Thermodynamic comparison among double-flash flash-Kalina and flash-ORC geothermal power plants

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Abstract:

The geothermal energy is renewable energy, which is viewed as a promising alternative to fossil energy. This paper conducts a comparative study among double-flash, flash-Kalina and flash-ORC geothermal power plants. The mathematical models of three different geothermal power plants are established. And parametric analyses are performed to examine the effect of some key parameters on system performance. The performance of each cycle has been discussed in terms of the net power output, thermal efficiency and exergy efficiency. Moreover, genetic algorithm (GA) is used to conduct optimization to obtain the best performance of three different geothermal power plants. Flash-ORC geothermal power plant yields the highest exergy efficiency of 46.121%. Exergy efficiency of Flash-Kalina geothermal power plant is 36.747%, but the inlet pressure of ammonia-water turbine is much higher than that of organic turbine and steam turbine. Double-flash has the lowest exergy efficiency of 31.922%.

Keywords:

Double-flash, Flash-Kalina, Flash-ORC, Geothermal energy, Thermodynamic analysis.

1. Introduction

The exhaustion of fossil fuel, the increase of economic activity and their detrimental environmental impacts have intensified the worldwide search for cleaner sources of energy [1]. Renewable energy including wind energy, solar energy and geothermal energy is an alternative to fossil fuel. Geothermal energy source is considered to be one of the most reliable renewable energy source options. It is known as the energy which is stored under the crust of the earth [2].

Nowadays, owing to the technical feasibility, geothermal water is widely utilized to generate electricity. Single-flash geothermal power plant is a simple and most widely used technology to exploit geothermal energy. Pambudi et al. [3] conducted exergy analysis and optimization of a single-flash geothermal power plant in Indonesia. Cerci [4] evaluated the performance of a single-flash geothermal power plant in Turkey based on the actual plant operation data. Amiri et al. [5] investigated the determination of the optimum flash pressure to get maximum efficiency in a single flash geothermal power plant.

However, the saturated geothermal water extracted from flash chamber still contains great amount of energy. In order to take full advantages of geothermal energy, many research have been carried out on double-flash and flash-binary geothermal power plants in which the organic Rankine cycle (ORC) is usually adopted to recover the energy taken along by saturated geothermal water. Dagdas [6] conducted a performance analysis of a double-flash geothermal power plant, and some key parameters are examined. Alicilar et al. [7] carried out an optimization for double-flash geothermal power plant to obtain optimum first and second flash temperatures. Jalilinasrabady [8] carried out an energy and exergy analysis of a double-flash geothermal power plant in the Mt Sabalan geothermal field, Iran, on the basis of mathematical model. The results showed that the optimum first flash pressure and second flash pressure are 0.55MPa and 0.9MPa, respectively. Pasek et al. [9] evaluated the performance of a flash-binary geothermal power plant. Working fluid selection and parametric analysis were conducted as well. Paloso and Mohanty [10] analysed the performance of a flash-binary geothermal power plant. Parametric analyses were carried out to determine the optimum performance and comparative evaluation with the simple flashing plant was made to assess its thermodynamic potential and economic viability. Luo et al. [11] discussed the effect of geothermal water temperature on the net power output, the thermal efficiency and explored the optimum geothermal temperature for flash-binary geothermal power plant.

Thanks to low boiling point and low latent heat of vaporization of working fluid, ORC is widely utilized in low temperature heat source recovery. Besides ORC, another power cycle, namely Kalina cycle which employs ammonia-water as working fluid, could also achieve efficient energy conversion for low temperature heat source owing to the behaviour of temperature glide of non-azeotropic mixture during the two-phase region. Therefore, Kalina cycle is expected to play a more significant role in the area of low temperature heat source utilization. Rogdakis [12] conducted a parametric study of a Kalina Power Unit. Elsayed et al. [13] investigated the performance of Kalina cycle used for low-temperature heat sources below 200℃ compared with the ORC based on pure ammonia and R134a. Results indicated that Kalina cycle was more efficient than ORC. Wang et al. [14] studied a solar driven Kalina cycle and performed a parametric analysis to examine the effects of some key thermodynamic parameters on the system performance. Lolos and Rogdakis [15] investigated a Kalina cycle using low-temperature heat sources provided by flat solar collectors to generate power. Sun et al. [16] examined a Kalina solar system with an auxiliary superheater and carried out parametric analyses on the system.

