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Thermodynamic analysis of a new ammonia-water power cycle

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Abstract

A new ammonia-water power cycle (AWPC) basing on Kalina cycle is presented in this paper, which supply an effective way for low-moderate temperature geothermal power in China. The thermodynamic models of AWPC are established considering of the ratio of power generation as the optimization objective, and the binary cycle systems are analyzed. The theoretical results of AWPC show that there exists the optimum circulation ratio of 4, along with concentration difference of the ammonia-water solution of 12%–13%. And higher concentration of the ammonia-water solution will improve the performance of AWPC, while adding terminal temperature difference of the solution heat exchanger will improve the ratio of power generation.

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Keywords: Kalina cycle; Ammonia-water mixture; Energy efficiency; Solution circulation ratio

1. Introduction

Currently, mid-low temperature geothermal power generation technology is mainly based on the organic Rankine cycle power generation system and the Kalina cycle of ammonia power cycle system.

There are more than a dozen companies engaged in designing and installing organic Rankine cycle system, and Israeli ORMAT company [1], the United States UTC [2] occupied almost all the mid-low temperature geothermal power generation market.

The Kalina Cycle is the most significant improvement in thermal power plant design since the advent of the Rankine Cycle in the mid 1800s. Kalina cycle system (KCS) was invented by Dr. Alexander Kalina specifically for generating electricity using low to medium temperature geothermal resources as a “topping” thermodynamic cycle prior to district heating.

In a typical Rankine Cycle power plant, a pure working fluid, water or low molecular weight organic compounds, is heated in a boiler and converted into high-pressure, high temperature vapor which is then expanded through a turbine to generate electricity in a closed loop system. The Kalina Cycle utilizes an ammonia-water mixture as a

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working fluid to improve system efficiency and provide more flexibility in various operating conditions. The Kalina Cycle can improve power plant efficiency by 10% to 50% over the Rankine Cycle depending on the application. As plant operating temperatures are lowered, the relative gain of the Kalina Cycle increases in comparison with the Rankine Cycle.

The U.S. UTC company developed the 100-kilowatt unit that used 90–150 °C heat carrier to heat the single organic working fluid, and the heated organic working fluid would promote turbine-powered cycle, the United States, Japan, Russia and New Zealand all introduced the unit and technology for geothermal and industrial waste heat power generation [3].

Kalina cycle system (KCS) was invented by Dr. Alexander Kalina [4] specifically for generating electricity using low to medium temperature geothermal resources as a “topping” thermodynamic cycle prior to district heating. In 1992, the U.S. Exergy company constructed of the world’s first commercial unit of the Kalina cycle, the capacity of the units was 3MW.

2. System design

2.1. Simplified Kalina cycle system

Fig. 1 shows the schematic diagram of simplified Kalina cycle for geothermal power plant which be used in this study. The absorption refrigeration cycle principle is introduced into simplified Kalina cycle, and in the system , evaporator is replaced by generator and condensator is replaced by absorber, so that the Kalina cycle is simplified [5].

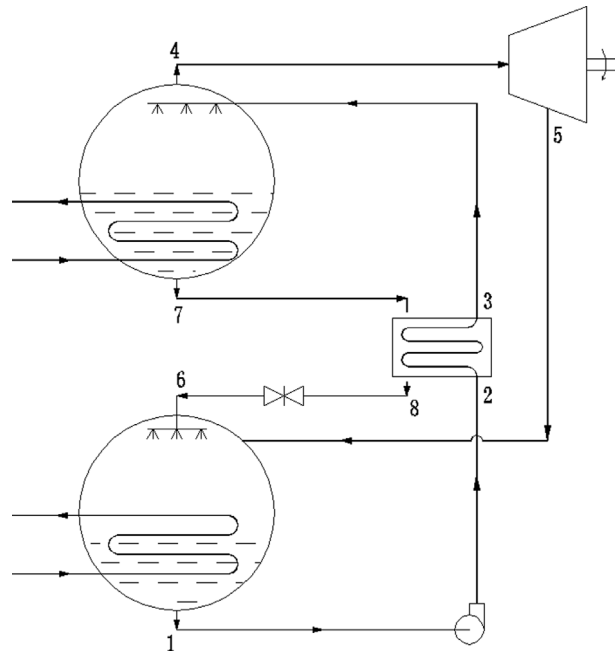


Fig. 1. Scheme of simplified Kalina cycle. 1 — Absorber solute outlet; 2 — heat exchanger cold solute inlet; 3 — heat exchanger cold solute outlet; 4 — generator gas outlet; 5 — turbine exhaust; 6 — absorber solute inlet; 7 — generator solute outlet; 8 — heat exchanger solute outlet.

