

ENERGY EFFICIENCY COMPARISON BETWEEN GEOTHERMAL POWER SYSTEMS

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The geothermal water which can be considered for generating electricity with the temperature ranging from 80°C to 150 °C in China because of shortage of electricity and fossil energy. There are four basic types of geothermal power systems, single flash, double flash, binary cycle and flash-binary system, which can be adapted to geothermal energy utilization in China. The paper discussed the performance indices and applicable conditions of different power system. Based on physical and mathematical models, simulation result shows that, when geofluid temperature ranges from 100°C to 130°C, the net power output of double flash power is bigger than flash-binary system. When the geothermal resource temperature is between 130°C and 150°C, the net power output of flash-binary geothermal power system is higher than double flash system by the maximum value 5.5%. However, the sum water steam amount of double flash power system is 2 to 3 times larger than flash-binary power system, which will cause the bigger volume of equipment of power system. Based on the economy and power capacity, it is better to use flash-binary power system when the geofluid temperature is between 100°C and 150°C.

Keywords: *geothermal power, double flash, binary cycle, flash-binary power system, thermal efficiency*

1 Introduction

The geothermal resources are divided into low (<90°C), medium (90~150°C) and high (>150°C) enthalpy (or temperature) resources, according to criteria which are generally based on the energy content of the fluids and their potential forms of utilization^[1]. In China, most of the geothermal resources are classified mid-low temperature resource, which is widely distributed in coastal areas of southeastern China^[2]. Most of geothermal resources are water-dominated or liquid-dominated geothermal resource in this paper.

In China, only two commercial geothermal power plants are in operation, Yangbajin power plant with 24.2 MW capacity and Fengshun power plant with 0.3 MW capacity^[3-4]. New geothermal power plants have not been built for 35 years because of technology problems and government policies. However, many big corporations have begun to invest the geothermal power

projects during the year 2016 to 2020, because of the increasing energy shortages and government promoting policies in China. In particular, two-stage geothermal power system becomes the focus of researches of Sinopec Star, State Grid Corporation of China and other energy solution companies. There are four basic types of geothermal power system: single flash, double flash, binary cycle and flash-binary power system, which can be adapted for geothermal power generation^[5]. The thermal and exergetic efficiency of double flash system were analyzed by Ronald Di Pippo and Sadiq Zarrouk^[6-7]. Yari and Clarke compared the exergetic efficiency between double flash and flash-binary power systems^[8-9]. However, the power output capacity, optimum flash temperature and other performance indices of the two-stage power system are not analyzed. Comparing with single flash power system, the total power production of flash-binary power system will be increased; Denizli power plant in Turkey gained extra 18% of power production by increasing a binary cycle system^[10]. Lahendong power plant in Indonesia was also a flash-binary power system, which shows that the power output of flash-binary system is more than binary system^[11]. Net power output, energy efficiency, exergy efficiency and thermal economics of binary-flash or flash plant are also studied theoretically^[12-13]. Sensitivity analysis showed that there is no significant effect against the significant input variables on the output for binary plant when the geothermal temperature is constant^[14-15].

The more energy conversion stage is, the more power output will be made. However, the power output is limited and the investment cost will be increased when power energy conversion stages are added. As a result, two-stage energy power conversion system is a best choice for countries in the world. One of objects of this research is to compare the performance of two-stage energy power system and give basis of the selected type of the power system.

2 Geothermal power system

There are four basic types of geothermal power system: single flash, double flash, binary cycle and flash-binary system. The flash-binary system consists of single flash and binary cycle. In this paper, the schematic of single flash and binary cycle are introduced in the flash-binary system, which can be referred to 2.1.1 and 2.1.2.

