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Thermodynamic Analysis of Geothermal Power Generation Combined Flash System with Binary Cycle

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ABSTRACT

This paper will analyze a special energy conversion system of geothermal power generation with a flash system combined with binary cycle and suggests a mathematic model of thermodynamic calculation for such combined geothermal power plants in detail. With such a mathematic model, both the capacity and efficiency of the power plants are calculated. The results are given in a diagram which displays the optimum flash temperature for combined power generation system and the optimum design parameters determined by the temperature. The calculated result shows that when the average temperature of cooling water from the environment is 28°C, the maximum total capacity of hybrid flash-binary system is at least 20% higher than that of flash system or binary cycle separately with a geothermal water resource of 110°C. In addition, the power plants produce hot water of about 60°C for direct utilization.

1. INTRODUCTION

In China, mid-low temperature geothermal resources are abundant and most of them are hot water of about 100°C, which is widely distributed throughout the world. Therefore, it is practical significance to use these resources to generate electricity.

The main purpose of geothermal plant is to generate electricity and provide hot water. If a flash system is combined with binary cycle, the power output of the plant and the ratio of geothermal resource utilization will be improved. The hybrid flash-binary system includes the flash system by using the steam generated by the flasher directly and then binary cycle using an organic fluid to exchange the thermal energy of hot water generated by the flasher. The thermodynamic schematic diagram of this hybrid system is shown in Fig.1, the total power output of the system is the sum of flash system and binary cycle.

2. THERMODYNAMICS OF THE HYBRID FLASH-BINARY SYSTEMS

Thermodynamic processes diagram of single-flash system and binary cycle are shown in Fig.2 and Fig.3. In this paper, according to Chinese geothermal resource, the two thermodynamic processes will be calculated separately. As electricity generated by hot water, the calculation formulas of optimum flash temperature and optimum evaporation temperature are listed in the following.

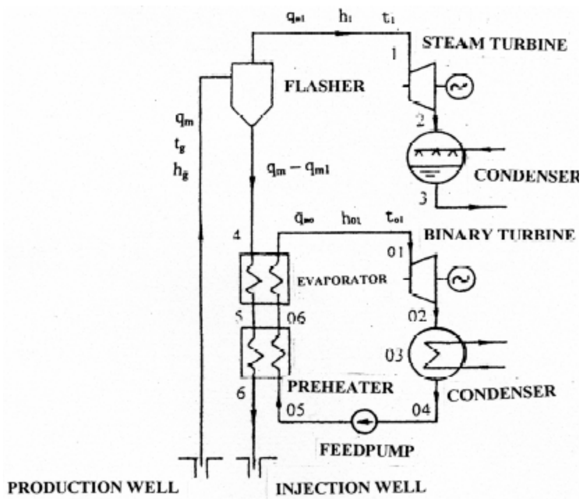

Fig.1 Schematic diagram of integrated flash-binary geothermal plant system

The optimum flasher temperature of flash system T_1,

$$T_1 = \sqrt{T_g T_c}\ \text{(K)} \tag{1}$$

$$t_1 = T_1 - 273\ \text{(°C)}$$

The optimum evaporator temperature of binary cycle T_{o1},

$$T_{o1} = \sqrt{T_1 T_{oc}}\ \text{(K)} \tag{2}$$

$$t_{o1} = T_{o1} - 273\ \text{(°C)}$$

Where T_g is geothermal water temperature (K), T_c is condensation temperature (K) of flash system, T_{oc} is condensation temperature (K) of binary cycle.

Obviously, t_{o1} and t_1 are assigned in formula (2). After the optimum temperature t_{o1} and t_1 are fixed, system parameters are calculated as follows.

2.1 Flash System

Referring to Fig.1 and Fig.2, The energy balance for the flasher is the following:

$$q_m\ (h_g - h_4) = q_{m1}\ (h_1 - h_4) \tag{3}$$

Where

q_m is the mass flow rate (t/h) of geothermal water, ande h_g,h_4,h_1 are the specific enthalpies of the fluid at different states (kJ/kg).

