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Proposal and thermoeconomic analysis of geothermal flash binary power plants utilizing different types of organic flash cycle

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ABSTRACT

In this work, an enhanced organic flash cycle (EOFC) employing an internal heat exchanger is proposed to be used to further recover the thermal energy of geofluid from a flash cycle for geothermal resources. The proposed flash-binary system is improved by applying two methods One method is usage of two separate flash evaporating steps instead of only one in EOFC (double flash). Another method is replacement of the throttling valve with a two- phase expander. A comprehensive thermoeconomic evaluation is carried out to investigate the effects of four key thermodynamic parameters on system performance. The results show that under the given condition, the net power output increases by 36.7% when two-phase expanders are employed in flash-binary geothermal cycle with single flash EOFC (TBSEOFC). Net power output increases by 1.2% for TBSEOFC by utilization of two separate flash steps in EOFC subsystem. In this case, unit cost of product insignificantly decreases. Moreover, a parametric optimization is conducted to obtain the optimum system performance.

1. Introduction

The inclusion of electricity production from conventional energy sources such as fossil fuels will become inevitably necessary in order to meet increasing global energy demands. Efficient and cost-effective utilization of renewable energy sources such as solar thermal and geothermal energy can lessen the reliance on unclean fossil fuels and reduce the emission of pollutants and potential climate changing agents. Geothermal energy is used to generate electricity and for direct uses such as space heating and cooling, industrial processes, and greenhouse heating. High-temperature geothermal resources (above 150 °C) are generally used for power generation. Moderate temperature (between 90 °C and 150 °C) and lower-temperature (below 90 °C) geothermal resources are best suited for direct uses (Kanoglu and Bolatturk, 2008). The Organic Rankine Cycle (ORC) is a favorite promising system for many researchers to generate power from low and medium temperature heat sources (Mosaffa et al., 2017a; Li et al., 2014; Astolfi et al., 2011; Liu et al., 2017; Proctor et al., 2016). Wei et al. (2007) presented an analysis and optimization of an ORC using R-245fa driven by exhaust waste heat. They showed that for high ambient temperature, the efficiency and generated power worsen possibly exceeding 30% by departing from nominal state. Shokati et al. (2015) compared different types of ORCs including basic, dual fluid and dual pressure ORC driven by geothermal energy from thermodynamic and exergoeconomic viewpoints. Their results showed that in optimal condition, dual pressure ORC generated about 15% and 35% more power than the corresponding values for the basic and dual fluid ORCs. Mosaffa et al., (2017a) applied a thermoeconomic analysis to four geothermal driven ORCs: simple, dual fluid, regenerative and with internal heat exchanger. They concluded that the highest first and second laws efficiencies are obtained for regenerative ORC while the maximum net power output is generated by dual fluid ORC at the same operating condition.

Blade reinforcing materials of turbine and hence turbine cost can be significantly reduced by using isentropic or dry working fluids in ORCs. Because, in these cases, a saturated vapor is expanded out to the saturation dome due to the infinite or positively sloped saturated vapor curve for isentropic and dry fluids, respectively (Wang et al., 2010). Also, temperature matching to the low grade thermal energy source is a major challenge while heat is transferred to the working fluid of ORCs. Temperature matching to the energy source plays an important role in reducing irreversibilities caused by heat transfer through a finite tem-

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Nomenclature

A	Heat transfer area (m^2)
c	Unit cost of exergy ($ kW^{-1})
C	Capital cost ($)
$\dot{C}$	Cost rate ($ s^{-1})
$\dot{E}x$	Exergy rate (kW)
i	Annual interest rate
IHE	Internal heat exchanger
h	Specific enthalpy (kJ kg^{-1})
HPT	High pressure turbine
LPT	Low pressure turbine
$\dot{m}$	Mass flow rate (kg s^{-1})
n	System life time (year)
OFC	Organic flash cycle
ORC	Organic rankine cycle
P	Pressure (kPa)
$\dot{Q}$	Heat rate (kW)
s	Specific entropy (kJ kg^{-1} K^{-1})
T	Temperature (K)
$\dot{W}$	Power (kW)
$\dot{Z}$	Capital cost rate ($ s^{-1})