In this study, we integrate a Kalina cycle into the single-flash geothermal power plant to propose a flash-Kalina geothermal power plant so as to recover the saturated geothermal water extracted from flash chamber and make a comparative study among double-flash, flash-Kalina and flash-ORC geothermal power plants. Based on the established mathematical model, parametric analyses are conducted to examine the effect of some key parameters on the system performances including net power output, system thermal efficiency and system exergy efficiency. Furthermore, double-flash, flash-Kalina and flash-ORC geothermal power plants are optimized with system exergy efficiency as objective function by method of genetic algorithm (GA).

2. Geothermal power plants

Figs 1 to 3 depict the double-flash, flash-Kalina and flash-ORC geothermal power plants. The geofluid keeps a high pressure in geothermal well. After exiting the geothermal well to surface, the geofluid is throttled down to a low pressure at constant enthalpy. And the two-phase fluid enters flash chamber in which liquid-vapour mixture is separated into saturated steam and saturated water. This process is flash process. The saturated steam passes through a high pressure turbine to generate power. For flash-Kalina and flash-ORC geothermal power plants, the saturated water gives off heat to Kalina cycle and ORC to generate extra power. And Kalina cycle 11 is chose as bottom cycle. The working fluid selected for ORC is R245fa. For double-flash geothermal power plant, the saturated water is delivered to another flash chamber to perform a “second flash process”. Saturated steam extracted from the second flash chamber is mixed with high pressure turbine exhaust to acquire greater steam quality. Afterwards, the mixture enters a low pressure turbine to generate extra power. Obviously, the pressure of saturated steam extracted from the second flash chamber is same with that of high pressure exhaust.