Net power output of the flash system:

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

Where

$$h_2 = h_3 + T_c\,(s_1 - s_3) \qquad (5)$$

$$X = \frac{P_c}{P}$$

$$P_{net1} = P - P_c = P\,(1 - X)$$

Net power output efficiency of flash system:

$$\eta_{net1} = \frac{3.6P_{net1}}{q_m(h_g - h_3)} \qquad (6)$$

Where

P_{net1} is the net power output of flash system (kW), P is the gross power output of the plant (kW), P_c is the electricity consumed by the plant itself (kW), X is the percentage of the plant self-consumption, s_1,s_3 are the specific entropies at different states (kJ/kg•K), η_{net1} is the net power output efficiency of flash system, η_{oi} is the isentropic turbine efficiency, η_m is the machinery efficiency, η_g is the electrical efficiency.

The efficiency of geothermal resource utilization is defined as the following:

$$\eta_{u1} = \frac{3600P_{net1}}{q_m w_{max} \times 10^3} \qquad (7)$$

The maximum possible specific work would be calculated by the following formula:

$$w_{max} = h_g - h_8 - T_e(s_g - s_8) \qquad (8)$$

Where

h_g,h_8 are the enthalpy at different states (kJ/kg), s_g,s_8 are the entropy at different states (kJ/kg•K), T_e is the environment temperature (K).

q_{m1}, *h1*, *h4*, and *s1* are determined by flash temperature *t1*; *h3* and *s3* are determined by the condensation temperature *tc*; *h8* and *s8* are determined by the environment temperature *te* [3]. The data of the plant is as follow: X = 0.25, $\eta_{oi} \times \eta_m \times \eta_g$ = 0.76×0.98×0.97 = 0.722.

2.2 Binary Cycle

Referring to Fig.1 and Fig.3, the basic equations in each component are as follows:

For the thermal balance of the evaporator and preheater:

$$(q_m - q_{m1})(h_4 - h_6) = q_{mo}(h_{o1} - h_{o5}) \qquad (9)$$

For the thermal balance of the evaporator:

$$(q_m - q_{m1})(h_4 - h_5) = q_{mo}(h_{o1} - h_{o6}) \qquad (10)$$

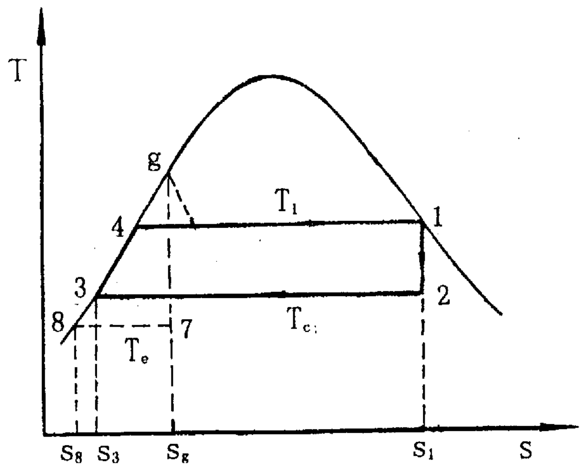

Fig.2 Temperature-entropy state diagram for flash system

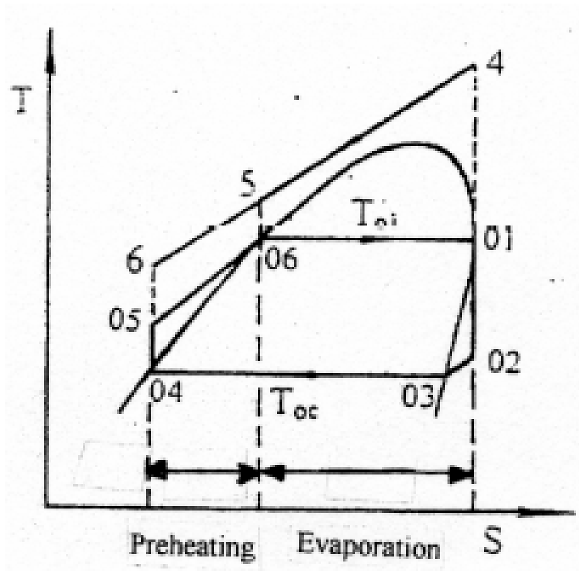

Fig.3 Temperature-entropy state diagram for binary cycle

Where

h_4 is determined by the flashing temperature t_1 (°C); h_{o1} and h_{o6} are determined by the working fluid evaporating temperature t_{o1} (°C); h_{o5} is obtained from condensate fluid enthalpy h_{o4} and compressor work w_p(kJ), namely, $h_{o5} = h_{o4} + w_p$, $w_p = (P_{o1} - P_{o4})\,v_{o4} / (10^3\,\eta_p)$. In order to solve the two equations above which consist of 3 unknown parameters (q_{mo} / h_5 /h_6), we usually selected h_6 as a known parameters, the value h_6 ($h_6 = ct_6$) is related to the preheater outlet temperature determined based on the utilization of user.

