Energy Conversion and Management 143 (2017) 377–390

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Exergoeconomic analysis and multi-objective optimization of a novel combined flash-binary cycle for Sabalan geothermal power plant in Iran

A. Aali [a], N. Pourmahmoud [b], V. Zare [a,*]

[a] Faculty of Mechanical Engineering, Urmia University of Technology, Urmia, Iran
[b] Mechanical Engineering Department, Faculty of Engineering, Urmia University, Urmia, Iran

ARTICLE INFO

Article history:
Received 27 December 2016
Received in revised form 5 April 2017
Accepted 7 April 2017

Keywords:
Exergoeconomic
Flash-binary cycle
Geothermal energy
Optimization
Organic Rankine cycle
Sabalan geothermal field

ABSTRACT

Employing high-efficiency thermodynamic cycles for power generation from available heat sources is an effective strategy for sustainable energy development. In this regard in the present work, a novel combined flash-binary cycle is proposed for power generation from Sabalan geothermal wells in Iran, considering the wellhead temperature and pressure differences of existing wells. Exergoeconomic approach is applied to investigate the proposed system performance from the viewpoints of both thermodynamics and economics. Using the real data and properties of brine exploited from Sabalan geothermal field, the cycle performance is assessed and a single-objective optimization is performed considering the specific cost of output power as the objective function for four candidate working fluids for binary unit. Then, a multi-objective optimization is conducted and the Pareto frontier as a set of optimal solutions is presented. The results showed that, when single-objective optimization is performed, the proposed cycle with R141b as the binary unit working fluid has the best performance for which the specific cost of output power is calculated to be 4.901 \$/GJ with an exergy efficiency of 52.56%. However, the multi-objective optimization leads to an exergy efficiency of 54.87% and a power cost of 5.068 \$/GJ at the selected optimal design point. Finally, a performance comparison is made between the proposed cycle in this work with the previously proposed systems for Sabalan geothermal reservoirs and it is concluded that the flash-binary system proposed here has significantly better performance than the previous systems.

1. Introduction

In recent years, renewable energy sources have received enormous interest due to the environmental impacts of fossil fuels. Of particular interest among the renewable energies, is geothermal one for its reliability, sustainability and high capacity factor. Geothermal energy, has been identified as a renewable energy source which comes from beneath the earth with varying temperatures from 50 to 350 °C [1].

There are four main kinds of geothermal resources including: hydrothermal, geopressured, hot dry rock and magma among which hydrothermal resources are the only kind in wide use. Depending on the geological conditions, hydrothermal resources may come in the form of either vapor-dominated or liquid-dominated. Liquid-dominated reservoirs are more common and the flash cycles [2,3] and binary cycles [4–6] are common systems to utilize these sources for power generation. Flash systems are favorable for relatively higher temperature resources while binary systems are proper for lower temperature resources [7]. Shokati et al. [2] analyzed and compared double flash and single flash/ORC combined cycles for geothermal power generation and reported that the double flash cycle has lower unit cost of produced power. The potential of ORCs for the exploitation of low temperature geothermal brine is investigated by Astolfi et al. [5], from thermodynamic and economic viewpoints and their results confirmed the primary importance of techno-economic optimization in the evaluation of ORC geothermal plants. Walraven et al. [6] analyzed the performance of different ORC types and the Kalina cycle, as binary units, for low-temperature (100–150 °C) geothermal heat sources and indicated that trans-critical and multi-pressure subcritical ORCs are in most cases the best cycles outperforming the Kalina cycle.

In order to maintain the increasing interest for geothermal power generation and reduce the cost per kW of output power, introducing novel systems with higher energy conversion efficiency is essential. Although, the single flash steam cycles are adopted as the most common geothermal power generation systems, however, various thermodynamic cycles such as; double flash cycles, combined flash-binary cycles and integrated

* Corresponding author.
E-mail address: v.zare@uut.ac.ir (V. Zare).

http://dx.doi.org/10.1016/j.enconman.2017.04.025
0196-8904/© 2017 Published by Elsevier Ltd.

