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Thermodynamic analysis and optimization of a flash-binary geothermal power generation system

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ABSTRACT

Due to a good behavior of ammonia–water mixture during the two-phase heat addition process, a Kalina cycle using ammonia–water as working fluid is employed to further recover the heat of geothermal water from a flash cycle for geothermal resources. The mathematical model of the flash-binary geothermal power generation system is established to simulate the system under steady-state conditions. The effects of several key thermodynamic parameters on system performance are examined, including flash pressure, ammonia mass fraction of basic solution, ammonia–water turbine inlet pressure and temperature, and pinch point temperature difference in vapor generator. A parametric optimization is carried out to obtain the optimum system performance with the system exergy efficiency as the objective function by genetic algorithm (GA). The results show that the five thermodynamic parameters have significant effects on system performance. There exists optimum flash pressure, ammonia–water turbine inlet pressure and temperature that yield the maximum system exergy efficiency. A higher ammonia mass fraction of basic solution and a lower pinch point temperature difference in vapor generator can obtain a higher system exergy efficiency. By optimization, the optimum system exergy efficiency could reach 37.01% under the given conditions and the maximum exergy loss occurs in the vapor generator.

1. Introduction

Geothermal power generation is one of the most significant methods for utilization of geothermal resources. The geothermal resources include geothermal dry steam, geothermal wet steam and geothermal water. The various geothermal power generation technologies are employed to utilize different geothermal resources effectively.

For the geothermal dry steam condition, the high-temperature and high-pressure dry steam is directly extracted from underground and expands through a steam turbine to drive an electricity generator. As to the geothermal wet steam condition, the wet steam is separated into saturated steam and saturated geothermal water. The saturated steam expands through a steam turbine to generate electricity. The saturated geothermal water can also be used for power generation by employing a flash device, i.e. dropping the pressure of the water in the flash device to yield low-pressure steam. The low-pressure steam continues to expand through a steam turbine to generate electricity. In addition, the flash geothermal power generation system also can be applied for the geothermal water resources. Several researchers have studied the flash geothermal power system. Jalilinasrabady et al. (2012) analyzed a single-flash geothermal power plant in Iran and evaluated a double-flash cycle for power generation to achieve optimum energy utilization. Dagdas (2007) conducted a performance analysis for a double-flash geothermal power plant and examined fundamental characteristics of the plant. Gerber and Maréchal (2012) presented a systematic methodology considering environmental criteria for the optimal design and configuration of different geothermal conversion cycles, including single and double-flash systems. In order to better exploit the geothermal resources potential in Iran, Yari (2010) conducted a comparative study of different geothermal power plant concepts based on the exergy analysis, including the single and double-flash cycles. Luo et al. (2012) made a thermodynamic comparison between a single-flash and a binary cycle geothermal power plant.

In addition, the geothermal water can act as the heat source to heat low-boiling point working fluids in heat exchanger to form high parameter vapor. The high parameter vapor expands through the turbine to generate power. This is called binary cycle geothermal power generation system. A great many of studies have been carried out on the binary cycle. Kanoglu and Bolatturk (2008) performed an exergy analysis for a binary geothermal power plant using actual data to assess the system performance and pinpoint

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Nomenclature

E	exergy, kW
h	enthalpy, kJ kg^{-1}
I	exergy loss, kW
m	mass flow rate, kg s^{-1}
P	pressure, kPa
s	entropy, kJ kg^{-1} K^{-1}
T	temperature, °C
W	power output/consumption, kW
x	ammonia mass fraction, %

Greek symbol

η	efficiency

Subscripts

apl	ammonia-poor liquid
arv	ammonia-rich vapor
AT	ammonia–water turbine
aws	ammonia–water separator
bs	basic solution
cnd	condenser
cw	cooling water
exg	exergy
fd	flash device
i	one certain position in the system
in	input
net	net power output
p	pump
pinch	pinch point temperature difference
reg	regenerator
rgw	re-injected geothermal water
s	isentropic
ST	steam turbine
tb	turbine
v	valve
vpg	vapor generator
0	under ambient conditions

