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Performance Analysis of a Hybrid Solar-Geothermal Power Generation System

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ABSTRACT

A medium-low temperature hybrid solar-geothermal plant (HSGP) model was established under the conditions of solar radiation intensity and ambient temperature in Lhasa, china. Based on the established MATLAB model, the net power output, thermal efficiency and exergy efficiency of the stand-alone geothermal power plant and the HGSP were calculated. The results show that the hybrid power plant has better performance than the stand-alone geothermal plant. By increasing solar energy assistance, the electricity generated by the HSGP increased by 9.4% on the summer solstice and 1.7% on the winter solstice respectively. From the perspective of exergy destruction, the loss of each part of the hybrid power generation system was analyzed and calculated, which indicates the direction for further improving the efficiency of the system. The results provide a theoretical basis for the design and performance evaluation of HSGP.

1. INTRODUCTION

The power generation cost of a stand-alone solar power plant is high, and the power generation is unstable due to the influence of solar radiation intensity. The stand-alone geothermal power plant is greatly affected by the distribution of geothermal resources, and the geothermal grade decreases as the mining continues. If the two systems are coupled, the disadvantages of the geographical location and resource constraints of the stand-alone geothermal power plants and the stand-alone solar power plants can be overcome, and the advantages of the two energy sources can be combined to improve the thermal efficiency of the power station.

At present, the hybrid modes of the HSGP are roughly divided into the following four types: solar energy is used for geothermal water preheating (increasing geothermal water temperature or increasing geothermal steam content) (Alvarenga, 2008), solar energy for overheating of working fluid (Zhou, 2011), steam overheating (Mir, 2011), or multiple coupling structure superposition (Greenhut, 2010). Different hybrid modes are applicable to different solar radiation intensities, geothermal reservoirs, and the main form of power cycling in geothermal power plants. Zhong et al carried out thermal calculations on the trough solar thermal power generation system and the geothermal dual-cycle power generation system, and proposed a combined power generation system based on the Kalina cycle. Zhang et al. proposed a combined power generation system with a solar superheater, and analyzed the feasibility of applying solar geothermal power generation system in Tibet. It was found that the hybrid power generation system could increase the power generation by 10% compared with conventional geothermal power generation system.

At present, research on hybrid power generation systems is mainly focused on improving the power generation of the system, but less research on the thermal efficiency of the system and the energy loss of various components of the system. Based on the meteorological conditions and geothermal resources in Lhasa, a hybrid solar-geothermal power generation model was constructed. The net power output, thermal efficiency of the hybrid power generation system and the stand-alone geothermal power generation system were calculated on a time-by-time basis. The thermal performance characteristics of the power generation system were analyzed and a preliminary economic analysis was carried out.

2. DESCRIPTION OF THE HYBRID SOLAR-GEOTHERMAL POWER GENERATION SYSTEM

2.1 Description of the hybrid solar-geothermal power generation system

The schematic diagram of the system structure is shown in Figure 1. The hybrid solar-geothermal power generation system mainly includes evaporator, steam turbine, air-cooled condenser, working fluid pump, solar collector and other components. The hybrid power generation system includes geothermal water circulation, solar heat transfer oil circulation and Organic Rankine Cycle (ORC). For geothermal water circulation: the geothermal water from production well firstly enters the evaporator, conducts heat to the working fluid, and undertakes evaporation and overheating of part of the working fluid. After that, the geothermal water flows into the preheater and preheats all the working fluid. Finally, geothermal water is injected into the reinjection well. For the solar heat transfer oil cycle: the heat transfer oil is heated in the solar collectors, and then flows into the evaporator to conduct heat to the working fluid, and undertakes evaporation and overheating of part of the working fluid.