2.1 Flash-binary system

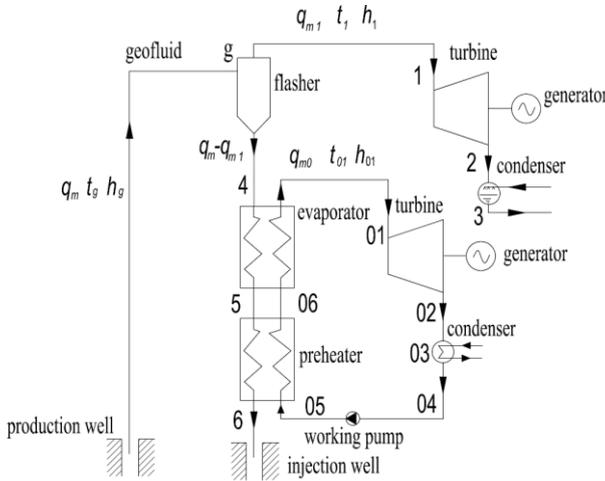


Figure.1 Schematic diagram of flash-binary system

Figure 1 shows the schematic of flash-binary system, which includes single flash power system and binary cycle system [16]. g, 1, 2, 3, 4, 5 and 6 are the geofluid states of flash system in flash-binary system. The geofluid from production well enters into the flasher, and then geothermal water steam (state 1) generated by the flasher is used to promote turbine in single flash system; the geothermal steam is exhausted by the turbine (state 2) and cooled by the condenser (state 3). After pressure drops in the flasher, the geothermal liquid (state 4) enters into the evaporator, preheater (state 5) and injection well (state 6). Where, q_m , t_g , and h_g are the mass flow rate, temperature and enthalpy of geofluid before entering into flasher; q_{m1} , t_1 , and h_1 are the mass flow rate, temperature and enthalpy of geothermal steam before entering into turbine; $q_m - q_{m1}$ is the mass flow rate of geothermal liquid at state 4.

01, 02, 03, 04, 05 and 06 are the working fluid states of binary cycle in flash-binary system. In the evaporator, the organic working fluid is vaporized by geothermal liquid to promote turbine in the binary system. The working fluid vapour (state 01) was sent to turbine and then exhausted (state 02), the vapour leaving the turbine is cooled (state 03) in the condenser and condensed to liquid (state 04). Finally the liquid will be pumped back to preheater and evaporator (state 05 and state 06) via the working pump. Where, q_{m0} , t_{01} , and h_{01} are the mass flow rate, temperature and enthalpy of working fluid vapour before entering into turbine.

The thermodynamic processes of flash and binary power system will be calculated separately according to Chinese geothermal resource. The geothermal resource temperature ranges from 80°C-150°C.

2.1.1 Single flash system

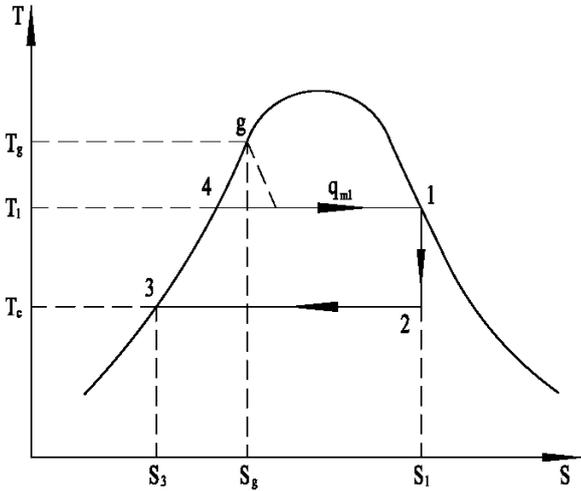


Figure.2 Thermodynamic cycle of flash system

The temperature-entropy (T - S) diagram of single flash system is shown in figure 2. Point g is the geofluid state before entering into flasher. 1-2-3 is the cycle of geofluid in the flash system. T_g , T_1 and T_c are the heat resource, flash and condensation temperature. S_1 , S_g and S_3 are the geothermal fluid entropy of each state. As electricity generated by geofluid, the calculation formulas of the single flash system are as follows [5, 17].

