

Geothermal Energy Conversion between Flash-Binary and Double Flash Power System

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ABSTRACT

To increase the energy conversion efficiency of geothermal resource, the paper proposes two-stage geothermal power system, the thermodynamic performance between double flash and flash-binary power system is compared basing on numerical simulation, the applicable conditions of different power system are also discussed in the paper. The simulation result shows that, when the geothermal resource temperature between 80-130 °C, the net power output of two stage flash geothermal power system is higher than flash-binary system by maximum value 19.4%; when the geothermal resource temperature between 130-150 °C, the net power output of flash-binary geothermal power system is higher than two stage flash system by maximum value 5.5%. However, the sum water gas production of double flash power system is 2-3 times than flash-binary power system, which will cause the bigger volume of equipment and higher cost of power system. When the temperature less than 130 °C, it is better to use flash-binary power system because the flash pressure of double system is in vacuum which will consume more power for running vacuum pump. When the temperature is higher than 130 °C, it is better to use double flash power system because of low initial and operation cost.

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 that are generally based on the energy content of the fluids and their potential forms of utilization. In China, most of the geothermal resource temperature is less than 125 °C and widely distributed in coastal areas of southeastern China, Zheng K.Y (2013). Most of geothermal resource is water- dominated or liquid-dominated geothermal resource in this paper.

In china, new geothermal power plants were not built for 30 years because of technology and government policy, and were only two commercial geothermal power plants were in operation, such as Yangbajain power plant with 24.2 MW capacity and Fengshun power plant with 0.3 MW capacity, Luo C (2012) and Zheng K.Y (2010). However, many big corporations begin to invest the geothermal power projects during the “Twelfth Five-Year” because of energy shortages and government energy policy in China, in particular, two-stage geothermal power system become the research focus of Sinopec Star, State Grid Corporation of China and other energy solution companies. There are two basic types of two-stage geothermal power system, one is double flash power system, and another is flash-binary power system. The thermal and exergetic efficiency of double flash system are analyzed by Dipippo R (2013) and Zarrouk S.J (2014). Yari M (2010) also compared the exergetic efficiency between double flash and flash-binary power system. However, the power output, optimum flash temperature and other performance of two-stage power system are not analyzed, Clarke J (2014). The flash-binary power system would increase the production compared with single flash power system, Denizli power plant in Turkey gain 18% of power production by increasing a binary cycle system, Dagdas A (2005). Lahendong power plant in Indonesia was also flash-binary power system, which shows that there are optimal evaporation pressure and flash pressure in the flash-binary system, Pasek A.D (2011). Net power output, energy efficiency, exergy efficiency and thermal economics are also studied in theoretically, Efstathios E (1984) and Jalilinasrabad S (2012). When the geothermal temperature is constant, sensitivity analysis shows that there is no significant effect against the significant input variables on the output, Rosyid H (2010) and Koch C (2007).

The more energy conversion stages, the more power output. However, the power output is finite and the invest cost increases, when power energy conversion stage is added. As a result, two-stage energy power conversion system is a best choice for countries in world. The object of this research is to compare the performance of two-stage energy power system and give basis of selected the type of the power system.

2. CALCULATIONS OF TWO-STAGE GEOTHERMAL POWER SYSTEM

2.1 Double Flash System

Figure 1 shows the schematic diagram of double flash system, the geofluid from production well is sent to the first separator, the primary separated steam enters the high-pressure cylinder of turbine and the primary separated liquid flows into the flasher, the steam from the flasher enters the low-pressure cylinder of turbine and the secondary flashing liquid is sent to injection well.