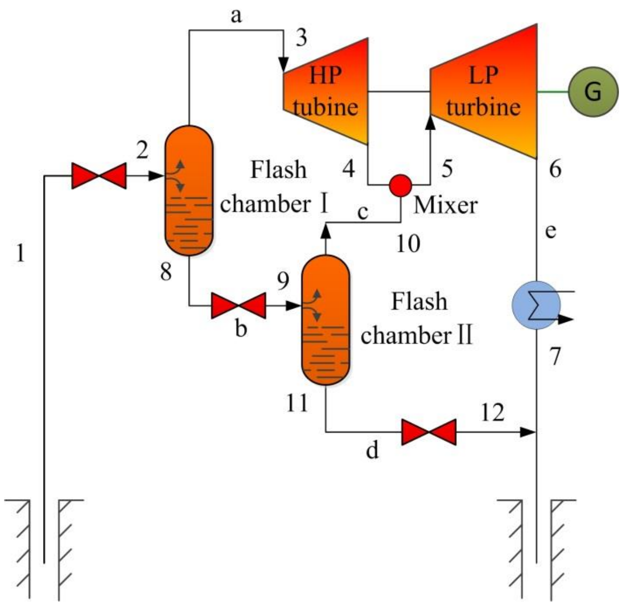

Fig. 1. Schematic diagram of double-flash geothermal power plant

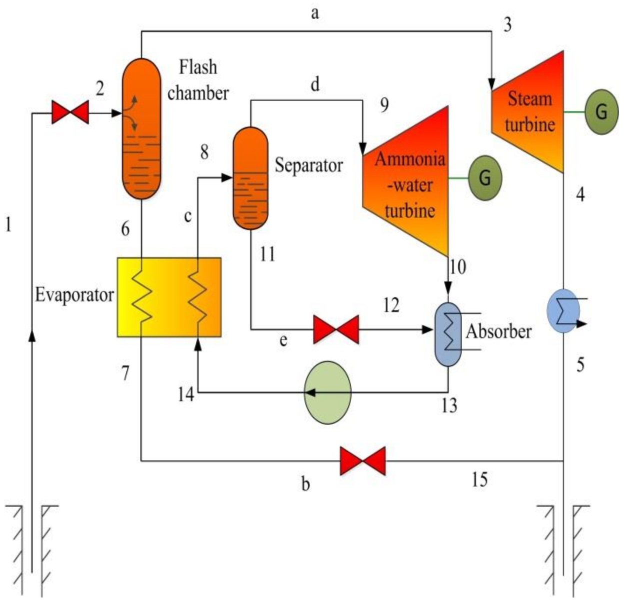

Fig. 2. Schematic diagram of flash-ORC geothermal power plant

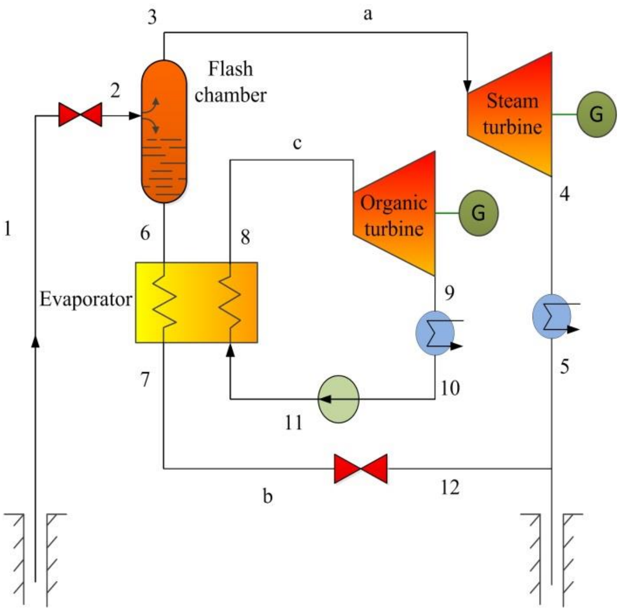

Fig. 3. Schematic diagram of flash-Kalina geothermal power plant

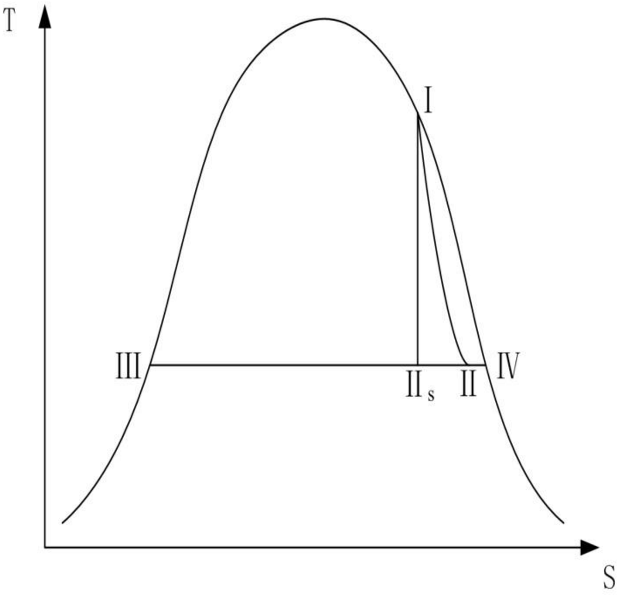

Fig. 4. Temperature-entropy state diagram for steam turbine

3. Mathematical model and performance criteria

Double-flash, flash-Kalina and flash-ORC geothermal power plants are modelled on mass and energy conservation. And the parameters of geofluid and ambient are listed in Table 1.

Table 1. Parameters of geofluid and ambient

Term	Value	Term	Value
Temperature of geofluid, ℃	230	Ambient temperature, ℃	20
Pressure of geofluid, MPa	2.795	Ambient pressure, MPa	0.101
Mass flow rate of geofluid, kg/s	1		

To simplify the theoretical model, some assumptions are made as follows:

1. Neglect pressure loss, heat loss and leakage of working fluid.
2. The systems reach steady state.
3. The turbines and the pumps have given isentropic efficiency, respectively.
4. The working fluid at the condenser and absorber outlet is saturated liquid, and the flows across the throttle valve are isenthalpic.