The optimum flash temperature of single flash power system T_1 ,

$$T_1 = \sqrt{T_g T_c} \quad (1)$$

Based on flasher energy balance, the mass flow rate of flash steam can be calculated as follows (Referring to Fig.1 and Fig.2):

The amount of single flasher steam:

$$q_{m1} = \frac{q_m(h_g - h_4)}{h_{1''} - h_4} \quad (2)$$

The fractional amount of single flasher steam:

$$m = \frac{q_{m1}}{q_m} = \frac{h_g - h_4}{h_{1''} - h_4} \quad (3)$$

Net power output of the single flash system:

$$W_{net1} = \frac{q_{m1}(h_1 - h_2)(1 - X)}{3.6} \eta_{oi} \eta_g \eta_m \quad (4)$$

2.1.2 Binary cycle

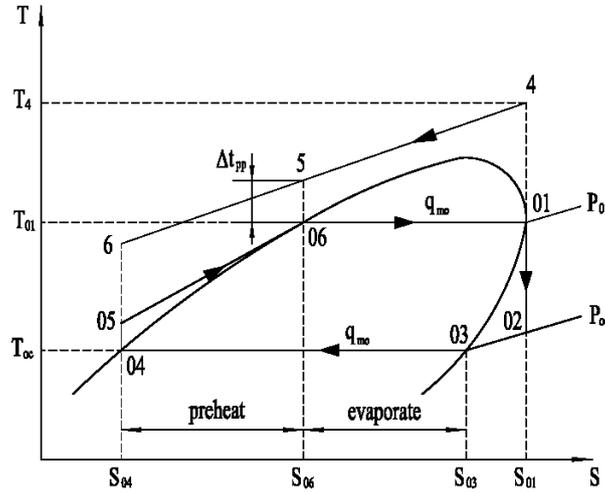


Figure.3 Thermodynamic cycle of binary system

Figure 3 shows the temperature-entropy (T - S) diagram of binary system. Δt_{pp} is the absolute temperature difference between evaporator/condenser end and environment, which value is assumed to be approximately 5 K. T_4 is the temperature of evaporator of heat resource, T_{01} and T_{0c} are the evaporation and condensation temperature of organic working fluid. P_{01} and P_{0c} are the evaporation and condensation pressure of organic working fluid. S_{04} , S_{06} , S_{03} and S_{01} are the organic working fluid entropy at each state. The calculation formulas of the binary power cycle are as follows ^[5, 17].

The optimum evaporation temperature of binary power cycle T_{01} :

$$T_{01} = \sqrt{T_1 T_{0c}} \quad (5)$$

Obviously, t_{01} and t_1 is associated through formula (5).

Based on evaporator and preheater energy balance, the mass flow rate of organic working fluid can be calculated as follows (Reference to Fig.1 and Fig.3):

$$q_{m0} = \frac{(q_m - q_{m1})(h_4 - h_6)}{h_{01} - h_{05}} \quad (6)$$

Net power output of binary cycle is defined as follows:

$$W_{net2} = \frac{q_{m0}[(h_{01}-h_{02})-(h_{05}-h_{04})](1-X)}{3.6} \eta_{oi} \eta_g \eta_m \quad (7)$$

After the parameters of single flash and binary cycle power system are fixed, flash-binary system parameters could be calculated as follows.

The net power output of flash-binary power system:

$$W_{net} = W_{net1} + W_{net2} \quad (8)$$

Net power output (kWh/t) per ton of geothermal water:

$$Ne = \frac{W_{net}}{q_m} = \frac{W_{net1}}{q_m} + \frac{W_{net2}}{q_m} \quad (9)$$