Where

h_4 is determined by flash temperature t_1; h_{o1} and h_{o6} are determined by the evaporation temperature t_{o1}; h_{o5} is obtained from h_{o4} and compressor work w_p(kJ), namely, $h_{o5} = h_{o4} + w_p$.

Net power output of binary cycle is defined as follows:

$$P_{net2} = \frac{q_{mo}[(h_{o1} - h_{o2}) - (h_{o5} - h_{o4})](1 - X)}{3.6}\eta_{oi}\eta_m\eta_g \quad (11)$$

Where

h_{o2} is determined by the organic fluid thermodynamic properties, and when the state of the turbine outlet is in the wet steam zone, formula (5) is effective; when in the superheated zone, the table "superheated steam thermodynamic properties"[4] can be referred. The data for the power plant is as follow: $X = 0.25$, $\eta_{oi} \times \eta_m \times \eta_g = 0.78 \times 0.98 \times 0.97 = 0.741$.

Net power output efficiency of binary cycle:

$$\eta_{net2} = \frac{3.6 P_{net2}}{q_{mo}(h_{o1} - h_{o5})} \quad (12)$$

The efficiency of geothermal resource utilization:

$$\eta_{u2} = \frac{3600 P_{net2}}{(q_m - q_{m1}) w_{\max} \times 10^3} \quad (13)$$

For a binary cycle, the maximum possible work would be as follows:

$$w_{\max} = c\,(T_1 - T_e) - T_e\, c \ln\frac{T_1}{T_e} \quad (14)$$

The net power output of hybrid flash-binary system:

$$P_{net} = P_{net1} + P_{net2} \quad (15)$$

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

$$Ne = \frac{P_{net}}{q_m} = \frac{P_{net1}}{q_m} + \frac{P_{net2}}{q_m} = N_{e1} + N_{e2} \quad (16)$$

3. ANALYSIS OF THE HYBRID FLASH-BINARY SYSTEMS

A numerical example will be presented to illustrate the analysis of this hybrid system (referring to Fig.1-Fig.3). Different flash temperatures will be selected for the thermodynamic calculation in order to study the effect on the P_{net1} and P_{net2}. The parameters of geothermal resource are assumed as follows: geothermal water temperature from production well: t_g=110°C, the mass flow rate of geothermal water: q_m=250t/h, the environment temperature: t_e = 28°C, the organic fluid is R600a.

3.1 Calculate The Basic Parameters

1) Assumed conditions

Geothermal water temperature, t_g = 110°C, T_g = 383 K; Geothermal water enthalpy and entropy, h_g = 461.32 kJ/kg, s_g = 1.4185 kJ/kg•K; Geothermal water enthalpy of the preheater outlet, h_6 = 250 kJ/kg; Geothermal water mass flow rate, q_m = 250 t/h; the environment temperature, t_e = 28°C, T_e = 301 K.

2) Confirmation of the condensation temperature t_c and t_{oc}

Flash system: The hybrid condenser is used in flash system and assuming cooling water temperature is increased by Δt_c = 10°C, the condensation temperature is defined as follows:

$$t_c = t_e + \Delta t_c = 28 + 10 = 38°C$$

Binary cycle: The surface condenser is used in binary cycle and assuming cooling water temperature is increased by Δt_c = 10°C and the minimum heat transfer temperature difference Δt_{pp} = 8°C, so the organic fluid condensation temperature is defined as follows:

$$t_{oc} = t_e + \Delta t_c + \Delta t_{pp} = 28 + 10 + 8 = 46°C$$

3) Confirmation of the optimum flash temperature t_1 and optimum evaporation temperature t_{o1}

Flash temperature is chosen from the range of t_c to t_g, which is between 38°C and 110°C. Evaporation temperature is followed by employing Eq. (2).