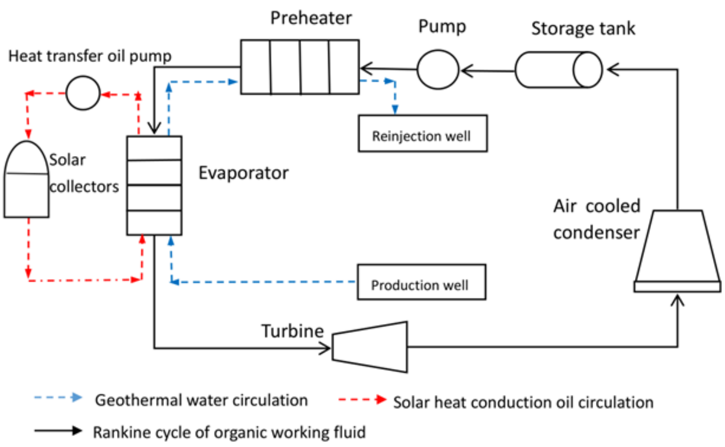

Fig. 1. Schematic diagram of the hybrid solar-geothermal power generation system

The basic working principle of ORC is shown in Fig. 2. The phase of working fluid changes after being heated by geothermal water and heat transfer oil in the evaporator (1-4). The high temperature and high pressure working gas then enters the steam turbine to produce work through expansion (4-5), which drives the generator to generate electricity. The exhaust gas is condensed into liquid in the air-cooled condenser (5-7), and will be pressurized after entering the working fluid pump (7-1).

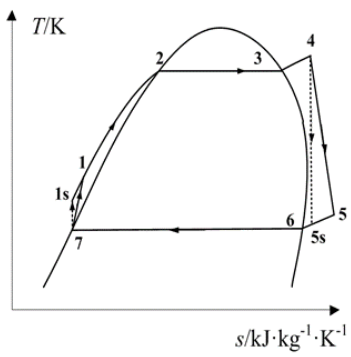

Fig. 2. T-S diagram of an ORC system

2.2 Thermodynamics analyses

The following thermodynamic model is used to analyze thermodynamic performance of the hybrid solar-geothermal power generation system.

For the hybrid power generation system, the heat absorption of the working fluid from the geothermal heat source can be expressed as

$$Q_{geo} = m_1(h_4 - h_1) = m_{geo} c_{p,geo} (T_{geo,in} - T_{geo,out}) \tag{1}$$

Where m_{geo} is the mass flow of geothermal water, $T_{geo,in}$ and $T_{geo,out}$ are the temperatures of the geothermal water entering and leaving the system, respectively. In the evaporator, the mass flow rate of the working fluid heated by the geothermal heat source is

$$m_1 = \frac{m_{geo} c_{p,geo} (T_{geo,in} - T_2 - \Delta T_p)}{(h_4 - h_2)} \tag{2}$$

Where $\triangle T_p$ represents the pinch point temperature difference of the heat exchanger. The heat absorbed by the working fluid from the solar heat source is

$$Q_{solar} = Q_{collector} - Q_{loss,total} - Q_{loss,piping} \tag{3}$$

Where $Q_{collector}$ is the effective solar radiation absorbed by the receiver, $Q_{loss,\ total}$ is the heat loss of the absorption tube, and $Q_{loss,\ piping}$ is the heat loss of the solar tube. In the evaporator, the mass flow rate heated by the solar heat source is

$$m_2 = \frac{Q_{\text{solar}}}{(h_4 - h_2)} \tag{4}$$

The total mass flow rate of the working fluid is

$$m_{\text{wf}} = m_1 + m_2 \tag{5}$$

The condenser heat transfer equation is

$$Q_{\text{c}} = m_{\text{c}} c_{\text{p,c}} (T_{\text{c,out}} - T_0) = m_{\text{wf}} (h_5 - h_7) \tag{6}$$

Steam turbine work volume and working fluid pump power consumption are obtained using Eqs.(8) and (9), respectively

$$W_{\text{t}} = m_{\text{wf}} (h_4 - h_5) \tag{7}$$

$$W_{\text{p}} = m_{\text{wf}} (h_1 - h_7) \tag{8}$$

The net power output of the system is

$$W_{\text{net}} = W_{\text{t}} - W_{\text{p}} \tag{9}$$

The thermal efficiency and exergy efficiency of the system are defined as follows Eq.10-11, E_{geo} is the exergy of geothermal energy absorbed by the system, E_{solar} is the solar energy exergy by the system.