2.2 Double flash system

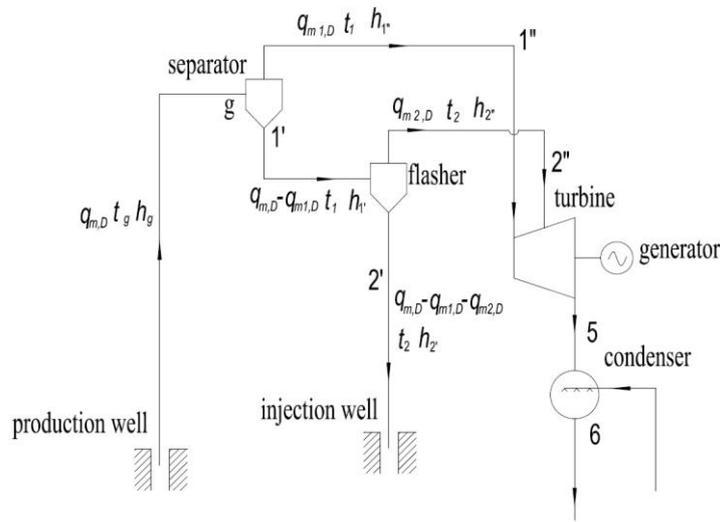


Figure.4 Schematic diagram of double flash system

Figure 4 shows the schematic diagram of double flash system, the geofluid (state g) from production well is sent to the first separator, the primary separated steam (state 1'') enters the high-pressure cylinder of turbine and the primary separated liquid (state 1') flows into the flasher, the steam (state 2'') from the flasher enters the low-pressure cylinder of turbine and the secondary flashing liquid (state 2') is sent to injection well. The steam of the separator and flasher was exhausted by the turbine (state 5) and cooled by the condenser (state 6).

In figure 4, $q_{m,D}$, t_g , and h_g are the mass flow rate, temperature and enthalpy of geofluid before entering into separator; $q_{m1,D}$, t_1 , and h_1 are the mass flow rate, temperature and enthalpy of geothermal steam at state 1''); $q_{m,D} - q_{m1,D}$, t_1 , and h_1 are the mass flow rate, temperature and enthalpy of geothermal fluid at state 1'; $q_{m2,D}$, t_2 , and h_2 are the mass flow rate, temperature and enthalpy of geothermal steam at state 2''); $q_{m,D} - q_{m1,D} - q_{m2,D}$, t_2 , and h_2 are the mass flow rate, temperature and enthalpy of geothermal fluid at state 2'.

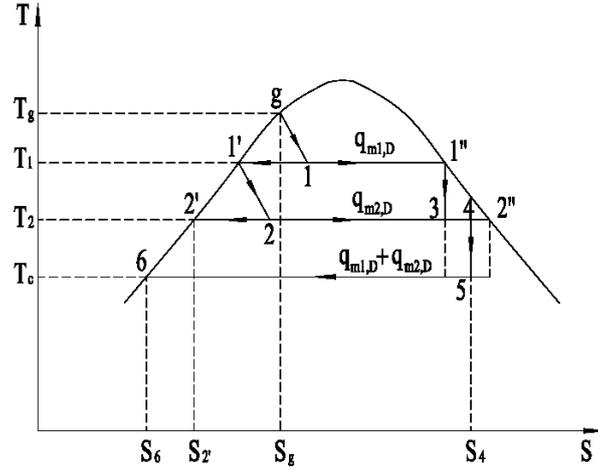


Figure.5 Thermodynamic cycle of double flash system

The temperature-entropy (T - s) diagram of the double flash system is shown in Fig. 2. The pressure and heat loss of the geofluid in the pipes were neglected. The sequence of processes begins with geofluid under pressure at state g , which closes to the saturation curve. The flashing process g -1 and $1'$ -2 generates a fractional amount of steam given by the quality, $m_{1,D}$ and $m_{2,D}$, of the 2-phase mixture. The state 4 is the mixed steam state of exhaust steam (state 3) of separator steam and the flash steam (state $2''$); the state 5 is the exhaust steam state of the turbine. Thermodynamic process of double flash system can be calculated as follow ^[5, 17]:

The optimum separator temperature:

$$T_{1,op} = \sqrt[3]{T_g^2 T_c} \quad (10)$$

The optimum flasher Kelvin temperature:

$$T_{2,op} = \sqrt[3]{T_g T_c^2} \quad (11)$$

The amount of separator steam:

$$q_{m1,D} = \frac{q_{m,D}(h_g - h_{1'})}{h_{1''} - h_{1'}} \quad (12)$$

The fractional amount of separator steam:

$$m_{1,D} = \frac{q_{m1,D}}{q_{m,D}} = \frac{h_g - h_{1'}}{h_{1''} - h_{1'}} \quad (13)$$

