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Thermodynamic, economic and thermo-economic optimization of a new proposed organic Rankine cycle for energy production from geothermal resources

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ABSTRACT

The main goal of this study is to propose and investigate a new organic Rankine cycle based on three considered configurations: basic organic Rankine cycle, regenerative organic Rankine cycle and two-stage evaporator organic Rankine cycle in order to increase electricity generation from geothermal sources. To analyze the considered cycles' performance, thermodynamic (energy and exergy based on the first and second laws of thermodynamics) and economic (specific investment cost) models are investigated. Also, a comparison of cycles modeling results is carried out in optimum conditions according to different optimization which consist thermodynamic, economic and thermo-economic objective functions for maximizing exergy efficiency, minimizing specific investment cost and applying a multi-objective function in order to maximize exergy efficiency and minimize specific investment cost, respectively. Optimized operating parameters of cycles include evaporators and regenerative temperatures, pinch point temperature difference of evaporators and degree of superheat. Furthermore, Peng Robinson equation of state is used to obtain thermodynamic properties of isobutane and R123 which are selected as dry and isentropic working fluids, respectively. The results of optimization indicate that, thermal and exergy efficiencies increase and exergy destruction decrease especially in evaporators for both working fluids in new proposed organic Rankine cycle compared to the basic organic Rankine cycle. Moreover, the amount of specific investment cost in new organic Rankine cycle is obtained less than basic organic Rankine cycle during thermodynamic and economic optimization for R123. Finally, a profitability evaluation of new proposed and basic systems is performed based on total production cost and return on investment for three countries: Iran, France and America. Its results show that Iran has the maximum amount of return on investment.

1. Introduction

Geothermal energy, as a low-grade heat source, could be used to produce and convert energy into useful work (i.e., electricity) by using organic Rankine cycle (ORC) technology [1]. This technology is based on principles of renewable energy, in which it could reduce the emission of greenhouse gases (GHGs) caused by fossil fuels. In other words, an ORC is widely used in the geo-plant in order to generate power in an environment friendly manner [2].

In such systems, at first water is injected into the ground, which its injection wells were calculated geometrically and adsorbs the certain amount of heat from the ground layers (geothermal energy). Then, hot water is pumped from production wells to an evaporator. In the evaporator, heat is transferred from the hot water to an organic fluid which is also known as "working fluid". As a result, the working fluid in the evaporator is vaporized or even superheated according to the amount of heat it takes. In the next stage, the saturated or superheated vapor expands through a turbine and produces electricity by an electrical generator which is transferred mechanical energy into electrical type. Afterwards, the expanded vapor is cooled by a condenser to liquefy and finally, to complete the cycle, working fluid is pumped to the evaporator [3].

Generally, the ORC system performance could be specified by thermodynamic efficiency which depends on several parameters, for instance the operating conditions, types of working fluids, the system components and also cycle configuration [4]. Accordingly, in recent decades, in order to improve the performance and

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Nomenclature

A	heat exchanger surface area
$\dot{Ex}$	exergy flow rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{I}$	flow rate of destroyed exergy (or irreversibility) (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (bar)
$\dot{Q}$	heat transfer flow rate (kW)
S	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
$\dot{W}$	power output/input (kW)
X	vapor quality
SIC	specific investment cost ($/kW)
PPTD	pinch point temperature difference (°C)
ROI	return on investment (%)
ORC	organic Rankine cycle
RORC	regenerative organic Rankine cycle
TSORC	two stage evaporator organic Rankine cycle
NORC	new proposed organic Rankine cycle

Greek letters

α	coefficient of linear weighted evaluation function
β	coefficient of linear weighted evaluation function
η	efficiency (%)

Subscripts/superscripts

cond	condenser/condensation
evap	evaporator/evaporation
t	turbine
p	pump
in/out	inlet/outlet
i/o	inside/outside
is	isentropic
hsi/hso	heat source (or geothermal water) inlet/outlet
csi/cso	heat sink (or cooling water) inlet/outlet
tot	total
h/c	heat source/sink or hot/cold
wf	Working fluid
elec	electrical
gen	generator
reg/regen	regenerative

increase the efficiency of ORC system, various studies have been considered which include the investigation of different working fluids effect, the optimization of operating parameters with an appropriate objective function such as thermodynamic, economic or thermo-economic and also variations in the cycle configuration.