$$\eta_{\text{th}} = \frac{W_{\text{net}}}{Q_{\text{geo}} + Q_{\text{solar}}} \tag{10}$$

$$\eta_{\text{ex}} = \frac{W_{\text{net}}}{\text{E}_{\text{geo}} - \text{E}_{\text{solar}}} \tag{11}$$

3. RESULTS AND DISCUSSION

Tibet belongs to China's first-level zoning of solar energy utilization, and is also rich in geothermal resources. The synergistic effect of two energy-coupled power generation can compensate for the defects of stand-alone power plants to some extent. The typical meteorological annual ambient temperature and solar direct normal irradiance data were used to simulate the thermodynamic performance of the hybrid power station in the Lhasa area of Tibet during the summer solstice and winter solstice, and the main factors affecting net power output were studied. The parameters used for the simulation calculation are shown in Table 1.

Table 1. Main parameters used in simulation calculation.

Parameter	Value	Parameter	Value
Geothermal production well water flow	30kg/s	Production well outlet temperature	125℃
Heat exchanger minimum temperature difference	10℃	Solar field area	2000m^2
Organic working fluid	Isopentane	Specular reflectance ρ	0.93
Absorption tube absorption rate α	0.96	Glass tube transmittance τ	0.95
Working fluid pump isentropic efficiency	80%	Turbine Isentropic Efficiency	75%

3.1 Performance analysis of the first law of thermodynamics

Figure 3 shows the time-by-time simulation results of the net power output of stand-alone geothermal power plants and the HSGPs on the summer solstice and winter solstice. The ambient temperature of Lhasa summer solstice varies from 9.72 °C to 25.72 °C, and the direct solar irradiance can be used for the HSGP from 9:00 AM to 8:00 PM local time. In a stand-alone geothermal power plant, the amount of electricity generated will gradually decrease as the ambient temperature increases during the day. When coupled with solar energy, the amount of electricity increases with the increment of solar radiation, reaching a peak of 169.1 kW·h at 3:00 PM, which is equivalent to an increase of 32.61% in the amount of power generated by a stand-alone geothermal power plant. A stand-alone geothermal power plant can generate 14,651.0 kW·h of electricity throughout the day; after being coupled with solar energy, it can produce 16,028.3 kW·h of electricity throughout the day, about 9.40% higher than a stand-alone geothermal power plant.

The ambient temperature of Lhasa winter solstice varies from -7.03 °C to 8.85 °C, and the direct solar irradiance can be used for HSGP from 11:00 AM to 6:00 PM local time. A stand-alone geothermal power plant can generate 22,596.5 kW·h of electricity throughout the day; after being coupled with solar energy, it can produce 22,978.5 kW·h of electricity throughout the day, about 1.69% higher than a stand-alone geothermal power plant.

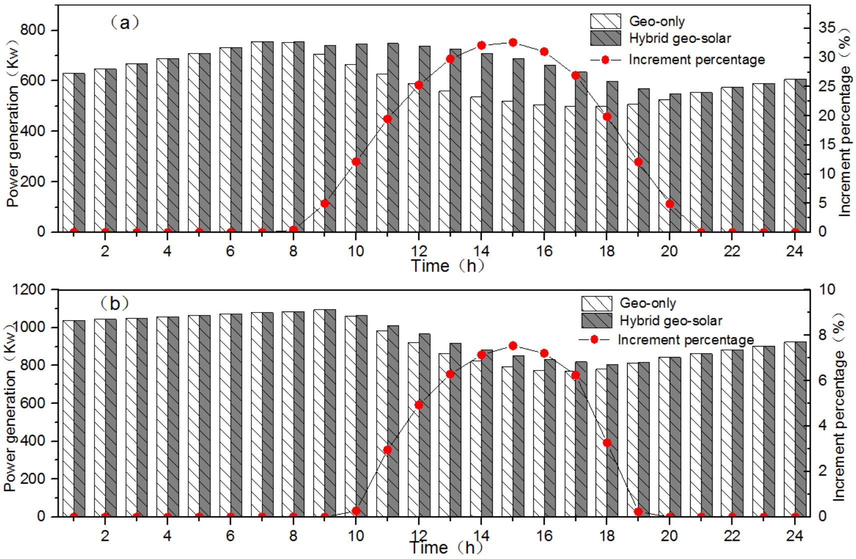

Fig. 3. Simulation results of net power output (a) summer solstice (b) winter solstice

