

From the figure 7 it can be seen when the warm seawater temperature is 29℃, and the other parameters are constant, the thermodynamic efficiency decreases and the exergy efficiency increases with the increasing of the cold seawater temperature. When the warm temperature rises from 4℃ to 8℃, thermodynamic efficiency decreases from 3.238% to 1.927% and the exergy efficiency increases from 15.41% to 15.89%.

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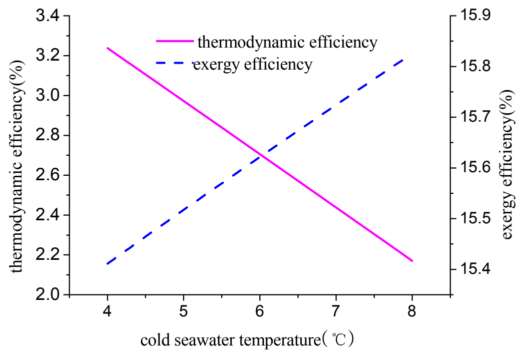

Figure 7: Relationship between thermodynamic and exergy efficiency and cold seawater

IV. Discussion

The OTEC system are analyzed according to the first and second law of thermodynamics, it is concluded that Rankine cycle thermodynamic and exergy efficiency increases with the turbine outlet pressure, but due to the limitation of the highest pressure, the thermodynamic and exergy efficiency will be lower when the pressure reaches a certain value.

Because ocean temperature difference energy is abundant, it doesn't consider exergy efficiency when the system operation parameters is determined, just need the largest net power output of the system

V. Conclusions

The effect of warm and cold seawater temperature on the OTEC system is very great. When the warm seawater temperature increases, thermal efficiency, turbine output power and net power output of system will be increased. Cold seawater temperature lower can improve cycle efficiency, turbine output power. So it is important to choose the location where surface temperature is higher and it doesn't need too long cold water pipe to obtained cold seawaters.

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