Simplified Kalina cycle system consists of a generator, a absorber, a steam turbine, a solution heat exchanger, a solution pump, and a throttle. And its working principle is: the geothermal water enter the generator, and the heat is transferred to ammonia-water and the ammonia-water with a little water vapor goes into turbine and the turbine generates the electricity, and after that the low pressure and temperature ammonia-water flows into the absorber and was absorbed by the dilute solution out of the generator, and the heat that released is carried away by the cooling water, and a new cycle begins. There is an ammonia-water solute cycle developed between the generator and absorber, concentrated solute that in the absorber is pumped to the solute heat exchanger, and over there it will receive some heat and enter the generator [6–10].

2.2. Thermodynamic performance

Thermodynamic process of Simplified Kalina cycle can be decomposed as follows:

Generator

Different from the evaporator of ORC cycle, ammonia solution in the generator is not only the heat transfer process but also a mass transfer process, the energy and the mass conservation equation can be shown as follows:

Energy conservation:

$$Q_G + m_3 h_3 = m_4 h_4 + m_7 h_7 \quad (1)$$

Heat transfer:

$$Q_G = m_g (h_{g1} - h_{g2}) \quad (2)$$

mass conservation:

$$m_4 + m_7 = m_3 \quad (3)$$

Generator heat transfer area:

$$A_G = \frac{Q_G}{\bar{U} \Delta T_{G,LMTD}} = \frac{m_g (h_{g1} - h_{g2})}{\bar{U} \Delta T_{G,LMTD}} \quad (4)$$

Turbine Generator

The acting process that ammonia vapor through the turbine is not a isentropic process, but shift to the direction of entropy increase, in the assumed conditions, the turbine energy conservation equation is:

$$P = m_4 (h_4 - h_5) \eta_m \eta_g = m_4 (h_4 - h_{5s}) \eta_{is} \eta_m \eta_g \quad (5)$$

In the later theoretical analysis, the value of η_{is} is 0.8, the value of $\eta_m \eta_g$ is 0.95.

Absorber

Similar to the generator, the ammonia aqueous solution in the absorber is also a heat and mass transfer process. The energy and mass conservation equations are as follows:

$$Q_A + m_1 h_1 = m_5 h_5 + m_6 h_6 \quad (6)$$

$$m_1 = m_5 + m_6 \quad (7)$$

$$Q_A = m_w (h_{w2} - h_{w1}) \quad (8)$$

The heat transfer area of the generator is:

$$A_A = \frac{Q_A}{\bar{U}_A \Delta T_{A,LMTD}} = \frac{m_w (h_{w2} - h_{w1})}{\bar{U}_A \Delta T_{A,LMTD}} \quad (9)$$

Solution pump

In fact, the boosting process of the solution pump is not an isentropic process, but a shift to the direction of increasing entropy. Under the above assumptions, the energy conservation equation of the solution pump is as follows:

$$W_p = m_1 (h_2 - h_1) = m_1 (h_{2s} - h_1) / \eta_p \quad (10)$$

In the theoretical analysis described later in this paper, the value is 0.8.

Solution heat exchanger

The main function of the solution heat exchanger is to recover the energy of the dilute solution from the generator. The energy conservation equation is as follows

$$m_7 h_7 + m_2 h_2 = m_3 h_3 + m_8 h_8 \quad (11)$$

Pressure relief valve

The process of ammonia aqueous solution passing through pressure reducing valve is an isoenthalpy process, and its equation is as follows:

$$h_6 = h_8 \quad (12)$$

The performance formulation of the simplified Kalina cycle system is as follows:

Net power (kW):

$$P_{net} = P - W_p \quad (13)$$

Electricity yield (kWh/t): net power generation per ton of geothermal water

$$N_e = \frac{P_{net}}{m_g} \quad (14)$$

Thermal efficiency:

$$\eta_t = \frac{P_{net}}{Q_G} = \frac{P - W_p}{m_g (h_{g1} - h_{g2})} \quad (15)$$

Heat Exchanger Area Ratio (m²/kW): The area of heat exchanger required for net power per kilowatt

$$\psi = \frac{A}{P_{net}} \quad (16)$$

3. Results and discussion

The biggest characteristic of simplified Kalina Cycle System is that the performance of the system can be changed by adjusting the concentration of ammonia aqueous solution. Therefore, the following focuses on the analysis of the cycle performance under different concentration conditions. The set operating parameters are as follows: the initial temperature of geothermal water is 100 °C, the flow rate of geothermal water is 20 kg/s (72 t/h), the initial temperature of cooling water is 20 °C, the circulation ratio is 4, the concentration of concentrated solution is 20%–60%, and the temperature difference between the end of generator and absorber is 5 K.

