ENERGY EFFICIENCY COMPARISON BETWEEN GEOTHERMAL POWER SYSTEMS

by

Chao LUO [a,b,c,d*], ***Jun ZHAO*** [d], ***Yulie GONG*** [a,b,c], ***Yongzhen WANG*** [d], ***and Weibin MA*** [a,b,c]

[a] Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangdong, China
[b] Key Laboratory of Renewable Energy, Chinese Academy of Sciences, Guangdong, China
[c] Guangdong Key Laboratory of New and Renewable Energy Research and Development, Guangdong, China
[d] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, Ministry of Education, Tianjin, China

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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.

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

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 south-eastern 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].

* Corresponding author, e-mail: luochao@ms.giec.ac.cn

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 systems: 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 analysed by Di Pippo [6] and Zarrouk and Moon [7]. Yari [8] and Clarke and James [9] compared the exergetic efficiency between double flash and flash-binary power systems. However, the power output capacity, optimum flash temperature and other performance indices of the two-stage power system are not analysed. 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.

Geothermal power systems

There are four basic types of geothermal power systems: 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 section *Single flash system* and section *Binary cycle*.

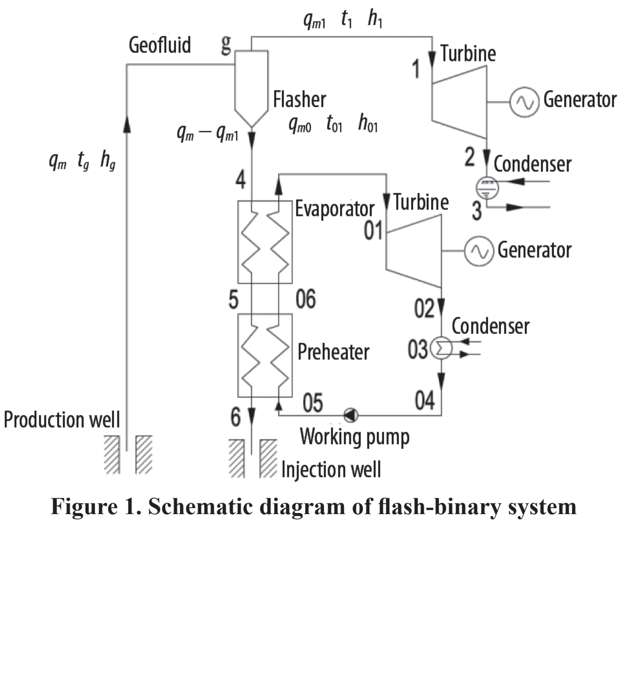

Figure 1. Schematic diagram of flash-binary system

Flash-binary system

Figure 1 shows the schematic of flash-binary system, which includes single flash power system and binary cycle system [16]. The state g, 1-6 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). Here, 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, and $q_m - q_{m1}$ is the mass flow rate of geothermal liquid at state 4.

The state 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 (states 05 and 06) via the working pump. Here, 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.

Single flash system

The temperature-entropy (*T-S*) diagram of single flash system is shown in fig. 2. Point g is the geofluid state before entering into flasher 1-2-3 is the cycle of geofluid in the flash system. The T_g, T_1, and T_c are the heat resource, flash, and condensation temperature. The 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:

$$T_1 = \sqrt{T_g T_c} \tag{1}$$

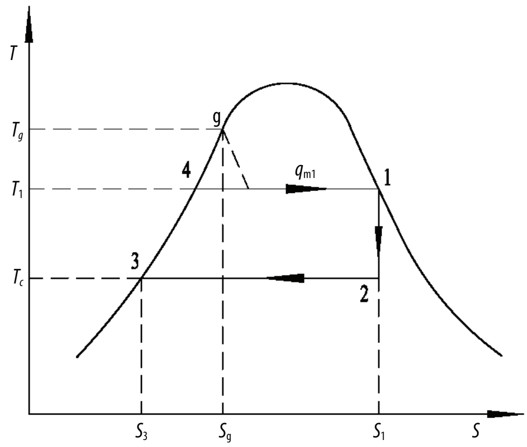

Figure 2. Thermodynamic cycle of flash system

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

The amount of single flasher steam:

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

The fractional amount of single flasher steam:

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

Net power output of the single flash system:

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

Binary cycle

Figure 3 shows the temperature-entropy (*T-S*) diagram of binary system. The Δt_{pp} is the absolute temperature difference between evaporator/condenser end and environment, which value is assumed to be approximately 5 K. The 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. The P_{01} and P_{0c} are the evaporation and condensation pressure of organic working fluid, respectively. The 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].