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, close to the saturation curve. The flashing process g-1 and 1'-2 generate a fractional amount of steam given by the quality, $m_{1,D}$ and $m_{2,D}$, of the 2-phase mixture. Each flash is followed by a separation process. Thermodynamic process of double flash system can be calculated as follow, Wu Z.J (2007):

The optimum separator Kelvin temperature:

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

$$t_{1,op} = T_{1,op} - 273.15 \text{ (}^\circ\text{C)}$$

The optimum flasher Kelvin temperature:

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

$$t_{2,op} = T_{2,op} - 273.15 \text{ (}^\circ\text{C)}$$

Where T_g is geothermal water Kelvin temperature (K), T_c is condensation Kelvin temperature (K) of flash system, $t_{1,op}$ is optimum separator Celsius temperature ($^\circ\text{C}$), $t_{2,op}$ is optimum flasher Celsius temperature ($^\circ\text{C}$).

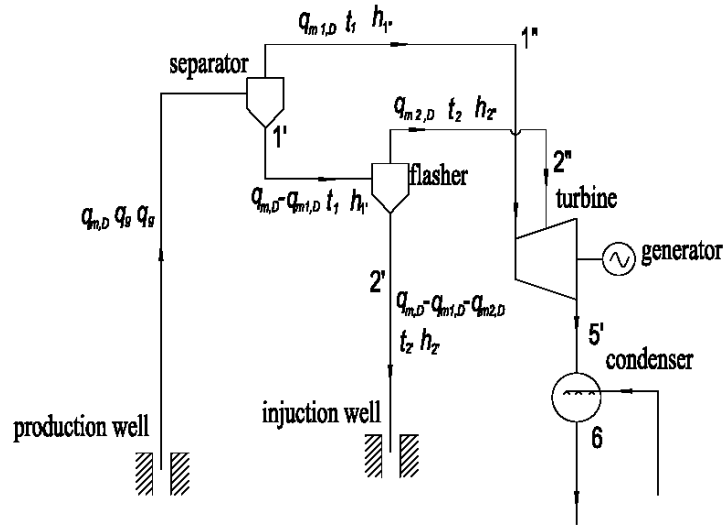


Figure 1: Schematic Diagram of Double Flash System

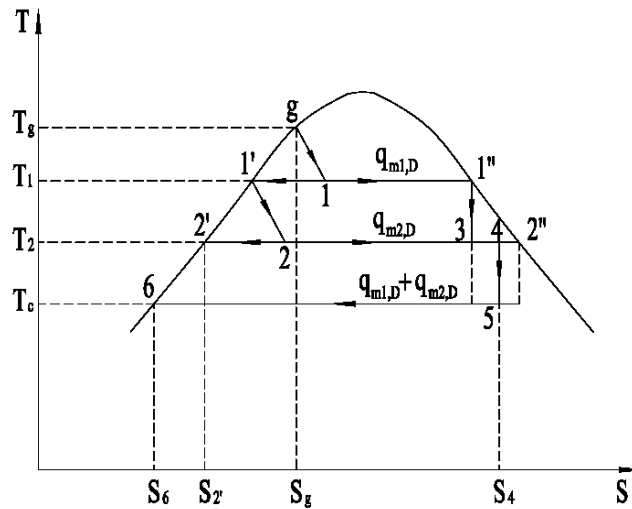


Figure 2: Thermodynamic Cycle of Double Flash System

The amount of separator steam:

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

The fractional amount of separator steam:

$$m_{1,D} = \frac{q_{m1,D}}{q_{m,D}} = \frac{h_g - h_{1'}}{h_{1''} - h_{1'}} \quad (4)$$

The amount of flasher steam:

$$q_{m2,D} = \frac{(q_{m,D} - q_{m1,D})(h_{1'} - h_{2'})}{h_{2''} - h_{2'}} \quad (5)$$

The fractional amount of flasher steam:

$$m_{2,D} = \frac{q_{m2,D}}{q_{m,D}} = \frac{(1 - m_{1,D})(h_{1'} - h_{2'})}{h_{2''} - h_{2'}} \quad (6)$$

Highest net power output of double flash system:

$$P_{net,D} = \frac{[q_{m1,D}(h_{1'} - h_3) + (q_{m1,D} + q_{m2,D})(h_4 - h_5)](1 - X)}{3.6} \eta_{oi} \eta_m \eta_g \quad (7)$$