3.1. Energy analysis

For a flash geothermal power plant, the steam turbine generally operates in the wet region. According to Baumann rule [15], a 1% average moisture causes roughly a 1% drop in steam turbine efficiency. Thus, the effect of moisture on steam turbine isentropic efficiency has to be taken into consideration. The temperature-entropy state diagram for steam turbine is presented in Fig. 4. The steam turbine outlet specific enthalpy can be written as follow [15]:

$$h_{\mathrm{II}} = \frac{h_{\mathrm{I}} - \dfrac{\eta_{\mathrm{ST,dry}}}{2}\left(h_{\mathrm{I}} - h_{\mathrm{II},s}\right)\left[x_{\mathrm{I}} - \dfrac{h_{\mathrm{III}}}{h_{\mathrm{IV}} - h_{\mathrm{III}}}\right]}{1 - \dfrac{\eta_{\mathrm{ST,dry}}\left(h_{\mathrm{I}} - h_{\mathrm{II},s}\right)}{2\left(h_{\mathrm{IV}} - h_{\mathrm{III}}\right)}} \tag{1}$$

where x is quality of steam and $\eta_{\mathrm{ST,dry}}$ is dry steam turbine isentropic efficiency.

Steam turbine power output is

$$W_{\mathrm{ST}} = m\left(h_{\mathrm{I}} - h_{\mathrm{II}}\right) \tag{2}$$

Mathematical model of flash chamber is given by

$$q_{\mathrm{in}} = \frac{h_{\mathrm{in}} - h_{\mathrm{out,liq}}}{h_{\mathrm{out,vap}} - h_{\mathrm{out,liq}}} \tag{3}$$

Energy balance of condenser is defined as

$$Q_{\mathrm{condenser}} = m\left(h_{\mathrm{in}} - h_{\mathrm{out}}\right) \tag{4}$$

Mass balance and energy balance of mixer can be represented as

$$m_{\mathrm{out}} = m_{\mathrm{in},1} + m_{\mathrm{in},2} \tag{5}$$

$$m_{\mathrm{out}} h_{\mathrm{out}} = m_{\mathrm{in},1} h_{\mathrm{in},1} + m_{\mathrm{in},2} h_{\mathrm{in},2} \tag{6}$$

For ammonia-water turbine or organic, isentropic efficiency can be expressed as

$$\eta_{\mathrm{AT}} = \frac{h_{\mathrm{in}} - h_{\mathrm{out}}}{h_{\mathrm{in}} - h_{\mathrm{out,s}}}, \eta_{\mathrm{OT}} = \frac{h_{\mathrm{in}} - h_{\mathrm{out}}}{h_{\mathrm{in}} - h_{\mathrm{out,s}}} \quad (7)$$

Power output of ammonia-water turbine and organic turbine can be written as

$$W_{\mathrm{AT}} = m\left(h_{\mathrm{in}} - h_{\mathrm{out}}\right), W_{\mathrm{OT}} = m\left(h_{\mathrm{in}} - h_{\mathrm{out}}\right) \quad (8)$$

Energy balance for evaporator is

$$m_1\left(h_{\mathrm{in,1}} - h_{\mathrm{out,1}}\right) = m_2\left(h_{\mathrm{in,2}} - h_{\mathrm{out,2}}\right) \quad (9)$$

Mass balance and ammonia mass balance equations of ammonia-water separator are

$$m_{\mathrm{in,b}} = m_{\mathrm{out,p}} + m_{\mathrm{out,r}} \quad (10)$$

$$m_{\mathrm{in,b}} x_{\mathrm{b}} = m_{\mathrm{out,p}} x_{\mathrm{p}} + m_{\mathrm{out,r}} x_{\mathrm{b}} \quad (11)$$

Isentropic efficiency of pump is

$$\eta_{\mathrm{pump}} = \frac{h_{\mathrm{out}} - h_{\mathrm{in}}}{h_{\mathrm{out,s}} - h_{\mathrm{in}}} \quad (12)$$

Mass balance and energy balance for mixer is given as

$$m_{\mathrm{out}} = m_{\mathrm{in,1}} + m_{\mathrm{in,2}} \quad (13)$$

$$Q_{absorber} = m_{\mathrm{in,1}} h_{\mathrm{in,1}} + m_{\mathrm{in,2}} h_{\mathrm{in,2}} - m_{\mathrm{out}} h_{\mathrm{out}} \quad (14)$$