The enthalpy difference of the steam turbine inlet and outlet, the work consumed by working fluid pump, the flow rate of working fluid and the total heat absorption of the evaporation process vary with the evaporation temperature. Therefore, there is an optimum evaporation temperature such that the net power output at this moment has a maximum value. The maximum value is taken as the optimal net power output at that time, and the optimal net power output and thermal efficiency also change with time.

Figure 4 shows the thermal efficiency time-by-time simulation results of the stand-alone geothermal power plant and the HSGP for the summer solstice and winter solstice. On the summer solstice day, the average thermal efficiency of a stand-alone geothermal power plant is 8.37%. After being coupled with solar energy, the average thermal efficiency increased by 0.40%. On the winter solstice day, the average thermal efficiency of a stand-alone geothermal power plant is 10.33%. After being coupled with solar energy, the average thermal efficiency increased by 0.07%.

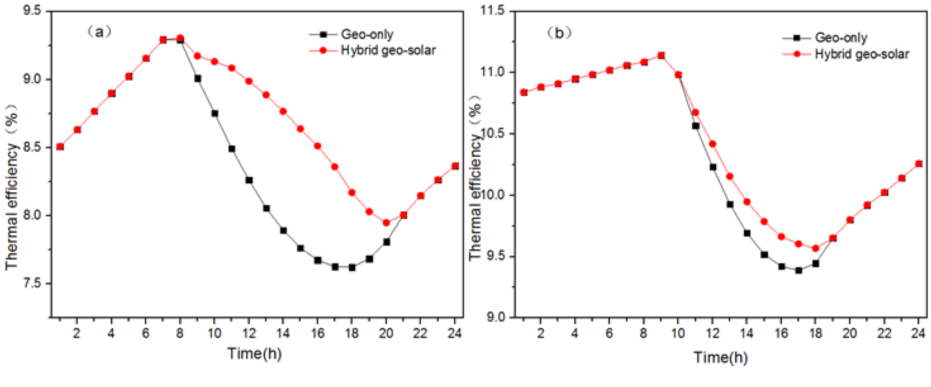

Fig. 4. Simulation results of thermal efficiency (a) summer solstice (b) winter solstice

From the data analysis, the amount of power generation and power generation efficiency of the stand-alone geothermal power plant is seriously affected by the change of the ambient temperature, but the addition of solar energy largely offsets the adverse effects. Because the summer ambient temperature is on average higher and the solar radiation conditions are better, the improvement effect on the summer power generation performance of the geothermal power plant is more obvious than that in winter.

3.2 Performance analysis of the second law of thermodynamics

Figure 5 shows the loss of each component of the system during the summer solstice. Whether it is a stand-alone geothermal power plant or a HSGP, the exergy destructions of the all-day evaporator is the largest, accounting for 55.11% and 34.08% of the system exergy destructions, respectively. This is mainly due to the large heat transfer temperature difference between the high temperature heat source and the ORC working fluid, so that a large amount of heat is not utilized after the geothermal water and the heat transfer oil pass through the evaporator. For the HSGP, the solar collector's exergy destruction begins to increase rapidly when there is solar radiation, reaching a peak at 15 o'clock, which accounts for 41.10% of the total exergy destructions. The exergy destructions of the HSGP ranked from biggest to smallest: evaporator (accounting for 44.74% of the total exergy destruction), solar collector (22.15%), air-cooled condenser (17.69%), and steam turbine (15.27%), working fluid pump (0.16%).

