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Performance optimization and improvement of a flash-binary geothermal power plant using zeotropic mixtures with PSO algorithm

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a novel approach for optimizing and also improving a flash-binary geothermal power plant whose binary cycle is an organic Rankine cycle (ORC) which is using various combinations of zeotropic mixtures as working fluid. All of the obtained results are optimized with particle swarm optimization (PSO) method for maximum total output power which is the objective function of the problem. First, the optimization is performed in the certain amounts of mixtures' mass fractions. Then, the optimal values for the mass fractions are found. The results indicate that Pentane containing combinations show better performances. For instance, when the ORC unit is using the mixture of Pentane(0.45)/Butane(0.55) the highest output power is gaining: 1376.87 (kW) from the ORC unit and 5726.44 (kW) from the whole system. Also, the highest improvements in utilization of zeotropic mixture instead of pure fluids are obtained by this mixture which are 18.769 (%) with respect to ORC's output power and 3.950 (%) with respect to total output power. Finally, an investigation on flash chamber pressure effect on the system performance is accomplished and the results reveal that with increasing the pressure, the total output power decreases. Although lower flash chamber pressure seems to be a suitable choice, the investigation on the size parameters (SP) of the turbines shows that it is better to choose a mean amount of pressure for the flash chamber, thereby having the affordable amounts for the size parameters and also obtaining an adequate amount of total output power.

1. Introduction

In the last several years, environmental issues such as ozone layer depletion and global warming have caused energy policy considerations for the nations. The increasing attention to pollutants and greenhouse gases emission from the power generation sector and the concerns about fossil fuels supply and price have been leading to a massive growth of those technologies that can produce electric energy from renewable sources and waste heat recovery (Astolfi et al., 2014a). Renewable energies like bioenergy, solar, wind or geothermal are widely used nowadays, while researching for novel and efficient energy systems development is one of main interests of researchers (Dincer, 2000). When the temperature and/or the thermal power available from the energy source is limited, it becomes attractive to adopt a different class of prime movers, universally known with the acronym ORC (Organic Rankine Cycle) (Macchi and Astolfi, 2016). Organic Rankine cycle is one of the effective and promising technologies, which allows utilizing low-medium temperature energy resources for power production (such as geothermal sources) (Tchanche et al., 2011).

Geothermal energy is a sustainable and low-grade heat source which can be considered as a potential energy source for ORCs (Shortall et al., 2015). Between different types of geothermal power plants, binary and combined flash-binary plants are more preferable then others. Yari (2010) compared various types of geothermal power plants from the perspective of energy and exergy analysis and concluded that the flash-binary cycle with R123 working fluid where the temperature and mass flow rate of geothermal heat source are 230 (°C) and 1 (kg/s), respectively, has the maximum thermal efficiency (11.81%) which is the highest amount between various configurations. Jalilinasrabady and Itoi (2012) compared three configurations of single-flash, double-flash and binary ORC plant; based on their results, the highest output power belongs to binary ORC plant. Utilization of double-flash, binary cycle, combined flash-binary, and Kalina cycle in a geothermal energy resource, are compared in the work of Coskun et al. (2014) from the perspectives of thermodynamic and economic analyses. Based on this research, in double flash and combined plants, flash chamber and turbine inlet pressures are separately optimizing the power generation. An exergoeconomic comparison between single and double-flash-ORC combined cycles is carried out by Shokati et al. (2015). They concluded that the highest energy and exergy efficiencies belong to single-flash-

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Abbreviations

Abbreviations

GWP	global warming potential (year)
ODP	ozone depletion potential
ORC	organic Rankine cycle
PSO	particle swarm optimization

Greek letters

η	efficiency (%)
ε	effectiveness of heat exchangers (%)

Symbols

$\dot{E}$	exergy (kW)
$\dot{E}_D$	exergy destruction (kW)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat absorbed or released (kW)
$\dot{W}$	output power (kW)
C	thermal conductivity (W/(m K))
D	vapor density of equilibrium phase
h	specific enthalpy (kJ/kg)
I_x	improvement of the parameter x (%)
m_f	mass fraction of fluid^{I} in fluid^{I}/fluid^{II} (kg/kg)
MM	molar mass (g/mol)
P	pressure (MPa)
s	specific entropy (kJ/(kg K))
SP	turbine size parameter (kW)
T	temperature (K)
V	dynamic viscosity (Pa s)
w	specific work (kJ/kg)