Highest net power output per ton geofluid:

$$Ne_D = \frac{[m_{1,D}(h_{1'} - h_3) + (m_{1,D} + m_{2,D})(h_4 - h_5)](1 - X)}{3.6} \eta_{oi} \eta_m \eta_g \quad (8)$$

Where, $q_{m,D}$ is the mass flow rate of geothermal water (t/h), $q_{m1,D}$, $q_{m2,D}$ is the mass flow rate of separator and flash steam (t/h), h_g , $h_{1'}$, $h_{1''}$, h_2 , $h_{2''}$, h_3 , h_4 , h_5 and h_6 are the enthalpy of geothermal water at different states (kJ/kg), $P_{net,D}$ is the net power output of double flash system (kW), X is the percentage of the plant self-consumption, η_{oi} is the isentropic turbine efficiency, η_m is the machinery efficiency, η_g is the electrical efficiency.

2.2 Flash-binary System

Figure 3 shows the schematic of flash-binary system, which includes single flash power system and binary cycle system. The geofluid steam generated by flasher was used to promote turbine in single flash system. After pressure dropping in flasher, the discharge geofluid liquid enters the evaporator and exchanges heat energy with organic fluid which vaporized to promote turbine in binary system. The processes and parameters can be confirmed qualitatively from figure 4 and 5.

The thermodynamic processes of flash and binary power system will be calculated separately according to Chinese geothermal resource. As electricity generated by geofluid, the calculation formulas and performance indicators of the flash-binary system are as follows, Wu Z.J (2007):

The optimum flash temperature of flash power system T_1 ,

$$T_1 = \sqrt{T_g T_c} \quad (K) \quad (9)$$

$$t_1 = T_1 - 273.15 \quad (^\circ C)$$

The optimum evaporation temperature of binary power cycle T_{o1} ,

$$T_{o1} = \sqrt{T_1 T_{oc}} \quad (K) \quad (10)$$

$$t_{o1} = T_{o1} - 273.15 \quad (^\circ C)$$

Where T_g is geothermal water Kelvin temperature (K), T_c is condensation Kelvin temperature (K) of flash system, T_{oc} is condensation Kelvin temperature (K) of binary cycle, t_g is geothermal water Celsius temperature ($^\circ C$), t_c is condensation Celsius temperature ($^\circ C$) of flash system, t_{oc} is condensation Celsius temperature ($^\circ C$) of binary cycle.

Obviously, t_{o1} and t_1 is associated through formula (10). After the optimum temperature t_{o1} and t_1 are fixed, system parameters could be calculated as follows.