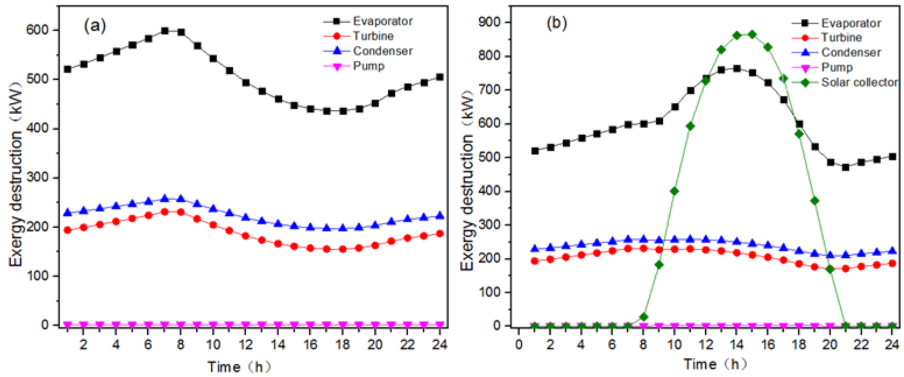

Fig. 5. Exergy destructions on the summer solstice (a) a stand-alone geothermal power plant (b) a HSGP

Figure 6 shows the loss of each component of the system during the winter solstice. For the HSGP, the exergy destructions of the solar collector gradually increases in the presence of solar radiation, reaching a peak at 15 o'clock, accounting for approximately 18.17% of the total exergy destruction. Due to the poor lighting conditions in winter, the amount of solar energy used for power generation is small, and the solar collector's exergy destruction is also small, accounting for 5.22% of the total exergy destruction.

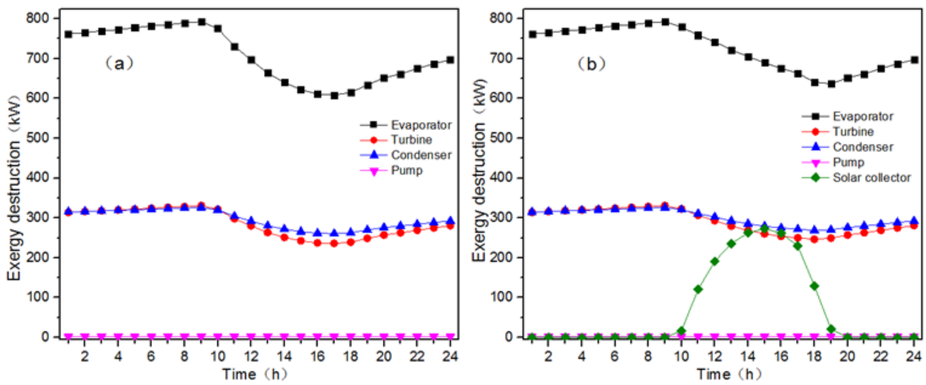

Fig. 6. Exergy destructions on the winter solstice (a) a stand-alone power geothermal plant (b) a HSGP

Figure 7 shows the exergy efficiency of the stand-alone geothermal power plant and the HSGP. Due to the optical loss and heat transfer loss of the solar collector, the exergy efficiency of the HSGP is lower than that of the stand-alone geothermal plant, and the lowest value is all around 15 o'clock on the summer solstice and winter solstice. On the summer solstice day, the average daytime exergy efficiency of a stand-alone geothermal power plant was 39.91%., the exergy efficiency decreased to 34.56%. On the winter solstice day, the average daytime exergy efficiency of a stand-alone geothermal power plant is 42.45%. After being coupled with solar energy, the exergy efficiency is reduced to 40.99%.