3.2. Performance criteria

The net power output of double-flash, flash-Kalina and flash-ORC geothermal power plant can be expressed as

$$W_{\mathrm{NET}} = W_{\mathrm{ST,HP}} + W_{\mathrm{ST,LP}} \quad (15)$$

$$W_{\mathrm{NET}} = W_{\mathrm{ST}} + W_{\mathrm{AT}} \quad (16)$$

$$W_{\mathrm{NET}} = W_{\mathrm{ST}} + W_{\mathrm{OT}} \quad (17)$$

Thermal efficiency and exergy efficiency of geothermal power plants are

$$\eta_{\mathrm{th}} = \frac{W_{\mathrm{NET}}}{m_{\mathrm{geofluid}}\left(h_{\mathrm{geofluid}} - h_{\mathrm{amb}}\right)} \quad (18)$$

$$\eta_{\mathrm{ex}} = \frac{W_{\mathrm{NET}}}{m_{\mathrm{geofluid}}\left[h_{\mathrm{geofluid}} - h_{\mathrm{amb}} - T_{\mathrm{amb}}\left(s_{\mathrm{geofluid}} - s_{\mathrm{amb}}\right)\right]} \quad (19)$$

4. Results and discussion

In this section, the parametric analysis as well as optimization of flash-Kalina and flash-ORC plants is presented. And double-flash plant has been discussed sufficiently, thus we just illustrate the optimization results. All thermodynamic properties of ammonia-water mixture are calculated by REFPROP 9.0. And parametric analysis and optimization process are carried out by MATLAB and GA. The analysis condition of system is listed in Table 1. In the parametric analysis, as one parameter is varied, others are kept constant as those in Table 2.

Table 2. Simulation condition of flash-Kalina and flash-ORC plants

Term	Value
Dry steam turbine isentropic efficiency, %	70
Ammonia-water turbine isentropic efficiency, %	70
Organic turbine isentropic efficiency, %	70
Pump efficiency, %	75
pinch-point temperature difference of evaporator,℃	10
Terminal temperature difference of condenser, ℃	10
Flash pressure for flash-Kalina plants, MPa	1.5
Ammonia-water turbine inlet pressure, MPa	3.0
Ammonia-water turbine inlet temperature, ℃	120
ammonia mass fraction of basic solution, %	70
Flash pressure for flash-ORC plants, MPa	0.8
Organic turbine inlet pressure, MPa	1.2

4.1. Parametric analysis of flash-Kalina cycle

Fig. 5 illustrates the effect of flash pressure on power output of ammonia-water turbine and steam turbine, net power output of system, system thermal efficiency and system exergy efficiency. As flash pressure increases, the saturated temperature of steam separated from flash chamber rise, which leads to an increase in specific enthalpy drop. However, the mass flow rate of saturated steam separated from flash chamber falls. And the reduction in mass flow rate has greater impact on the power output of steam turbine. Consequently, the power output of steam turbine decreases. Meanwhile, the mass flow rate and temperature of saturated liquid separated from flash chamber go up when the flash pressure increases. The saturated liquid provides more thermal energy to the bottom Kalina cycle, which results in an increase in power output of ammonia-water turbine. As a consequence, the net power output increases firstly and then declines. And the system thermal efficiency and system exergy efficiency share the same variation trend with net power output owing to the constant energy and exergy input.

Fig. 6 shows the effect of ammonia-water turbine inlet pressure on power output of ammonia-water turbine and steam turbine, net power output of system, system thermal efficiency and system exergy efficiency. The power output of steam turbine remains unchanged because the ammonia-water turbine inlet pressure is irrelevant to the power out of steam turbine. An increase in the ammonia-water turbine inlet pressure leads to an increase in the specific enthalpy drop through the ammonia-water turbine. According to the assumption, we neglect the pressure loss in separator. Therefore, the separator pressure equals the ammonia-water inlet pressure. As separator pressure increases, the mass flow rate of saturated ammonia-water vapour separated from separator decreases, namely, ammonia-rich vapour. The power output of ammonia-water turbine is under combined impact of the growth of specific enthalpy drop through ammonia-water turbine and the reduction in mass flow rate of ammonia-rich vapour. And the rise in power output of ammonia-water turbine can be attributed to former cause. Thus the variation tendency of net power output, system thermal efficiency and exergy efficiency is consistent with that of power output of ammonia-water turbine.