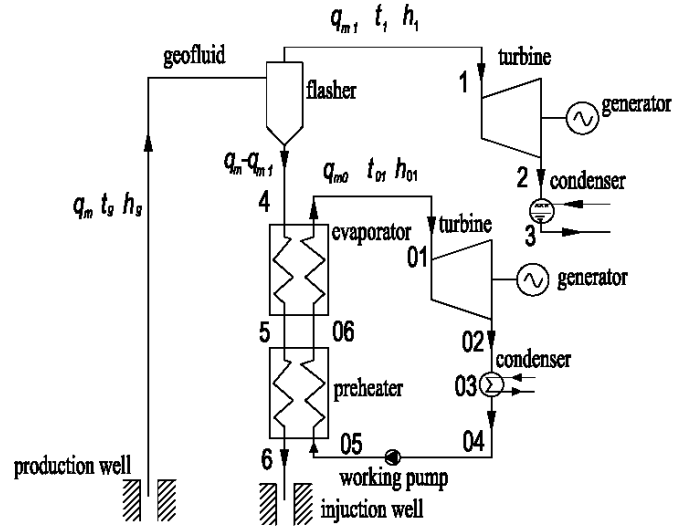


Figure 3: Schematic Diagram of Flash-Binary System

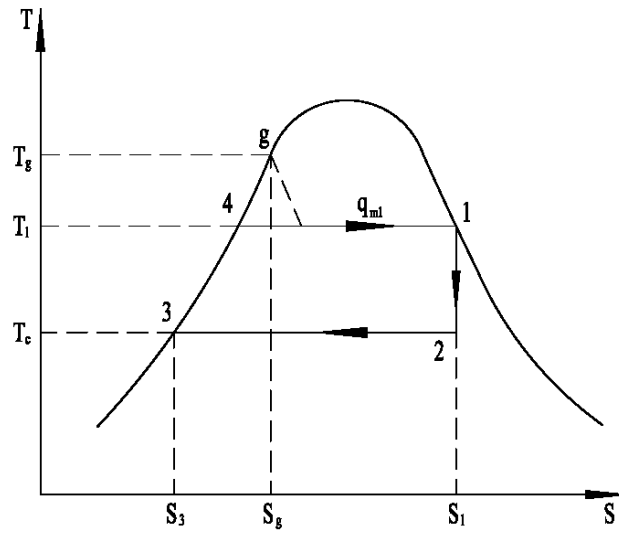


Figure 4: Thermodynamic Cycle of Flash System

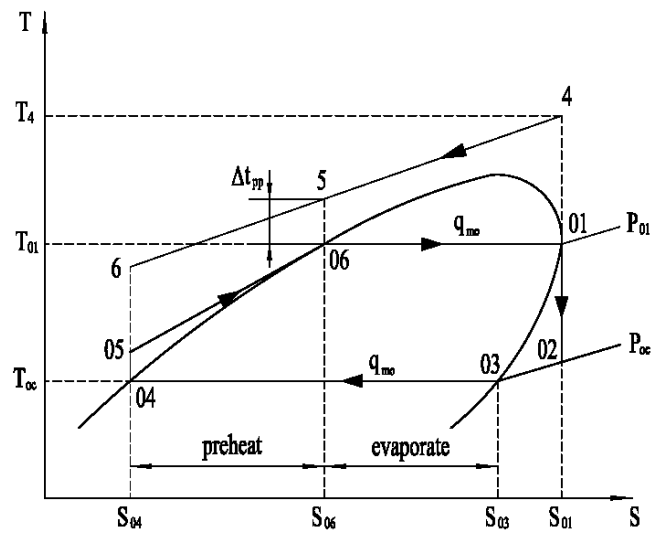


Figure 5: Thermodynamic Cycle of Binary System

2.2.1 Flash Subsystem

Based on flasher energy balance, the mass flow rate of flash steam can be calculated as follows (Referring to Fig.3 and Fig.4):

The amount of flasher steam:

$$q_{m1} = \frac{q_m (h_g - h_4)}{h_{1''} - h_4} \quad (11)$$

The fractional amount of flasher steam:

$$m = \frac{q_m}{q_{m1}} = \frac{(h_g - h_4)}{h_{1''} - h_4} \quad (12)$$

Net power output of the flash subsystem:

$$P_{net,1} = \frac{q_{m1} (h_1 - h_2) (1 - X)}{3.6} \eta_{oi} \eta_m \eta_g \quad (13)$$

Where, q_m is the mass flow rate of geothermal water (t/h), $h_g, h_4, h_{1''}, h_2, h_3, h_6$ are the enthalpy of geothermal water at different states (kJ/kg), P_{net1} is the net power output of flash subsystem (kW), η_{net1} is the net power output thermal efficiency of flash subsystem, X is the percentage of the plant self-consumption, η_{oi} is the isentropic turbine efficiency, η_m is the machinery efficiency, η_g is the electrical efficiency.