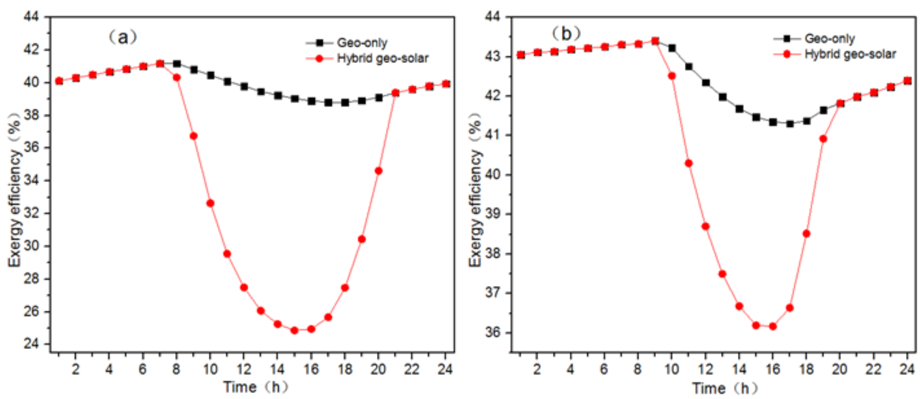

Fig. 7. Simulation results of exergy efficiency (a) summer solstice (b) winter solstice

4 ECONOMIC ANALYSIS

Under the meteorological conditions in the Lhasa area, the geothermal production well exit temperature is 125 °C and the mass flow rate is 30 kg/s. The 3,000 m^2 solar collector is coupled into a stand-alone geothermal power plant, which has a significant improvement in thermal performance and technical advantages. In order to evaluate the hybrid power plant reasonably, the levelized cost of electricity (LCOE) was selected as an indicator for economic analysis and evaluation. According to the literature , its formula can be expressed as:

$$LEC=\frac{crf\cdot K_{\text{invest}}+K_{\text{OM}}+K_{\text{fuel}}}{E_{\text{annual}}} \quad (12)$$

$$crf=\frac{i(1+i)^n}{(1+i)^n-1}+k_{\text{insurance}} \quad (13)$$

Where i represents the actual interest rate; $k_{insurance}$ represents the annual premium, K_{invest} represents the total investment, K_{OM} represents the annual operating management fee, K_{fuel} represents the annual fuel cost, E_{annual} represents the annual net power generation, and n represents the power plant life cycle.

The total investment amount is closely related to the scale of the power plant, solar radiation intensity, geothermal reservoir depth, land and labor costs. The cost of the heat collecting part of the trough solar thermal power station project accounts for more than 55% of the total investment, and the cost of the heat collecting part includes the cost of the solar collector field (trough solar collector), the cost of the heat transfer oil system and the cost of the heat storage system. A stand-alone solar power plant requires a thermal storage system to maintain continuous power production, but the thermal storage system constitutes a large portion of the cost of the heat collection. The HSGP uses geothermal energy as the basis for continuous power generation of the power plant, eliminating the investment in the heat storage system. The main investment of geothermal power plants is concentrated in the initial investment construction, and as the depth of geothermal reservoirs deepens, the cost of geothermal wells continues to increase. Assume that the operation and management cost of the power plant accounts for 8% of the initial investment, the loan interest rate is 7.5, and the life time of the power plant is 30 years. After the solar energy was coupled into the stand-alone geothermal power plant, the LCOE of the HSGP reduced relative to the stand-alone geothermal power plant.

5. CONCLUSIONS

In this paper, the thermodynamic performance of a HSGP in Lhasa was simulated and the following conclusions are drawn:

(1)The HSGP has a more net power output and thermal efficiency than the stand-alone geothermal power plant, which compensates for the influence of the rising ambient temperature on the thermal performance of the power plant. After the solar energy was coupled with the stand-alone geothermal power plant, the power generation capacity increased by 9.40% on the summer solstice and 1.69% on the winter solstice day.

(2)The exergy destruction of each major equipment of the cycle was analyzed and calculated, and the exergy destruction of the evaporator and the solar collector was found to be large. Due to the optical loss and heat transfer loss of the solar collector portion, the exergy efficiency of the HSGP reduced compared to the stand-alone geothermal power plant.

(3)The introduction of LCOE as an evaluation index, economic analysis and evaluation of stand-alone geothermal plant and HSGP, found that the HSGP has a slightly lower cost than LCOE of the stand-alone power plant.

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