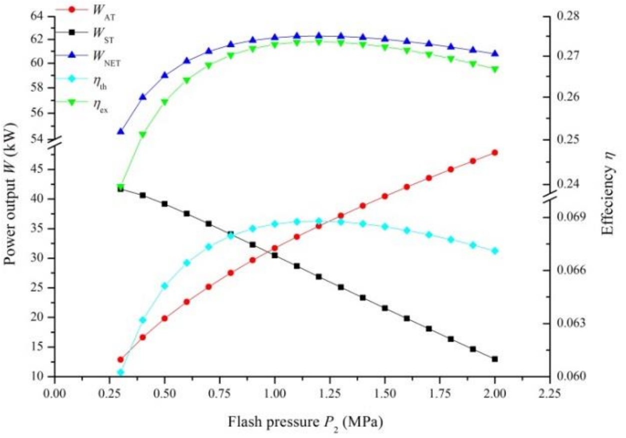

Fig. 5. Effect of flash pressure on power output, system energy and exergy efficiency

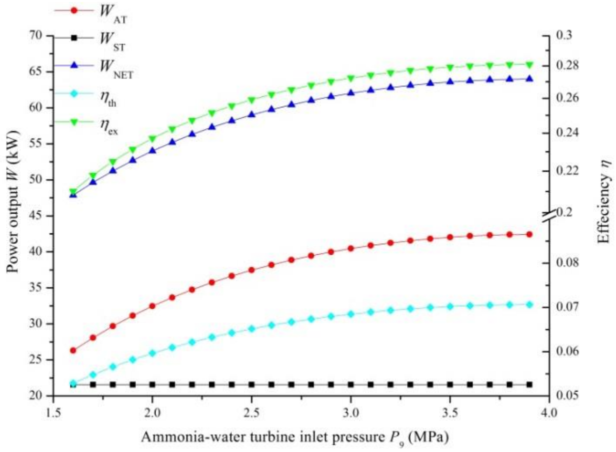

Fig. 6. Effect of ammonia-water turbine inlet pressure on power output, system energy and exergy efficiency

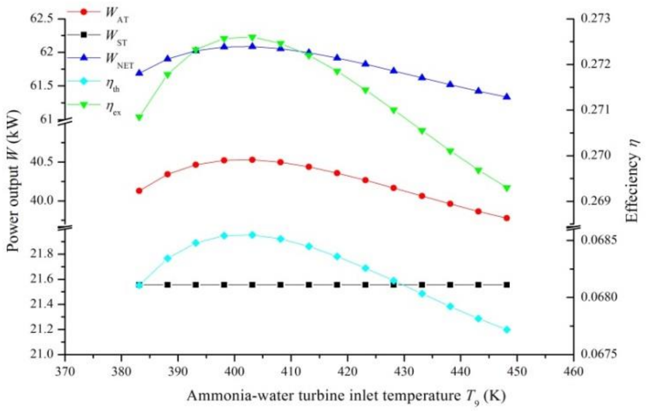

Fig. 7. Effect of ammonia-water turbine inlet temperature on power output, system energy and exergy efficiency

Fig. 7 presents the effect of ammonia-water turbine inlet temperature on power output of ammonia-water turbine and steam turbine, net power output of system, system thermal efficiency and system exergy efficiency. The power output of steam turbine keeps constant because the ammonia-water inlet temperature has no effect on the power output of steam turbine. The specific enthalpy drop through the ammonia-water turbine increases with the ammonia-water turbine inlet temperature. And separator temperature equals ammonia-water turbine inlet temperature. When the separator temperature increases, the mass flow rate of basic solution decreases. As a consequence, the mass flow rate of ammonia-rich vapour decreases as well. Under the combined effect of the growth of specific enthalpy drop through ammonia-water turbine and the reduction in mass flow rate of ammonia-rich vapour, the power output of ammonia-water turbine increases firstly and then goes down. Therefore, the net power output, system thermal efficiency and exergy efficiency share the same variation tendency with the power output of ammonia-water turbine.