2.2.2 Binary Cycle Subsystem

Based on evaporator and preheater energy balance, the mass flow rate of organic working fluid can be calculated as follows (Referring to Fig.3 and Fig.5):

The amount of working fluid:

$$q_{mo} = \frac{(q_m - q_{m1})(h_4 - h_6)}{(h_{o1} - h_{o5})} \quad (14)$$

Where, $h_{o5} = h_{o4} + w_p$, $w_p = (P_{o1} - P_{o4})v_{o4}/(10^3 \eta_p)$, $h_{o1}, h_{o2}, h_{o4}, h_{o5}$ are the enthalpy of organic working fluid at different states (kJ/kg), h_{o1} and h_{o6} are determined by the evaporation temperature t_{o1} ; h_{o5} is obtained from h_{o4} and compress work w_p (kJ), namely, $h_{o5} = h_{o4} + w_p$; P_{o1} is the evaporation pressure (Pa), P_{o4} is the condensation pressure (Pa), v_{o4} is the specific volume of condensation working fluid, η_p is the working fluid pump efficiency.

Net power output of binary subsystem is defined as follows:

$$P_{net,2} = \frac{q_{mo} [(h_{o1} - h_{o2}) - (h_{o5} - h_{o4})] (1 - X)}{3.6} \eta_{oi} \eta_m \eta_g \quad (15)$$

The net power output of flash-binary power system:

$$P_{net} = P_{net,1} + P_{net,2} \quad (16)$$

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

$$Ne = \frac{P_{net}}{q_m} = \frac{P_{net,1}}{q_m} + \frac{P_{net,2}}{q_m} = Ne_1 + Ne_2 \quad (17)$$

3. THE RESULTS OF TWO-STAGE POWER CONVERSION

The performances of the two-stage geothermal power system are compared when the geofluid temperature ranges from 80 to 150 °C. The cooling water inlet temperature is 20 °C, the organic fluid in binary subsystem is R245fa. The power output will be different when we geofluid temperature changed. The power output and steam quality are compared between double flash and flash-binary system based on variable geofluid temperature less than 130 °C. The value of various efficiencies can be assumed as follow: $X = 0.3$, $\eta_{oi} \cdot \eta_m \cdot \eta_g = 0.76 \times 0.98 \times 0.97 = 0.722$. The condenser temperature of flash system and binary cycle are 30 °C by direct cooling system and 35 °C by indirect cooling system. Numerical simulation is followed by Eq. from (1) to (17).

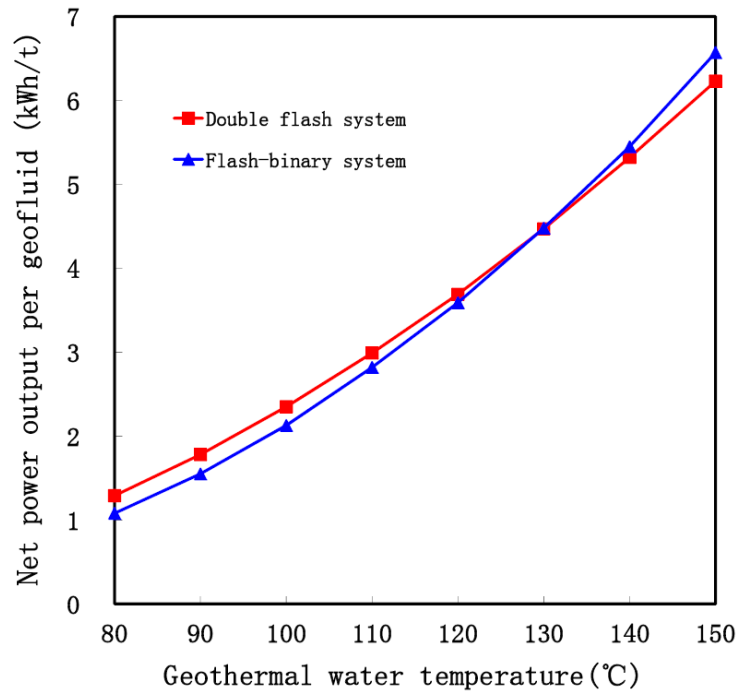


Figure 6: The Influence of Geothermal Water Temperature on Net Power Output

Figure 6 shows the influence of geothermal water temperature on net power output of two stage power system. From the figure, we can see that the higher geothermal temperature, the higher net power output. When the geothermal water temperature is 130 °C, the net power output of double flash system and flash-binary system are fairly close. When geothermal water temperature is ranged from 80-130 °C, the net power output of double power system is more than up to 19.5% of flash-binary power system. However, when geothermal water temperature is ranged from 130-150 °C, the net power output of flash-binary power system is more than up to 5.5% of double power system.