Fig. 2 shows the variation trend of electric power yield and thermal efficiency with concentration of concentrated solution. It can be seen from the figure that with the increase of concentration of concentrated solution, both electric power yield and thermal efficiency begin to decrease, and reach the lowest when concentration of concentrated solution is 35%, then there is an increasing trend. When the concentration of ammonia water is low, the steam produced in the generator is mainly water vapor, mainly water vapor, which drives the steam turbine to work and produces higher power yield and thermal efficiency; with the increase of concentration, the steam produced in the generator is mainly ammonia vapor, and ammonia vapor drives the steam turbine to work; when the power yield and thermal efficiency reach the lowest, the concentrated solution occurs at this time. When the concentration of concentrated solution is higher than the most disadvantageous point, the net power of power generation system increases with the increase of the mass content of ammonia vapor. When the concentration of concentrated solution is lower than the most disadvantageous point, the mass content of water vapor decreases and the net power of power generation system decreases. Therefore, the power yield and thermal efficiency decrease first and then increase with the increase of the concentration of concentrated solution.

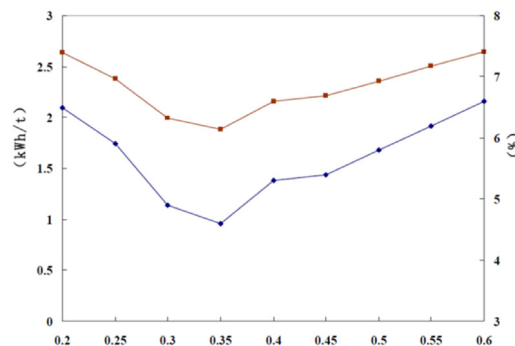


Fig. 2. Variations of net power per unit geofluid and energy efficiency with ammonia water mass fraction.

Fig. 3 shows that the occurrence pressure and absorption pressure increase with the concentration of concentrated solution, and the pressure difference between them increases gradually. For the lower concentration of solution, the pressure and absorption pressure of the system are lower, especially the absorption pressure. Negative pressure may

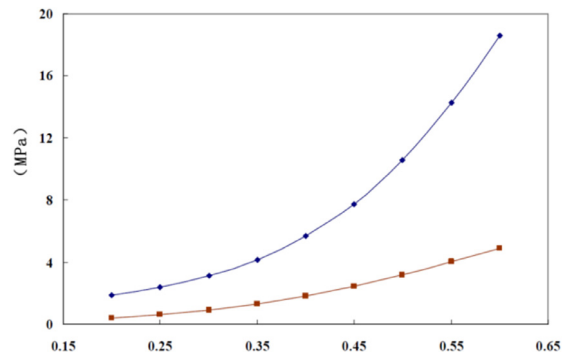


Fig. 3. Variations of generation and absorption pressure with ammonia water mass fraction.

occur at the lower concentration, which is very disadvantageous to the system. Therefore, although the performance of the system is higher at the lower concentration, because the system is in negative pressure at the absorber end, it is necessary to add a suction system, which will significantly increase the system's power consumption. The actual output of the system is not dominant.

Fig. 4 shows that there exists an optimal cycle rate for the simplified Kalina cycle. The optimal cycle rate is about 4 with the objective of “power yield”, while the optimal cycle rate is about 5 with the objective of “thermal efficiency”. It is worth noting that there is a turning point when the cycle ratio is 4.5. This is probably because when the cycle ratio reaches 5, some ammonia vapor is precipitated from the aqueous ammonia solution after working through the turbine. If the concept of “dryness” of organic working medium is used, the dryness of ammonia vapor is 0.96 at this time, while the dryness of ammonia vapor after working is 1 when the cycle ratio is 4.5.

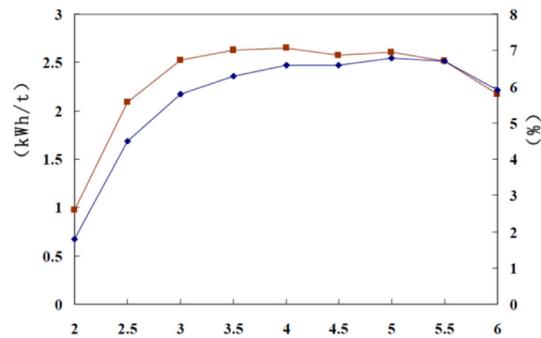


Fig. 4. Variations of net power per unit geofluid and energy efficiency with circulation ratio.