Subscripts

$C1$	condenser 1
$C2$	condenser 2
cr	critical point
Ev	evaporator
I	energy efficiency
II	exergy efficiency
in	inlet
OT	ORC's turbine
out	outlet
P	pump
pp_{C2}	condensation pinch point
pp_{Ev}	evaporator pinch point
ST	steam turbine
tot	total

ORC combined cycle. Yilmaz et al. (2015) produced hydrogen by a flash-binary geothermal power plant and stated that 0.0498 (kg/s) of hydrogen can be produced by a geothermal heat source at the temperature of 200 (°C) and mass flow rate of 100 (kg/s). Zeyghami (2015) conducted a comprehensive study on working fluid selection for a combined flash-binary geothermal system and concluded that for each working fluid there is an optimum separator pressure which maximizes system efficiency and minimizes the exergy destruction. Also, it realized that some of the working fluids are more suitable in different ranges of geothermal sources' temperatures. Zhao and Wang (2016) investigated a flash-binary geothermal power plant which was utilizing an ORC system as a binary unit and also studied different design variables on exergoeconomic performance of system; their results implied that the best thermodynamic performance of the system could not lead to the best exergoeconomic results and vice versa.

High values of exergy destruction, especially in evaporator is one of the major problems in the ORC systems that the temperature mismatching between hot and cold streams is the main source of exergy destruction (Venkatarathnam et al., 1996). Some practical solutions for decreasing the exergy destruction in the evaporator of the ORCs are utilization of transcritical cycles, trilateral cycles, flash cycles, two-stage cycles and also using zeotropic mixtures as working fluid of the system. One of the most interested method in the studies of the recent years is selection of zeotropic mixtures as working fluid which are some combinations of different pure fluids. Phase change process of the zeotropic mixtures is not an isothermal process and it leads to different temperatures for saturated liquid and vapor in a specific pressure. Chys et al. (2012) investigated the potential of zeotropic mixture for using as working fluid in ORC systems which are powered by a geothermal heat source; and concluded that utilizing zeotropic mixture instead of pure fluid at the temperatures of 150 and 250 (°C) of the geothermal source, increases the thermal efficiency about 16 and 6 (%), respectively. Heberle et al. (2012) used organic Rankine cycles for power production from low-enthalpy heat sources by zeotropic mixtures with the combinations of Isobutane/Isopentane and R227ea/R245fa; from their results for the heat source temperatures of below 120 (°C), the increment of exergy efficiency is about 15 (%) for mixtures in comparison to the pure fluids. In the other research work, Lecompte et al. (2014) analyzed the influence of zeotropic mixtures on the exergetic performance of a geothermal powered ORC system. They stated that by using zeotropic mixtures instead of pure fluids, the exergy efficiency can be improved between 7.1 and 14.2 (%). The influence of zeotropic mixtures on the performance of a supercritical ORC system for power production from low temperature geothermal heat source was investigated by Radulovic and Castaneda (2014). Based on their results, the thermal efficiency of the system in utilization of a zeotropic mixture instead of pure R-143a can be improved by 15 (%) at the same operational conditions. Zhang et al. (2014) designed a regenerative organic Rankine cycle system whose working fluids were pure R245fa and the mixture of Isopentane/R245fa with mass fraction of 0.7/0.3, to recover the exhaust heat of a diesel engine. The results showed that the zeotropic mixture performs better and for the combined system of ORC and the diesel engine, 10.54% and 9.55% of improvements can be obtained in power output and fuel economy, respectively. Habka and Ajib (2015) examined different zeotropic mixtures in an ORC system for geothermal water heat recovery. They concluded that in both cogeneration and simple systems, zeotropic mixtures show better performance than pure fluids and also, in each temperature values of geothermal water, different mixtures are preferable from the perspective of power production. The effect of 10 groups of mixtures on the ORC system performance was investigated by Kang et al. (2015). They found that the combination of R245fa/R600a with the mass fraction of 0.9/0.1 is the most preferable working fluid for power production. Performance of a geothermal organic Rankine cycle by zeotropic mixture working fluids is studied by Yue et al. (2015). From their results the mixture of Isobutane/Isopentane with the with the mass fraction of 0.8/0.2 at the evaporator pinch point temperature difference of 16 (K) shows the best first and second law performances. The effect of different zeotropic mixtures on various configurations of geothermal powered ORC systems was studied by Sadeghi et al. (2016). Based on their results, zeotropic mixtures in comparison to a pure fluid such as R245fa, increase the power production about 24.79 to 27.76 (%) in different configurations of the ORC system.

The presented brief review on the literature indicates that most of