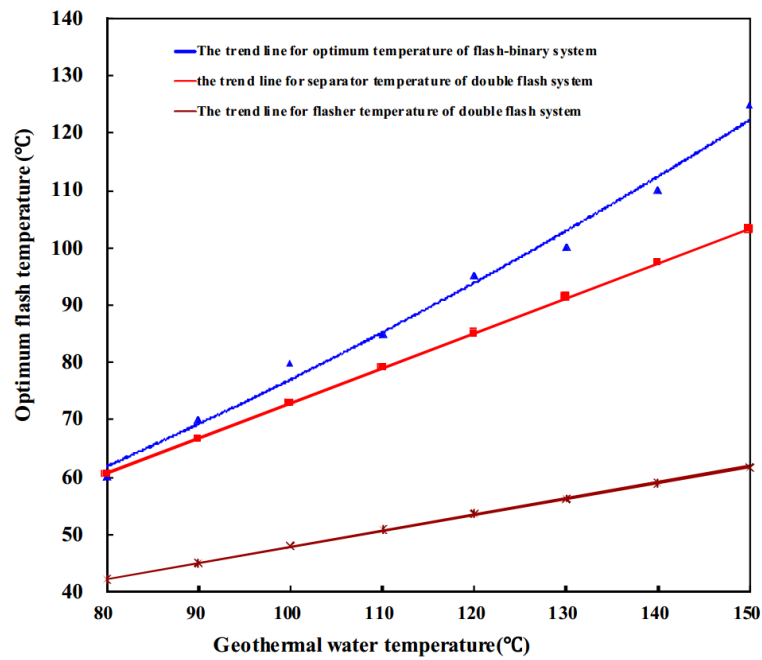


Figure 7: The Influence of Geothermal Water Temperature on Optimum Flash Temperature

Figure 7 shows the optimum flash temperature of the double flash and flash-binary power system. For each choice of separator (or flasher) temperature, 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, there will be corresponding separator (or flasher) temperature that yields the highest power output which defines the optimum plant choices for both separator and flash conditions.

The higher optimal flash temperature, the higher flash pressure, and which will ensure that the system will be operation not in negative pressure.

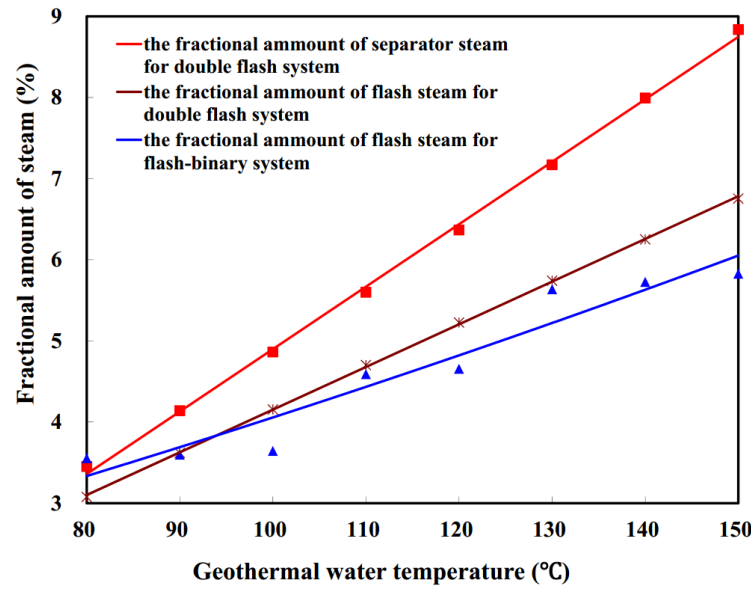


Figure 8: The Relationship between Geothermal Water Temperature and Fractional Amount of Steam