The amount of flasher steam:

$$q_{m2,D} = \frac{(q_{m,D} - q_{m1,D})(h_{1'} - h_{2'})}{h_{2''} - h_{2'}} \quad (14)$$

The fractional amount of flasher steam:

$$m_{2,D} = \frac{q_{m2,D}}{q_{m,D}} = \frac{(1 - m_{1,D})(h_{1'} - h_{2'})}{h_{2''} - h_{2'}} \quad (15)$$

Maximum net power output of double flash system:

$$W_{net,D} = \frac{[q_{m1,D}(h_{1''} - h_3) + q_{m,D}(h_4 - h_5)](1 - X)}{3.6} \eta_{oi} \eta_g \eta_m \quad (16)$$

Maximum net power output per ton geofluid:

$$Ne_D = \frac{[m_{1,D}(h_{1''} - h_3) + (m_{1,D} + m_{2,D})(h_4 - h_5)](1 - X)}{3.6} \eta_{oi} \eta_g \eta_m \quad (17)$$

3 Results of geothermal power systems

The energy efficiency of geothermal power system is compared when the geofluid temperature ranges from 80°C to 150°C, the cooling water inlet temperature is 20°C, the organic fluid in binary power cycle is R245fa. The value of various efficiencies can be assumed as follow:

$$X = 0.3, \eta_{oi}\eta_g\eta_m = 0.76 \times 0.98 \times 0.97 = 0.722.$$

Numerical simulation is followed by Eq. from (1) to (17).

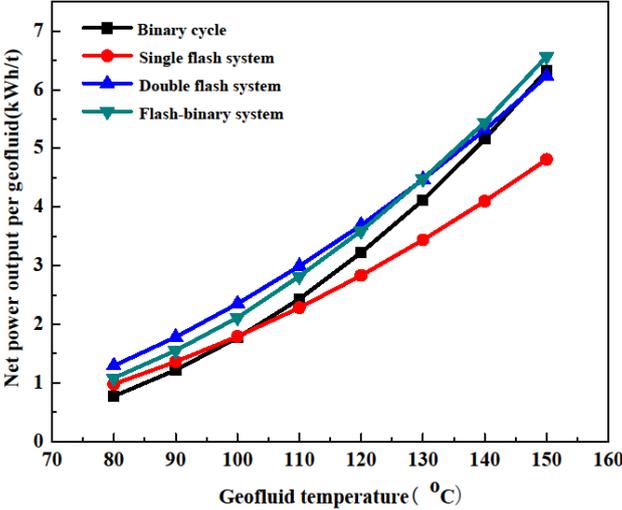


Figure.6 The influence of geofluid temperature on net power output

Figure 6 shows the influence of geofluid temperature on net power output of different power systems. From the figure, we can see that the higher geothermal temperature is, the higher net power output will be made. When geofluid temperature ranges from 80 to 100°C, the net power output of single flash power system is bigger than binary cycle power system, when ranges from 100 to 130°C, the double flash power is bigger than flash-binary system. When the geofluid temperature is 130°C, the net power output of double flash system and flash-binary system are fairly close. However, when geothermal water temperature ranges from 130°C to 150°C, the net power output of flash-binary power system is more than by 5.5% of double power system.