3.2 Power Output and Efficiency Calculation

Power output and efficiency are calculated by formulas (1)-(16). Different flash temperatures and related thermodynamic parameters are selected based on given parameters, and then used to calculate corresponding net power output and efficiency. Table 1 and table 2 show the main result about power output and efficiency under different flash temperature.

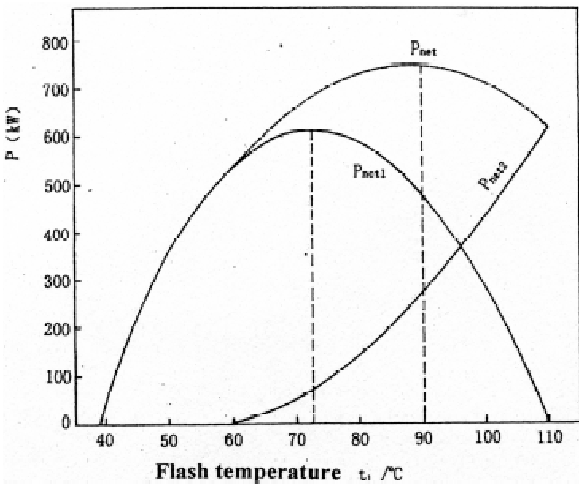

Fig.4 The effect of flash temperature on the capacity

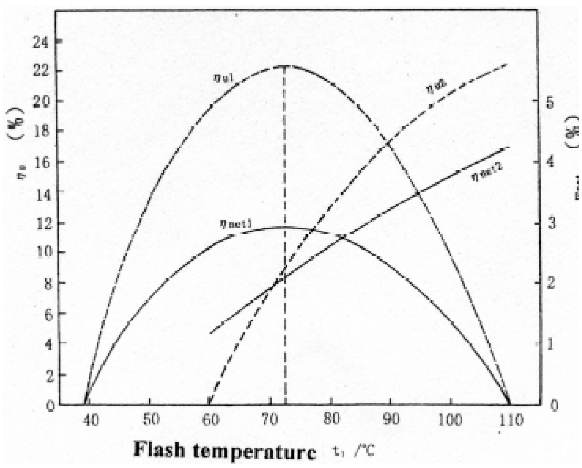

Fig.5 The effect of flash temperature on the efficiency

3.3 RESULT AND DISCUSSION

Fig.4 and Fig.5 show the effect of flash temperature on the power output and efficiency. Maximum values of P_{net1} and

P_{net} appear as t_1 is varied, and corresponding optimum flash temperatures are 72.5°C and 90°C respectively. In addition, net power output of binary cycle P_{net2} is increasing with t_1 which is the heat source temperature for the binary cycle. The total net power output is more than 20% higher than flash system and binary cycle separately, which shows that the hybrid flash-binary systems can generate more based on the conditions of the same geothermal resource. Correspondingly, we must estimate investment cost and perform an economic analysis of the power plant in the design stage because installing two units in the system will increase the initial investment cost. According to the assumed conditions, the optimum flash temperature t_1 of the hybrid flash-binary system is defined as 90°C related to the optimum evaporate temperature t_{o1} of the binary cycle, and the optimum parameters of the system can be derived from t_1 and t_{o1}.

Fig.5 shows that η_{net1} and η_{u1} appear to have maximum values when varying t_1, and the optimum flash temperature is defined as 72.5°C similarly P_{net1}, η_{net2} and η_{u2} increase with increasing t_1.

For a geothermal power plant, in order to improve the turbine power we have to increase the mass flow rate of geothermal water. According to the calculation above, net power output per ton of geothermal water N_{e1} is 1.914kWh/t for flash system and N_{e2} is 1.079kWh/t for binary cycle at optimum flash temperature of 90°C. The relationship between q_m and P_{net} can be obtained, with increasing q_m the P_{net} will be increased, which is shown in the table 3. For example, when geothermal water mass flow rate is 350t/h, the total capacity can reach 1047.6kW, and the greater capacity, the better economic the system is. Therefore, geothermal water mass flow rate should be increased under the conditions imposed by the geothermal reservoirs.

In this calculation, the temperature of geothermal water after the preheater can reach 59.7°C, which can be used for other fields to improve the efficiency of the power plant.

