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Thermodynamic and economic analysis and optimization of power cycles for a medium temperature geothermal resource

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ABSTRACT

Geothermal power generation technologies are well established and there are numerous power plants operating worldwide. Turkey is rich in geothermal resources while most resources are not exploited for power production. In this study, we consider geothermal resources in Kutahya–Simav region having geothermal water at a temperature suitable for power generation. The study is aimed to yield the method of the most effective use of the geothermal resource and a rational thermodynamic and economic comparison of various cycles for a given resource. The cycles considered include double-flash, binary, combined flash/binary, and Kalina cycle. The selected cycles are optimized for the turbine inlet pressure that would generate maximum power output and energy and exergy efficiencies. The distribution of exergy in plant components and processes are shown using tables. Maximum first law efficiencies vary between 6.9% and 10.6% while the second law efficiencies vary between 38.5% and 59.3% depending on the cycle considered. The maximum power output, the first law, and the second law efficiencies are obtained for Kalina cycle followed by combined cycle and binary cycle. An economic analysis of four cycles considered indicates that the cost of producing a unit amount of electricity is 0.0116 $/kW h for double flash and Kalina cycles, 0.0165 $/kW h for combined cycle and 0.0202 $/kW h for binary cycle. Consequently, the payback period is 5.8 years for double flash and Kalina cycles while it is 8.3 years for combined cycle and 9 years for binary cycle.

1. Introduction

The rising energy demand, the limited supply of fossil fuels and their detrimental environmental impacts (e.g. global warming) have intensified the worldwide search for cleaner sources of energy. Among renewable energy sources, geothermal energy has a special place largely because of its vast worldwide resources and its capacity to provide base-load electricity due to non-intermittent nature of geothermal energy [1].

Geothermal heat comes from beneath the earth surface with temperatures varying between 50 and 350 °C. It occurs mainly in the form of steam, mixtures of steam and water or just liquid water [2].

In literature, there are many studies related to analysis of geothermal power plants. Aneke et al. [2] investigated the IPSEpro model of the Chena Geothermal Organic Rankine Cycle (ORC) Power Plant and the results are validated using actual data. IPSEpro is modular-mode as well as equation-oriented steady state energy simulation software. The validated model was used to investigate the effect of variation in the geothermal source temperature on plant performance. The analysis showed that an increase in the geothermal source temperature above the design point increases the working fluid flow rate, decreases the working fluid degree of superheat at the inlet of the turbine (evaporator exit), increases the plant net power output, and reduces the efficiency. Kanoglu and Bolatturk [3] studied a binary geothermal power plant exergetically using actual plant data to assess the plant performance and pinpoint sites of primary exergy destruction. In this study, the energy and exergy efficiencies of the plant were obtained to be 4.5% and 21.7%, respectively. Also, the effects of turbine inlet pressure and temperature and the condenser pressure on the exergy and energy efficiencies, the net power output and the brine reinjection temperature are investigated and the trends are explained.

Gabbrielli [4] proposed a novel approach for the design point selection of small scale ORC binary geothermal power plants. Four design points relative to different values of the brine temperature during geothermal well exploitation have been compared from the economic point of view using off-design simulations of the whole operating life. In particular, the large increase of the R134a mass flow rate and, consequently, of the highest pressure implies severe modifications of the expander outlet. Yari [5] investigated the different geothermal power plant concepts, based on the exergy anal-

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Nomenclature

COE	capital cost per unit energy ($/kW h)
C	the total expenditure amount including escalation ($)
$C_{capital}$	constant annual capital cost ($)
C_{CE}	constant expenses ($/kW year)
C_{esc}	the amount of total escalation expenditure ($)
$C_{non\text{-}esc}$	the amount of non-escalation expenditure ($)
$C_{O\&M}$	annual operation and maintenance expense ($)
C_{plant}	the amount of physical construction ($)
C_{surf}	unit cost for surface equipment ($/kW)
C_{total}	total cost (M$)
C_{unit}	unit cost of plant ($/kW)
e	specific exergy (kJ/kg)
e_r	escalation rate (%)
$\dot{E}$	exergy rate (kW)
E_e	annual electrical energy production amount (MW h)
E_p	unit price of electricity ($/kW h)
E_{per}	percentage of annual expenditure during construction (%)
f	average annual producer prices inflation (%)
HTR	high temperature recuperator
h	specific enthalpy (kJ/kg)
i	annual interest rate (%)
$i*$	the interest rate including inflation rate (%)
$\dot{I}$	exergy destruction (kW)
L_f	load factor (%)
LTR	low temperature recuperator
$\dot{m}$	mass flow rate (kg/s)
n	lifetime of the power plant (year)
$PWF_{O\&M}$	present value of annual operation and maintenance expenses ($)
$PWF_{capital}$	present value of the capital cost ($)
ORC	Organic Rankine cycle
$\dot{Q}$	heat flow rate (kW)
SPP	payback periods (year)
s	specific entropy (kJ/kgK)
T	temperature (°C)
t	escalation period (year)
$\dot{W}_{net}$	net power (kW)
η_{th}	thermal efficiency
η_e	exergetic efficiency