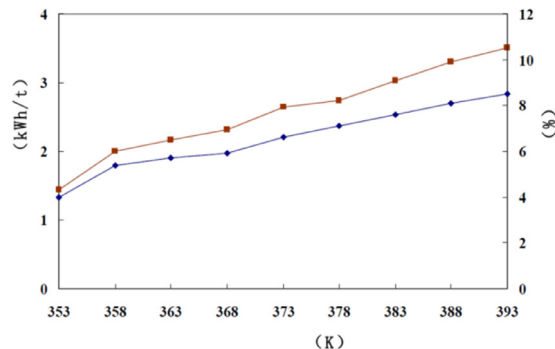


Fig. 5. Variations of net power per unit geofluid and energy efficiency with geofluid initial temperature.

Fig. 5 shows the change trend of electric power yield and thermal efficiency with the initial temperature of geothermal water. It can be seen that with the increase of initial temperature of geothermal water, the electric

power yield and thermal efficiency are significantly increased due to the increase of pressure and ammonia vapor. As shown in Fig. 6, the increase of initial temperature of geothermal water will also significantly reduce the ratio of heat exchange area, which means that the higher the temperature of geothermal water, the unit composition of the unit. The lower Ben will be.

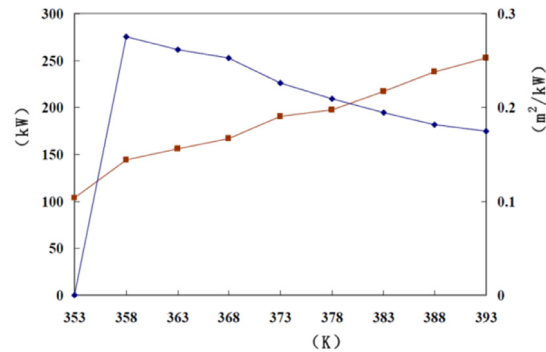


Fig. 6. Variations of net power and heat exchange area rate with geofluid initial temperature.

Fig. 7 investigates the influence of initial temperature of cooling water on power yield and thermal efficiency. The lower the temperature of the cooling source, the lower the condensation temperature and the lower the absorption pressure. Therefore, it is helpful to improve the output of the unit.

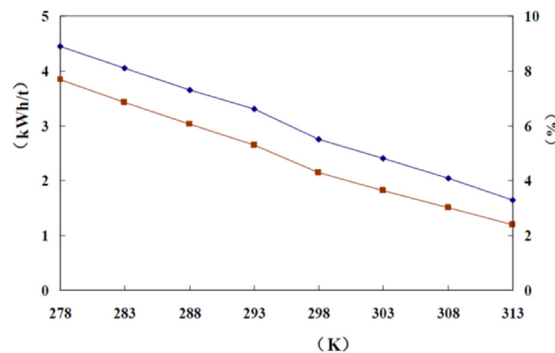


Fig. 7. Variations of net power per unit geofluid and energy efficiency with cooling water temperature.

4. Conclusion

In this chapter, ammonia water solution is used as working fluid to simplify the Kalina Cycle System and build the thermodynamic model of the cycle. The following conclusions are obtained through theoretical simulation and analysis:

(1) The factors affecting the performance of simplified Kalina Cycle are complex. Among these factors, ammonia concentration, circulation ratio, temperature of heat and cold sources, and temperature difference at the end of heat exchanger are the key factors.

(2) Simplified Kalina Cycle performance can be changed by adjusting the concentration of ammonia aqueous solution. In order to avoid negative pressure in the system, higher concentration of ammonia aqueous solution is conducive to improving the system performance, while too high concentration will also make the system pressure too high, and the requirements for equipment are more stringent.

(3) For the simplified Kalina Cycle system, there is an optimal cycle ratio, which is about 4 for the medium and low temperature geothermal conditions, while the corresponding concentration difference of ammonia aqueous solution is 12%–13%.

Symbol table	
T — temperature, K	T_{LMTD} — Logarithmic Temperature Difference, K
P — Output Power, kW	A — Heat Exchange Area, M ²
N_e -Electricity Yield, kWh/t	
ψ — heat transfer area ratio, m ² /kW	Subscript
W — Power Consumption, kW	g-geothermal water
η — Thermal efficiency of power plant, %	w-Cooling Water
M — mass flow rate, kg/s	p-working fluid pump
U — heat transfer coefficient, w/(m ² .k)	net-net power generation
Q — heat transfer, kW	A-Absorber
H — enthalpy, kJ/kg	G-generator

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