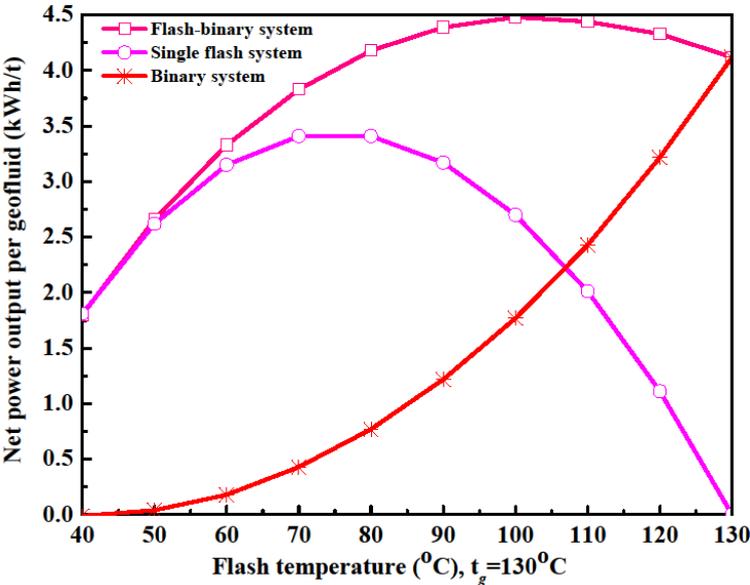


Figure. 7 The influence of flash temperature on net power output for flash-binary system

What we concern in the flash-binary power system is the optimum flash temperature at different geofluid temperature. The optimum flash temperature can be defined when the net power output reaches the maximum. Figure 7 shows the influence of flash temperature on net power output for flash-binary system at geofluid temperature $t_g=130^\circ\text{C}$.

The power output of the single flash system is a complete parabola in the flash-binary system, because when the flash temperature is condensing temperature, the steam vapor enthalpy drop is zero in the flash turbine; when the flash temperature is geothermal water temperature, the steam mass flow rate is zero in the flash turbine. The higher flash temperature is, the higher power output for binary cycle will be made. The optimum flash temperature of flash-binary system is 100°C while geofluid temperature $t_g=130^\circ\text{C}$ from figure 7.

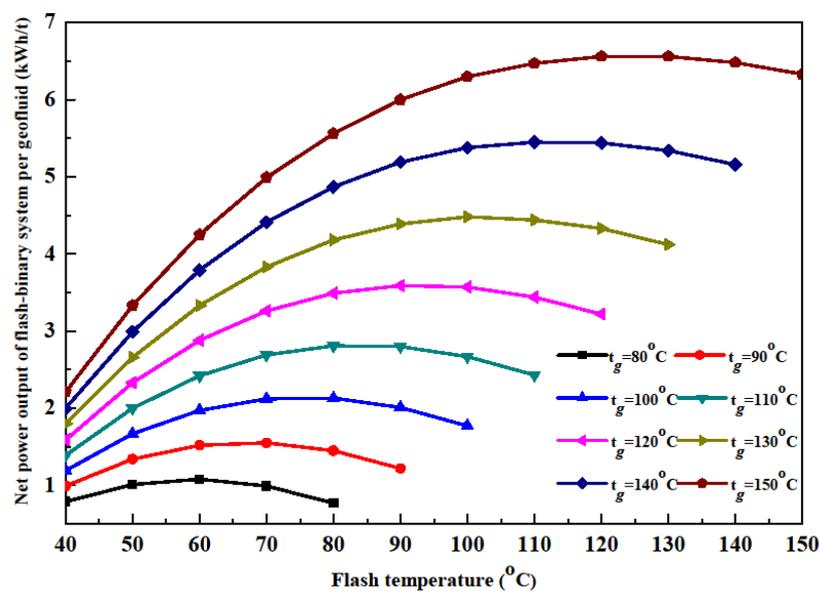


Figure. 8 the influence of flash temperature on power output for flash-binary system

Figure 8 gives the net power output curve of flash-binary system at different geofluid temperature and the flash temperature ranges from condensation temperature to geofluid temperature. When the geofluid temperature is constant, the power output increases and then decreases with higher flash temperature. The higher geofluid temperature is, the higher optimal flash temperature will be made. figure 8 shows that the optimal flash temperature are 60°C , 70°C , 80°C , 85°C , 95°C , 100°C , 110°C and 125°C when the geothermal water are 80°C , 90°C , 100°C , 110°C , 120°C , 130°C , 140°C and 150°C .