Greek symbols

ε	Thermal effectiveness of heat exchanger
ϕ	Maintenance factor
η	Efficiency
φ	Availability of transferred heat (kW)
τ	Operational time in a year (s)
ψ	Flow availability (kJ kg^{-1})

Subscripts

0	Ambient
c	Condenser
cw	Cooling water
D	Destruction
ep	Two-phase expander
en	Energy
ex	Exergy
f	Flashing temperature
fs	Flashing separator
gf	Geofluid
hf	High flashing temperature
lf	Low flashing temperature
p	Pump
s	Isentropic
t	Turbine
tv	Throttling valve

perature difference (Vargas and Bejan, 2000). Ho et al. (2012a) proposed that due to the near perfect temperature matching, heat is transferred from thermal energy source to the ORC until the working fluid reaches a saturated liquid state. This saturated liquid would then be throttled to produce a two-phase mixture and allowed to enter the separator. The saturated vapor is separated and then expanded in a turbine to generate power. This cycle was named the Organic Flash Cycle (OFC). Also, they proposed several methods to enhance the OFC performance (Ho et al., 2012b). They conducted the theoretical analysis using the Span-Wagner, BACKONE and REFPROP equations of state and examined ten aromatic hydrocarbon working. The results showed that greatest efficiency obtains when the flash evaporation throttling valve replaces with a two-phase expander. In this case, the utilization efficiency increased by 5%-20% over the optimized ORC. Mondal and De (2016) conducted a comparison study between a transcritical CO_2 power generation cycle and OFC from the thermodynamic and economic points of view. Lee et al. (2016) presented a thermodynamic performance and optimization analyses for basic OFC, OFC with two-phase expander and ORC with different working fluids. The results showed that in OFC with two-phase expander, higher evaporating temperature leads to a reduction in steam content of the saturated mixture in the separator. Therefore, mass flow rate of working fluid reduces at turbine, and leads to higher temperature at the turbine exit.

In a flash geothermal power plant, the vapor and liquid phase of high temperature and high pressure geofluid is separated using flash device by dropping pressure. Saturated vapor extracted from separator is used to drive a turbine to produce power. Dagdas (2006) performed a thermodynamic analysis for a hypothetical double flash geothermal power plant and examined variations of fundamental characteristics of the plant. Yari (2010) presented a comparative study and optimization of single and double flash geothermal power plant based on the first and second laws of thermodynamic analyses. Gerber and Maréchal (2012) conducted a methodology for the optimal configuration and design of different geothermal driven cycles, including single and double flash systems.

In the flash geothermal power plant, the saturated geofluid generated in the separator still contains considerable amounts of energy. It can be recovered by a binary cycle which driven by low grade heat source. That is called flash-binary geothermal power plant. Dağdaş et al. (2005) performed a thermodynamic optimization of an existing geothermal power plant using real data. They estimated optimum flashing pressure and found that generated power increases by 18% when the cycle operates at this state. Dagdas (2011) investigated the optimal operating conditions of a single flash-binary geothermal power system to determine the relationship between flash evaporating pressure, total heat transfer area of the heat exchanger and turbine inlet pressure of the binary cycle for maximization of generated power of the plant. Pasek et al. (2011) conducted the performance evaluation of a geothermal flash–binary cycle with four types of organic working fluids. They also discussed the limitation factor to reach maximum net power including: flash evaporating pressure, evaporator pressure and thermal design in heat exchangers. Wang et al. (2015) investigated a flash-binary geothermal power generation system by utilizing a Kalina cycle as bottoming cycle. They concluded that the flash pressure, inlet pressure and inlet temperature of turbine in Kalina subsystem, mass fraction of basic solution and pinch point temperature difference in evaporator have significant effects on system performance.

Exergy analysis is major methodology in designing and optimization of thermodynamics cycles. Exergy analysis is now a vital for determining the system's inefficient components in terms of exergy destruction, i.e., the depreciation of the system's ability to produce work with respect to its surroundings (Dincer and Rosen, 2013). Bodvarsson