As show in figure 8, For double flash system, the fractional amount of separator steam and flasher steam range from 3.5% to 8.8% and 3.1% to 6.8%; for flash-binary system, the fractional amount of flasher steam range 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 be result to bigger volume and higher cost of power equipment. In contrary, the optimal flasher temperature of flash-binary system is higher than double flash, which will help for minimizing the volume and cost of power equipment. When the temperature less than 130 °C, it is better to use flash-binary power system because the flash pressure of double system is in vacuum which will consume more power for running vacuum pump. When the temperature is higher than 130 °C, it is better to use double flash power system because of low initial and operation cost.

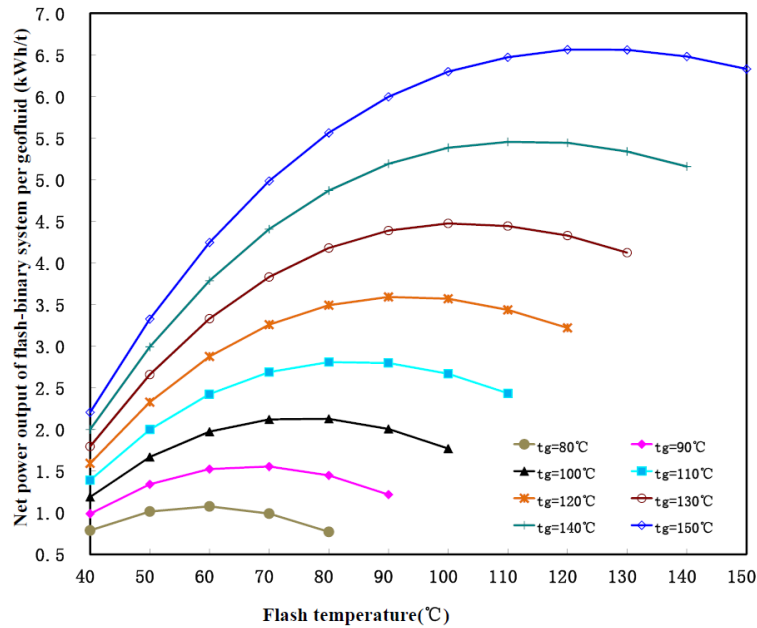


Figure 9: The Influence of Flash Temperature on Power Output of Flash-Binary System

For different geothermal water temperature in the flash-binary power system, the trend of power output is drawn when the flash temperature ranges from condensation temperature to geothermal water temperature basing on trial calculation. When the geothermal water temperature is constant, the power output increases and then decreases with higher flash temperature. The higher

geothermal water temperature, the higher optimal flash temperature. Figure 9 shows that the optimal flash temperature are 60 °C and 125 °C when the geothermal water are 80 °C and 150 °C.

4. CONCLUSIONS

Two-stage geothermal energy conversion power system is analyzed for enhancing the efficiency the geothermal resource utilization in China. The conclusions as follow:

The increasing amount of flash-binary power system is bigger than double power system with increasing geothermal water temperature. When geothermal water temperature is ranged from 80-130 °C, the net power output of double flash power system is more than up to 19.5% of flash-binary power system. However, when geothermal water temperature is ranged from 130-150 °C, the net power output of flash-binary power system is more than up to 5.5% of double power system.

The optimal flash temperature of flash-binary system is higher than the second flash system of double flash system. When the temperature less than 130 °C, it is better to use flash-binary power system because the flash pressure of double system is in vacuum which will consume more power for running vacuum pump. When the temperature is higher than 130 °C, it is better to use double flash power system because of low initial and operation cost.

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