The effect of ammonia mass fraction of basic solution on power output of ammonia-water turbine and steam turbine, net power output of system, system thermal efficiency and system exergy efficiency is presented in Fig. 8. Owing to the uncorrelation between steam turbine and ammonia mass fraction of basic solution, the power output of steam turbine remains the same. As the ammonia mass fraction of basic solution increases, the mass flow rate of ammonia-rich vapour increases and the specific enthalpy drop through turbine decreases. Actually, the increases in mass flow rate of ammonia-rich vapour plays a major role. As a result, the power output of ammonia-water turbine increases with ammonia mass fraction of basic solution. Consequently, the net power output of system, system thermal efficiency and system exergy efficiency are positively correlated with the ammonia mass fraction of basic solution.

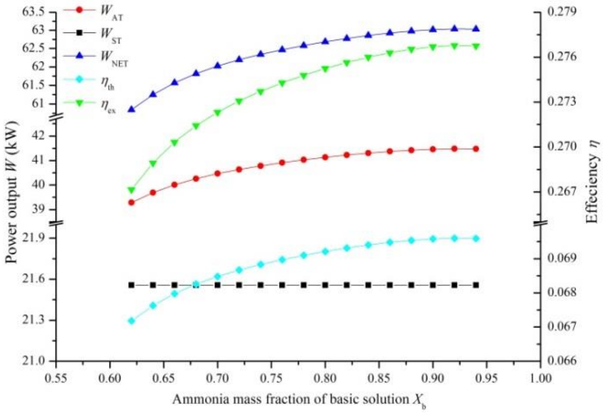

Fig. 8. Effect of ammonia mass fraction of basic solution on power output, system energy and exergy efficiency

4.2. Parametric analysis of flash-ORC cycle

The effect of flash pressure on power output of organic turbine and steam turbine, net power output of system, system thermal efficiency and system exergy efficiency is illustrated in Fig. 9. As the flash pressure rise, the power output of steam turbine declined for the same reason mentioned above. The mass flow rate and temperature of saturated liquid separated from flash chamber increase with flash pressure, which leads to an increase in the mass flow rate of organic working fluid. Therefore, the power output of organic turbine goes up as well. And growth of power output of organic turbine has greater impact on the net power output of system. As shown in the figure, the net power output of system increases with flash pressure. The system thermal efficiency and system exergy efficiency share the same variation trend with net power output.

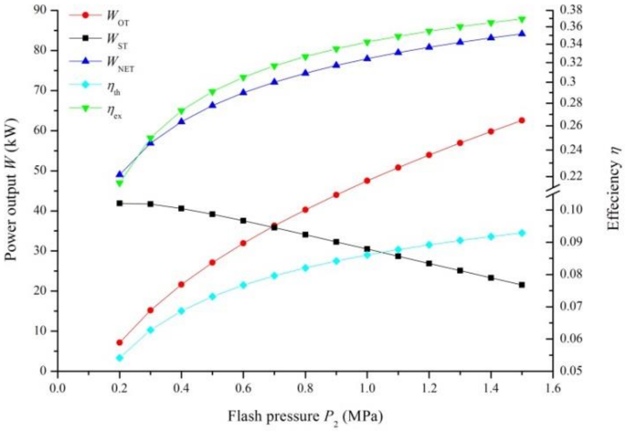

Fig. 9. Effect of flash pressure on power output, system energy and exergy efficiency

Fig. 10 depicts the effect of organic turbine inlet pressure on power output of organic turbine and steam turbine, net power output of system, system thermal efficiency and system exergy efficiency. The power output of steam turbine remains unchanged when the organic turbine inlet pressure increases. This is because the power output of steam turbine is irrelevant to the organic turbine inlet pressure. As the organic turbine inlet pressure increases, the specific enthalpy drop through turbine increases and the mass flow rate of organic working fluid decreases. Consequently, the power output of organic turbine increases firstly and then decreases. Due to the constant energy and exergy input, the system thermal efficiency and system exergy efficiency increase firstly and then decrease as well.