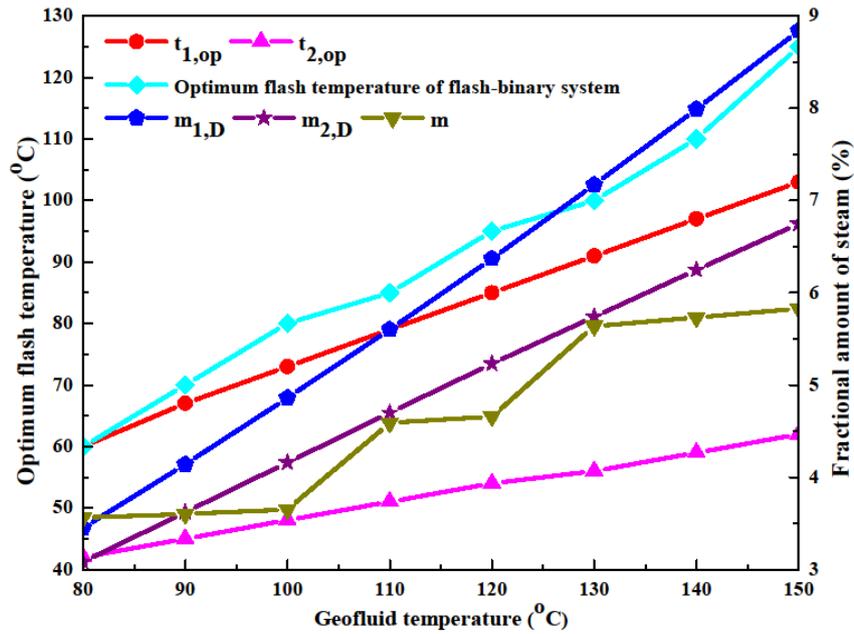


Figure.9 The influence of geofluid temperature on optimum flash temperature and fractional amount of steam

For flash power system, there will be a range of possible separator (or flasher) temperature, one of which will yield the highest power output. Over the spectrum of separator (or flasher) temperature, a corresponding separator (or flasher) temperature that yields the highest power output which defines the optimum plant choices for both separator and flash conditions. Figure 9 shows the optimal flash temperature of the double flash and flash-binary power system. The higher the optimal flash temperature is, the higher flash pressure will be, which will ensure that the system will not be operated in a vacuum.

For double flash system, the fractional amount of separator steam and flasher steam ranges from 3.5% to 8.8% and 3.1% to 6.8%; for flash-binary system, the fractional amount of flasher steam ranges from 3.6% to 5.8%. When the geothermal temperature is below 130°C, flash pressure of the double power system will be close to vacuum, which will result in bigger volume of power equipment. In contrary, the optimal flasher temperature of flash-binary system is higher than double flash, which will help to minimize the volume of power equipment. For the two-stage energy conversion system, when the geothermal water temperature is below 130°C, the flash-binary power system is a better choice.