Nomenclature

$\dot{C}$	cost rate ($ h^{-1})
c	specific exergy cost ($ GJ^{-1})
$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ kg^{-1})
i_r	interest rate
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (bar)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C or K)
$\dot{W}$	power (kW)
Z	investment cost of components ($)
$\dot{Z}$	investment cost rate of components ($ h^{-1})

Subscripts and abbreviations

0	ambient
CI	capital investment
CRF	capital recovery factor
D	destruction
GPP	geothermal power plant
HPT	high pressure turbine
HTW	high temperature well
LTW	law temperature well
LPT	low pressure turbine
OM	operation and maintenance
ORC	organic Rankine cycle
P	pump
Ph	physical
PP	pinch point
PEC	purchased equipment cost

Greek symbols

τ	annual plant operation hours
η_{th}	thermal efficiency
η_{ex}	exergy efficiency
η_P	pump isentropic efficiency
η_T	turbine isentropic efficiency

flash-binary systems have been proposed and analyzed recently. The combined flash-binary cycle is proved to be an efficient system to yield high efficiency for Geothermal Power Plants (GPPs) [8] and a number of papers are published in this regard. Coskun et al. [7] compared the performance of double-flash, binary, combined flash-binary and Kalina cycles for low temperature geothermal reservoirs and concluded that the combined flash-binary cycle has the highest energy conversion efficiency. Performance of a combined flash-binary cycle for medium temperature geothermal fields is investigated by Zeyghami [8], who reported exergy efficiencies of 48%, 55% and 58% for geofluid temperatures of 150, 200 and 250 °C, respectively. The performance of a binary-flash cycle for low temperature geothermal resources (90–160 °C) is analyzed by Edrisi and Michaelides [9,10], who examined the effects of employing different working fluids for binary unit and reported that, pentane is one of the suitable working fluids for this system. Zhao and Wang [11] conducted exergoeconomic analysis of a single flash-binary GPP and optimized the system performance with respect to the cost per unit of product exergy. Their results showed that the significant improvement in system's economy can be achieved at the expense of a slight diminishment in system's thermodynamic performance. Wang et al. [12] examined the performance of a Kalina cycle for the binary unit of a flash-binary GPP and conducted a parametric optimization for exergy efficiency as the objective function. They showed that the optimum system exergy efficiency could reach 37.01% under the given conditions. For a geothermal brine temperature of 170 °C, the performance of a binary-flash geothermal system from the viewpoint of the first thermodynamics law, is analyzed by Pasek et al. [13], who reported a thermal efficiency of 12.29% and a utilization efficiency of 23.06% for the considered system. Yilmaz et al. [14] proposed a combined flash-binary geothermal plant, the power of which is used for hydrogen production by water electrolysis. A geothermal resource temperature of 200 °C with a flow rate of 100 kg/s is considered and thermodynamic and exergoeconomic analyses are performed. They reported an exergy efficiency of 46.6% for the power plant and a unit exergetic cost of electricity of 4.76 and 3.35 $/GJ for the generated power of binary and flash turbines.

In recent years, the performance of operating or under construction GPPs are assessed thermodynamically, using the real site data, to pinpoint the sources of inefficiencies or to propose more efficient thermodynamic cycles. In this respect, Agung et al. [15] analyzed the performance of the single-flash system that is applied for Dieng GPP in Indonesia. They reported an exergy efficiency of 36.48% and an amount of 21.71 MW power generation for the operating plant. In another research work [16], they proposed a double-flash system for the Dieng GPP and compared it with the existing single-flash system and concluded that the double-flash system power output and exergy efficiency are 29.155 MW and 44.04%, respectively. For a geothermal resource in New Zealand with brine temperature of 173 °C and flow rate of 8 kg/s, Budisulistyo and Krumdieck [17] proposed and compared different cycle configurations and concluded that the most technically and economically favorable system is an ORC with a two stage turbine and n-pentane as the working fluid. Using advanced exergy method, performance of Bereket GPP in Denizli-Turkey, as an operating system, is evaluated by Yürüsoy and Keçebas [18], who reported an exergy efficiency of 9.60% for the system and indicated that it can be increased up to 15.40% by making improvements in the system components. For a geothermal resource available in Turkey with brine temperature of 240 °C, Ates and Serpen [19], analyzed and compared five cycle configurations and concluded that the single flash-binary combined cycle works better than the other investigated systems.

Sabalan geothermal field located in northwest Iran is currently under development for which the reservoir numerical modeling has shown a potential of providing enough steam for a 55 MW GPP. For this geothermal field, at the pre-feasibility study stage, a single flash cycle has been selected as the power generation unit for which Jalilinasrabadi et al. [20] reported a maximum exergy efficiency of 32.7%. They also compared the double flash system performance with the single flash one and reported an exergy efficiency of 43.3% for the double flash system.

The aim of the present work is to design and propose a new configuration of combined flash-binary cycle which can efficiently utilize the available heat source energy in Sabalan geothermal field. At this geothermal field, there are high and low-temperature (pressure) brines with specified properties, so the proposed system is designed in such a way that it can efficiently employ the available brines of existing wells. The performance of the proposed system is assessed from the viewpoints of both thermodynamics and eco-