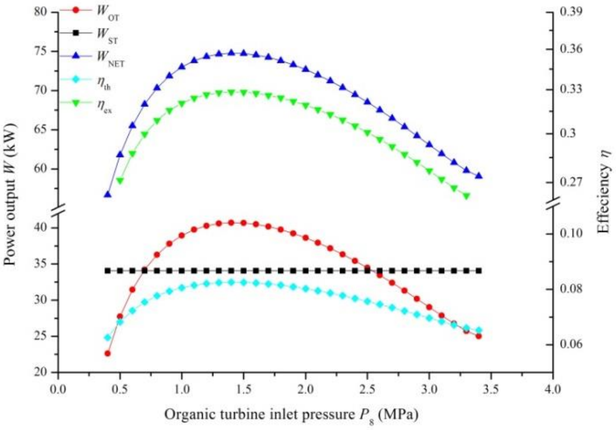

Fig. 10. Effect of organic turbine inlet pressure on power output, system energy and exergy efficiency

4.3. Optimization results and comparison

According to the previous study for double-flash geothermal plants and parametric analysis for flash-Kalina and flash-ORC geothermal power plants, there may be an optimum system performance for three geothermal power plants, respectively. Thus, we conduct an optimization for double-flash, flash-Kalina and flash-ORC geothermal power plants by employing GA and make comparison among three geothermal power plants.

We select system exergy efficiency as objective function. The key thermodynamic parameters that are chose as decision variables and ranges of key thermodynamic parameters for double-flash, flash-Kalina and flash-ORC geothermal power plants are listed in Table 3. Moreover, we set some restricts in optimization program because the results are not available in all conditions. For example, the quality of turbine exhaust should not be lower than 0.9; after heated by evaporator, the basic solution should be in two-phase region; pinch-point temperature difference is the minimum temperature difference in process of evaporation. The results of optimization are listed in Table 4.

From Table 4, we can see that the system exergy for double-flash, flash-Kalina and flash-ORC geothermal power plants are 31.922%, 36.747% and 46.121%, respectively. And net power output for double-flash, flash-Kalina and flash-ORC geothermal power plants are 54.356kW, 76.614kW and 101.280kW. Flash-ORC geothermal power plant has the best thermodynamic performance. And flash-Kalina geothermal power plant requires a very high ammonia-water turbine inlet pressure to obtain a relatively good thermodynamic performance. Double-flash geothermal power plant possesses lowest system exergy efficiency and generates the least power, but double-flash geothermal power plant requires the lowest flash pressure.

Table 3. Operation parameters for optimization

Term	Value
Population size	60
Stall generation	100
Ranges of flash pressure, MPa	0.200-2.000
Ranges of second flash pressure, MPa	0.060-0.120
Ranges of ammonia-water turbine inlet pressure, MPa	1.400-5.000
Ranges of ammonia-water turbine inlet temperature, ℃	70.000-200.000
Ranges of ammonia mass fraction of basic solution, %	0.440-0.960
Ranges of organic turbine inlet pressure, MPa	0.200-3.600

Table 4. Optimization results

Term	Double-flash	Flash-Kalina	Flash-ORC
Flash pressure, MPa	0.586	1.998	1.536
Second flash pressure, MPa	0.070		
Turbine inlet pressure, MPa		4.999	2.777
Turbine inlet temperature, ℃		141.715	
Ammonia mass fraction of basic solution, %		0.945	
System exergy efficiency, %	31.922	36.747	46.121
Net power output, kW	54.356	76.614	101.280

5. Conclusion

Double-flash, flash-Kalina and flash-ORC geothermal power plants are investigated in this paper. We explore the effect of some key parameters on system performance. And GA is employed to conduct a single-objective optimization for three geothermal power plants. We select system exergy efficiency as objective function and compare the optimization results. Main conclusions are summarized as follow:

1. Flash-ORC geothermal power plant has the best performance, whose exergy efficiency is approximately 9.374% and 14.199% higher than that of flash-Kalina and double-flash geothermal power plants, respectively.
2. Flash-Kalina geothermal power plant requires the highest turbine inlet pressure which is 0.4MPa and 1.4MPa higher than that of Organic turbine and steam turbine, respectively.

Acknowledgments

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Nomenclature

h	enthalpy, kJ/kg
m	mass flow rate, kg/s
Q	heat, kJ/s
q	quality
s	entropy, kJ /(kg K)
T	temperature, K
W	power, kW
x	ammonia mass fraction, %

Greek symbols

η	efficiency, %

Subscripts

amb	ambient
AT	ammonia-water turbine
b	ammonia-water basic solution
ex	exergy
in	inlet
liq	liquid phase
OT	organic turbine
out	outlet
r	ammonia-rich solution
ST	steam turbine
s	isentropic
th	thermal
vap	vapour phase

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