High-temperature industrial waste heat resources can also be used to generated electricity as well as geothermal resources, so the hybrid flash-binary system can be also used for the waste heat energy utilization.

Table 1 The known preset parameters

Geofluid parameters	Flash system parameters	Binary cycle parameters	Environment cooling water parameters
t_g = 110°C	t_c = 38°C	t_{oc} = 46°C	t_e = 28°C
T_g = 383 K	T_c = 311 K	T_{oc} = 319 K	T_e = 301 K
h_g = 461.32 kJ/kg	h_3 = 159.09 kJ/kg	h_{o4} = 312.79 kJ/kg	h_8 = 117.31 kJ/kg
s_g = 1.4185 kJ/kg•K	s_3=0.5453 kJ/kg•K	P_{o4} = 6.2091×10^{5}Pa	s_8= 0.4088 kJ/kg•K
q_m = 250 t/h	h_6 = 250 kJ/kg	v_{o4}=1.912×10^{-3}m^3/kg	
	$\eta_{oi} \times \eta_m \times \eta_g$ = 0.722	$\eta_{oi} \times \eta_m \times \eta_g$ = 0.741	
	X = 0.25	X = 0.25	

Table 2 The main result

t_1/°C	t_{o1}/°C	P_{net1}/ kW	P_{net2}/ kW	P_{net}/ kW	N_e/ kWh/t	η_{net1}/%	η_{u1}/%	η_{net2}/%	η_{u2}/%
60	52.9	536.0	0.8	536.8	2.147	2.55	19.3	1.15	0.19
65	55.4	585.7	21.6	607.3	2.429	2.79	20.0	1.54	3.82
70	57.8	610.6	52.3	662.8	2.651	2.91	21.9	1.89	7.20
75	60.2	611.9	92.7	704.6	2.818	2.92	22.0	2.23	10.2
80	62.6	589.9	142.7	732.6	2.930	2.81	21.2	2.56	12.8
85	64.9	545.2	201.1	746.3	2.985	2.60	19.6	2.87	15.1
90	67.3	478.5	269.7	748.2	2.993	2.28	17.2	3.18	17.1
95	69.6	390.2	348.8	739.1	2.956	1.86	14.0	3.49	18.9
100	71.9	280.9	429.4	710.3	2.841	1.34	10.1	3.73	20.2
110	76.5	0.00	623.1	623.1	2.492	0.00	0.00	4.25	22.5

Table 3 The relation of flux and capacity as flash temperature is 90℃

Geothermal water flux q_m/t/h	Flash system P_{net1}/kW	Binary cycle P_{net2}/kW	Total power output P_{net}/kW
200	382 . 8	215 . 8	598 . 6
250	478 . 5	269 . 7	748 . 2
300	574 . 2	323 . 7	897 . 9
350	669 . 9	377 . 7	1047 . 6
400	765 . 6	431 . 6	1197 . 2
450	861 . 3	485 . 6	1346 . 9
500	957 . 0	539 . 5	1496 . 5

4. CONCLUSION

1) The paper proposed an integrated flash-binary system and established a thermodynamic model of the geothermal plant in order to enhance the efficiency of resource utilization.

2) The results show that for the assumed conditions, there is an optimum value of the flash temperature t_1, power output of flash system P_{net1}, and total power output P_{net} as shown in Fig.4. In this study, power output of flash system P_{net1} and total power output P_{net} reached maximum values under flash temperature t_1=72.5°C and 90°C respectively.

3) The results show that for the assumed conditions, the maximum net capacity of the hybrid flash-binary system is more than 20% higher than for a flash system and binary cycle separately. The optimum flash temperature value of the maximum capacity hybrid flash-binary system is 90°C, from which optimum thermodynamic parameters can be derived. Correspondingly, we must estimate investment cost and perform an economic analysis of the power plant in the design stage because using two units in the system will increase the initial investment cost.

4) For a geothermal power plant, in order to improve efficiency of turbine we have to increase the mass flow rate of geothermal water while keeping a small enthalpy difference; the greater the capacity, the more favorable the economic analysis. Therefore, geothermal water mass flow rate should be increased as much as geothermal reservoirs' conditions allow.

5) The combined flash-binary system could also provide prospects for the utilization of industrial waste heat energy.

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