In this respect, Yang and Yeh [5] analyzed an ORC system performance by using economic optimization. Their results showed that R600 gave the best performance under economic optimization among working fluids which have the lower global warming potential (GWP) like R290, R600a, R1233zd, R1234yf and R1234ze. Also, the pinch point temperature differences in the evaporator altered more compared to the condenser.

Shokati et al. [6] carried out a comparative study in order to investigate an exergoeconomic analysis by optimization of basic, dual-pressure and dual-fluid ORCs and Kalina for geothermal applications in power plants. They optimized parameters of mentioned cycles in order to maximize the energy production and minimize the cost of power generation. Their optimization results showed that dual-pressure ORC generated the maximum value of electricity and also Kalina cycle had the minimum value of unit cost of power produced.

Yang and Yeh [7] used thermo-economic optimization in order to evaluate the performance of R245fa, R1234yf, R1234ze, R152a, and R600a as working fluids in ORC systems. The results illustrated that R1234yf gave the best performance in thermo-economic investigation among all considered working fluids.

Dai et al. [8] investigated the performance of ORC for different working fluids using genetic algorithm. In their study, exergy efficiency was chosen as an objective function to optimize operating parameters including inlet temperature and pressure of the turbine. They found, the working fluid R236EA has the highest exergy efficiency (35.43%) and thermal efficiency (12.37%).

A research was carried out by Xi et al. [9] in order to maximize the exergy efficiency of ORC using single or double-stage regenerative. They presented that an ORC with two-stage regenerative had higher exergy efficiency comparing to a basic ORC. Roy and Misra [10] optimized different parameters and analyzed the performance of a regenerative organic Rankine cycle (RORC) for waste heat recovery. They recognized, the performance of R123 as a working fluid is better than R134a for this specified cycle within a superheating at a constant pressure of 2.5 MPa. Thermo-economic optimization of RORC in order to recover the amount of heat losses were investigated by Imran et al. [11]. The results of optimization showed that R245fa is the best possible working fluid under their cycle conditions and also, the thermal efficiency of ORC was improved by adding a regenerative to the cycle.

Li et al. [12] optimized the operating parameters of a two-stage evaporator organic Rankine cycle (TSORC). Their studies showed that the system performance would increase with geothermal water inlet temperature and different range of evaporator temperature. Moreover, they figured out the irreversible losses would decline to a minimum value in the evaporator by using two-stage evaporator within two different temperature range. Li et al. [13] investigated the performance of the ORCs in order to use two stage evaporation strategies (parallel and series). In their research, R245fa and geothermal water with a temperature range of 90–120°C were selected as working fluid and heat source, respectively. Although, they recognized both strategies could reduce the system irreversibility, significant reduction was found in series two-stage evaporator. Li et al. [14] proposed an ORC with double parallel evaporator which their research results stated a decrease in irreversible energy loss and an increase in production capacity from geothermal resources.

Zare [15] evaluated the performance of three different configurations (basic ORC, regenerative ORC and an ORC within an internal heat exchanger) through thermodynamic and exergoeconomic optimization. The results illustrated that although the ORC within an internal heat exchanger gave a premier performance in thermodynamic optimization, basic ORC showed the best behavior in economic optimization compared to the other considered cycles.

In this paper, three different points of view, including the change in basic ORC configuration (a new arrangement of the cycle equipment), optimization of cycles operating parameters by using three different objective functions (thermodynamic, economic and thermo-economic) and survey of the effect of various working fluids are considered to improve and increase the efficiency of a basic ORC. In other words, the restructuring of basic ORC equipment has been investigated by adding an evaporator and a regenerative, simultaneously. Also, three selected objective functions have been applied to optimize heat exchangers temperatures (excluding