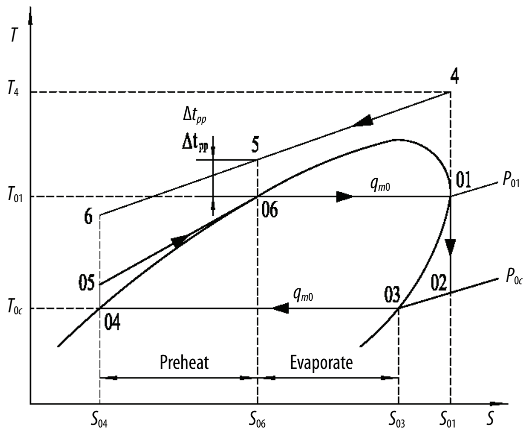

Figure 3. Thermodynamic cycle of binary system

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

$$T_{01} = \sqrt{T_1 T_{0c}} \tag{5}$$

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, (reference to figs. 1 and 3):

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

Net power output of binary cycle is defined:

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

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

The net power output of flash-binary power system:

$$W_{net} = W_{net1} + W_{net2} \tag{8}$$

Net power output [kWh/t] per ton of geothermal water:

$$Ne = \frac{W_{net}}{q_m} = \frac{W_{net1}}{q_m} + \frac{W_{net2}}{q_m} \tag{9}$$

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 fig. 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'.

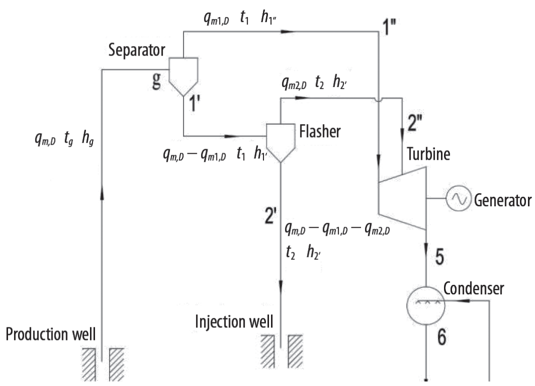

Figure 4. Schematic diagram of double flash system

The temperature-entropy (*T-S*) diagram of the double flash system is shown in fig. 5. 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, $m_{1,\mathrm{D}}$ and $m_{2,\mathrm{D}}$, 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]:

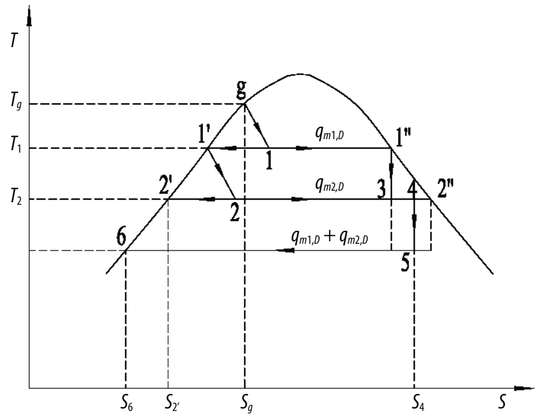

Figure 5. Thermodynamic cycle of double flash system

The optimum separator temperature:

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

The optimum flasher Kelvin temperature:

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

The amount of separator steam:

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

The fractional amount of separator steam:

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

The amount of flasher steam:

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

The fractional amount of flasher steam:

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

Maximum net power output of double flash system:

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

Maximum net power output per ton geofluid:

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

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, and the organic fluid in binary power cycle is R245fa. The value of various efficiencies can be assumed:

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

Numerical simulation is followed by eqs. from (1)-(17).

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.

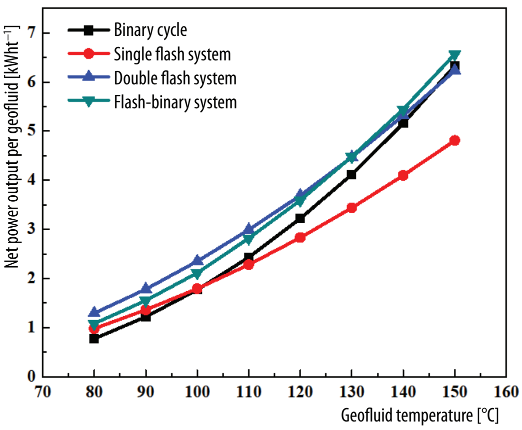

Figure 6. The influence of geofluid temperature on net power output

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 °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 vapour enthalpy drop is zero in the flash turbine and 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 °C from fig. 7.

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.