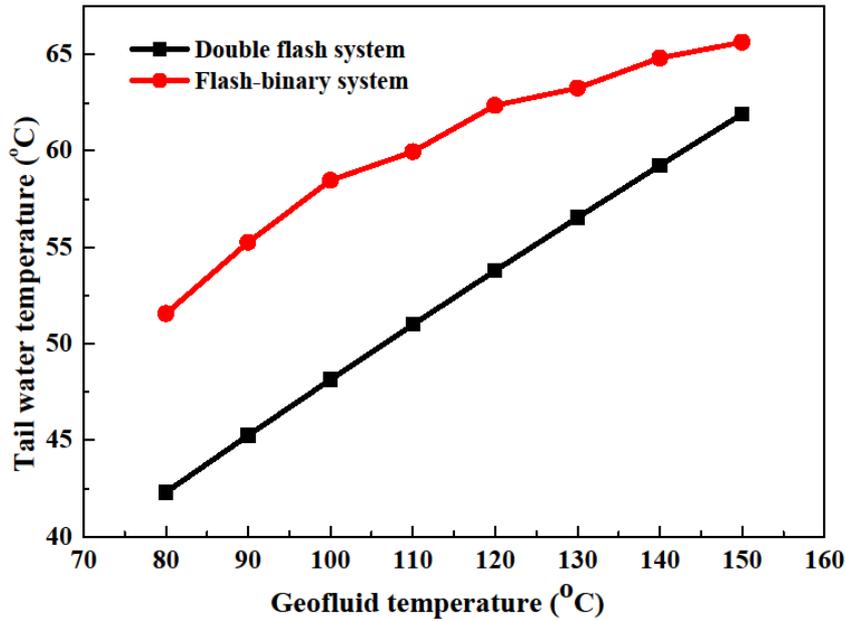


Figure.10 The influence of geofluid temperature on injection water temperature

Figure 10 shows that the injection water temperature increases with higher geothermal water temperature. The injection water temperature of flash-binary system is higher by about 10°C than the of double flash system. For one hand, the optimum flash temperature of flash-binary is higher than separator temperature of double flash temperature; for another, the condensation temperature of binary cycle in flash-binary system is higher than double flash system. The injection water of flash-binary system can be considered for heating and bathing in cascade comprehensive utilization. When the geothermal water temperature ranges from 130°C to 150°C, flash-binary power system is also a better choice

4. Conclusions

The performance indices of geothermal power systems are analyzed for enhancing the efficiency of geothermal resource utilization in China. The conclusions as follow:

(1) The increasing amount output power of flash-binary power system is some larger than double power system with increasing geothermal water temperature. When geofluid temperature ranges from 100°C to 130°C, the net power output of double flash power is bigger than flash-binary system. However, When geothermal water temperature ranges from 130°C to 150°C, the net power output of flash-binary power system is more than by 5.5% of double power system.

(2) The optimal flash temperature of flash-binary system is higher than the second flash system of double flash system. Based on the consideration of equipment size and power output, when the geofluid temperature is between 100°C and 150°C, the flash-binary power system is a better choice.

(3) Compared with double flash system, the injection water temperature of flash-binary system is higher than double flash system, which can be considered for heating and bathing in cascade comprehensive utilization.

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Nomenclature

- Ne - Net power output per ton geothermal water in flash-binary cycle, kWh t⁻¹
 Ne_D - Net power output per ton geothermal water in double flash system, kWh t⁻¹
 P_{01} - Evaporation pressure, Pa
 P_{04} - Condensation pressure, Pa
 T_1 - Flash temperature in flash-binary cycle, K
 T_c - Condensation temperature of flash system, K
 T_{oc} - Condensation temperature of binary system, K
 T_g - Geothermal resource temperature, K
 W_{net1} - Net power output of flash system in flash-binary cycle, kW
 W_{net2} - Net power output of binary cycle in flash-binary cycle, kW
 W_{net} - Total net power output of flash-binary cycle, kW
 $W_{net,D}$ - Net power output of double flash system, kW
 X - Electricity consumption percentage by self, %
 c - Specific heat, kJ kg⁻¹ K⁻¹
 h - Specific enthalpy at different states, kJ kg⁻¹
 m - The fractional amount of flasher steam in flash-binary cycle, %
 $m_{1,D}$ - The fractional amount of separator steam in double flash system, %
 $m_{2,D}$ - The fractional amount of flasher steam in double flash system, %
 q_m - Mass flow rate of geothermal water in flash-binary system, t h⁻¹
 q_{m1} - Mass flow rate of flash steam in flash-binary system, t h⁻¹
 q_{mo} - Mass flow rate of working fluid vapor in flash-binary system, t h⁻¹
 $q_{m,D}$ - Mass flow rate of geothermal water in double flash system, t h⁻¹
 $q_{m1,D}$ - Mass flow rate of separator steam in double flash system, t h⁻¹
 $q_{m2,D}$ - Mass flow rate of flash steam in double flash system, t h⁻¹
 s - Specific entropy at different states, kJ kg⁻¹ K⁻¹
 t_1 - Flash temperature in flash-binary cycle, °C
 t_c - Condensation temperature of flash system, °C
 t_{oc} - Condensation temperature of binary system, °C
 $t_{1,op}$ - Optimum separator temperature of double flash system, °C
 $t_{2,op}$ - Flasher separator temperature of double flash system, °C
 t_g - Geothermal water temperature, °C
 η_{oi} - Turbine isentropic efficiency, %
 η_m - Machinery efficiency, %
 η_g - Generator efficiency, %

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