sites of primary exergy destruction. Frick et al. (2010) carried out a life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Franco and Villani (2009) analyzed the exploitation of low-temperature, water-dominated geothermal fields and discussed a methodology for optimizing geothermal binary plants. Ghasemi et al. (2013) developed a model for an existing ORC-based binary geothermal power plant by Aspen Plus software and maximized the net power output of the system. Coskun et al. (2011) investigated the effect of eight thermodynamic parameters on the energetic and exergetic performance of an operational binary geothermal power plant. Shengjun et al. (2011) examined the thermodynamic and economic performance of both subcritical ORC and transcritical power cycle systems for low-temperature geothermal heat source and performed parameter optimizations of the ORC systems using 16 different working fluids with five indicators. DiPippo (2004) made a comparison between the ORC-binary and the Kalina-binary geothermal plant based on the second law of thermodynamics and introduced a methodology to make the comparison of plant efficiencies on common input and environmental conditions. Walraven et al. (2013) investigated and optimized the performance of different types of ORC and Kalina cycle for low-temperature geothermal heat sources. Arslan and Yetik (2011) and Arslan (2011) conducted a thermodynamic optimization for an ORC-binary and a Kalina-binary geothermal power plant respectively by the artificial neural network method.

From mentioned above, in the flash geothermal power generation system, the saturated geothermal water generated in the flasher still contains large amounts of energy. It could be recovered by a binary cycle with low-boiling point working fluids. That is the flash-binary combined geothermal power generation system, which realizes the energy cascade utilization and contributes to raise the utilization efficiency of geothermal resources. Some investigations have been done on the flash-binary combined cycle. Paloso and Mohanty (1993) analyzed the performance of a flashing binary combined cycle for geothermal power generation and compared it with the simple flash plant to assess its thermodynamic potential and economic viability. Kanoglu and Cengel (1999) evaluated the performance and determined the optimum operating conditions of a combined flash-binary design comparing to an existing single-flash geothermal power plant. Dağdaş et al. (2005) proposed a new flash-binary model for the improvement of an existing geothermal power plant and found its optimal operating pressure that achieved the maximum power output. Dağdaş (2011) also investigated the optimal operating conditions of a single flash-binary geothermal power plant and determined the relationship among some thermodynamic parameters for the maximum power output. Pasek et al. (2011) considered four types of organic working fluids to evaluate the performance of a flash-binary geothermal power plant and carried out an optimization on the performance of plant systems.

From the research mentioned above, the flash-binary geothermal power plant usually adopts the organic Rankine cycle (ORC), which has been widely applied in the field of low-grade heat source recovery, to further utilize the heat of the saturated geothermal water from flash device. Another well-known cycle, namely Kalina cycle, which employs ammonia–water mixture as its working fluid, also shows a good performance to utilize the low-grade heat source. Owing to variable evaporation temperature during evaporation process, the ammonia–water mixture can achieve a good thermodynamic match between the heat absorption of working fluid and the heat ejection of heat source, resulting in a decrease in irreversible loss during heat exchange process. Few studies have been carried out on the Kalina cycle-based flash-binary geothermal power generation system.

In this study, we investigate a flash-binary geothermal power generation system that uses a Kalina cycle as bottoming cycle to recover the heat of the saturated geothermal water from the flash device. By establishing the mathematical model to simulate the system under steady-state conditions, we analyzed the effects of several key thermodynamic parameters on the system performance. In addition, a parametric optimization is carried out to obtain an optimal system performance using genetic algorithm.

2. System description

Fig. 1 illustrates the schematic diagram of a flash-binary geothermal power generation system. After exploited from underground, the high temperature and high pressure geothermal water is delivered to a flash device to transformed into two-phase fluid by dropping pressure. The two-phase fluid is separated into steam and liquid. The steam stream is delivered to a steam turbine to drive a generator to produce electricity. The other liquid stream enters a vapor generator to heat the ammonia–water mixture which is the working fluid in Kalina cycle. The ammonia–water is partially vaporized by absorbing heat in the vapor generator. The two-phase ammonia–water mixture is delivered to an ammonia–water separator where the ammonia–water solution is separated into ammonia-rich vapor and ammonia-poor liquid. The ammonia-rich vapor expands to a low pressure through an ammonia–water turbine to drive a generator to generate electricity. The ammonia-poor