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

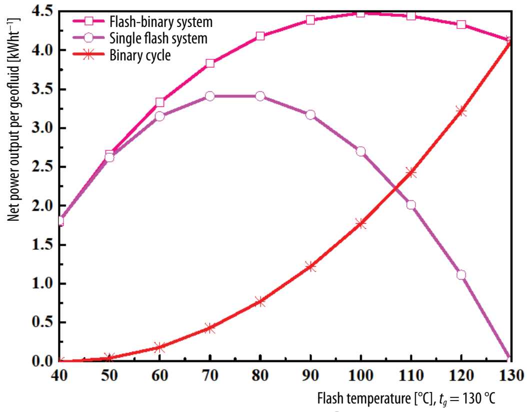

Figure 7. The influence of flash temperature on net power output for flash-binary system

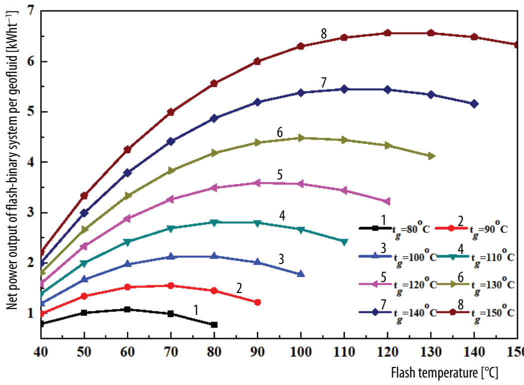

Figure 8. The influence of flash temperature on power output for flash-binary system

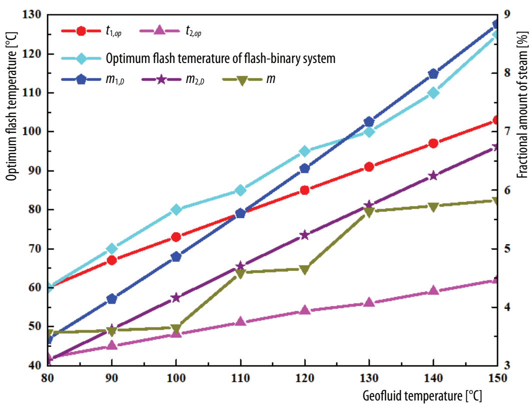

Figure 9. The influence of geofluid temperature on optimum flash temperature and fractional amount of steam

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 blow 130 °C, the flash-binary power system is a better choice.

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 and 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

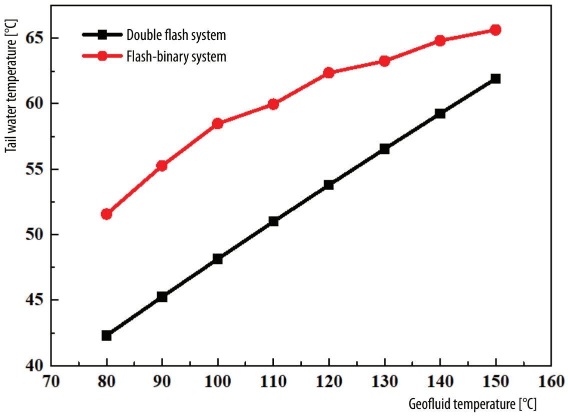

Figure 10. The influence of geofluid temperature on injection water temperature

Conclusions

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

- 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.
- 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.
- 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.

Acknowledgment

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Nomenclature

h – specific enthalpy at different states, [kJkg^{-1}]
m – fractional amount of flasher steam in flash-binary cycle, [%]
$m_{1,D}$ – fractional amount of separator steam in double flash system, [%]
$m_{2,D}$ – fractional amount of flasher steam in double flash system, [%]

Ne – net power output per ton geothermal water in flash-binary cycle, [kWht^{-1}]
Ne_D – net power output per ton geothermal water in double flash system, [kWht^{-1}]
P_{01} – evaporation pressure, [Pa]
P_{04} – condensation pressure, [Pa]
q_m – mass flow rate of geothermal water in flash-binary system, [th^{-1}]
$q_{m,D}$ – mass flow rate of geothermal water in double flash system, [th^{-1}]
q_{m1} – mass flow rate of flash steam in flash-binary system, [th^{-1}]
$q_{m1,D}$ – mass flow rate of separator steam in double flash system, [th^{-1}]
$q_{m2,D}$ – mass flow rate of flash steam in double flash system, [th^{-1}]
q_{mo} – mass flow rate of working fluid vapor in flash-binary system, [th^{-1}]
S – specific entropy at different states, [kJkg^{-1}K^{-1}]
T_c – condensation temperature of flash system, [K and °C]
T_g – geothermal resource temperature, [K]
T_{oc} – condensation temperature of binary system, [K and °C]
T_1 – flash temperature in flash-binary cycle, [K]
$T_{1,op}$ – 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]
t_1 – flash temperature in flash-binary cycle, [°C]
W_{net} – total net power output of flash-binary cycle, [kW]
$W_{net,D}$ – net power output of double flash system, [kW]
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]
X – electricity consumption percentage by self, [%]

Greek symbols

η_g – generator efficiency, [%]
η_m – machinery efficiency, [%]
η_{oi} – turbine isentropic efficiency, [%]

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