Subscripts

0	dead state
Cond	condenser
f	saturated liquid
geo	geothermal fluid
HE	heat exchanger
in	inlet
p	pump
pp	pinch point
r	reversible
t	turbine
out	outlet
reinj	reinjection

ysis for high-temperature geothermal resources. In this study, the considered cycles are a binary geothermal power plant using a simple ORC, a binary geothermal power plant using an ORC with an internal heat exchanger (IHE), a binary cycle with a regenerative ORC, a binary cycle with a regenerative ORC with an IHE, a single-flash geothermal power plant, a double-flash geothermal power plant and a combined flash-binary power plant. With respect to each cycle, a thermodynamic model had to be developed. The performance of each cycle has been discussed in terms of the second-law efficiency, exergy destruction rate, and first-law efficiency. The maximum first-law efficiency was obtained to be 7.7% for the ORC with an IHE with R123 as the working fluid. The first-law efficiency based on the energy input to the ORC in binary cycle with the regenerative ORC with an IHE and R123 as the working fluid is 15.4%. The value for the flash-binary with R123 as the working fluid was 11.8%.

Hettiarachchi et al. [6] investigated a cost-effective optimum design criterion for ORC utilizing low-temperature geothermal heat sources. The optimum cycle performance is evaluated and compared for working fluids that include ammonia, HCFC123 and *n*-Pentane. Ammonia has minimum objective function and maximum geothermal water utilization, but not necessarily maximum cycle efficiency.

DiPippo [7] presented the second law assessment of binary plants generating power from low-temperature geothermal sources. The results show that binary plants can operate with high second law or exergetic efficiencies even when the motive fluids are low-temperature and low-exergy. Exergetic efficiencies of 40% or higher have been achieved in certain plants. The main design feature leading to a high second law efficiency lies in the design of the heat exchangers to minimize the loss of exergy during heat transfer processes. Shengjun et al. [8] investigated the parameter optimization and performance comparison of the fluids in subcritical ORC and transcritical power cycle in low-temperature binary geothermal power system. The optimization procedure was conducted with a simulation program written in Matlab using five indicators: thermal efficiency, exergy efficiency, recovery efficiency, heat exchanger area per unit power output and the levelized energy cost. The analysis showed that the choice of working fluid varies the objective function and the value of the optimized operation parameters are not all the same for different indicators. R123 in subcritical ORC system yields the highest thermal efficiency and exergy efficiency of 11.1% and 54.1%, respectively. Although the thermal efficiency and exergy efficiency of R125 in transcritical cycle is 46.4% and 20% lower than that of R123 in subcritical ORC, it provides 20.7% larger recovery efficiency. The levelized energy cost value is relatively low.

DiPippo [9] found that actual binary plants can achieve relative efficiencies as high as 85%. The paper discusses cycles using two-phase expanders that in principle come close to the ideal triangular cycle. Franco and Villani [10] analyzed that the brine specific consumption, ranging from 20 to 120 kg/s for each net MW produced, and the efficiency of the plants, ranging from 20% to 45% in terms of second law efficiency, are dictated mainly by the combination of the brine inlet temperature, the brine rejection temperature and the energy conversion cycle being used. It is shown that optimization of the plant can yield improvements of up to 30–40% in terms of reduction of brine specific consumption compared to conventional design.

Coskun [11] studied geothermal sources with low, medium and high temperatures that may be suitable for power generation in Turkey. Optimum plants chosen in terms of maximum net power, thermal and exergetic efficiency were selected according to properties of these sources. These plants are single flash, double flash,