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Optimal production of power from mid-temperature geothermal sources: Scale and safety issues

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ABSTRACT

In this work we have optimized the operation of a geothermal facility. Benzene, toluene and cyclohexane are selected as candidate fluids based on previous studies. We formulated a superstructure optimization problem for the optimal use of geothermal energy using a binary cycle with either one or two turbine expansions. Surrogate correlations for the thermodynamic properties of the fluids have been developed (i.e. enthalpy, entropy) to model the operation of the turbine and the heat exchanger network. A single economic objective and a normalized multiobjective function accounting for economic, environmental and safety issues are used. The economic optimization selects a two expansion cycle using toluene as organic fluid, producing 10.4 MW at 0.075 €/kWh with an investment of 102 M€. Safety considerations slightly change the operating conditions, reducing the pressures and temperatures, but not the selection of the working fluid. Sustainable and economic terms overcome safety issues. The results are competitive with other renewable-based technologies for thermal power production such as CSP or biomass.

1. Introduction

Geothermal energy is a promising source from within the Earth's interior. In spite of its potential, it has not been extensively exploited yet. High-temperature reservoirs, with temperatures above 220 °C, are the ones most suitable for commercial production of electricity. However, the medium- and low-temperature water-dominated systems, with temperatures between 110 and 160 °C, are the most abundant [1]. So far most of the work focuses on evaluating the Organic Rankine Cycles (ORC), to determine their capacity of extracting energy from low temperature sources and the fluid that can be used. With regards to the structure of the cycle, there are a number of alternatives. We can find, either single- or double-flash geothermal power plants, dry-steam power plants and binary cycle power plants. Single-flash plants were the first type of geothermal facilities installed. The thermal fluid is evaporated one time only. Double-flash facilities include a second evaporation step to increase the power produced by 15–25%. Dry-steam power plants consist of a simpler technology since no condensation is expected in the expansion and typically only one expansion in the turbine is allowed. Finally, binary cycle power plants are used when the steam from the well has impurities that prevent from its direct use as well as for low temperature sources. Steam or hot brine is used to heat up and evaporate a thermal fluid whose expansion in the turbine will provide the power [2,3]. Therefore, dry-steam and flash systems are widely used to produce electricity from high-temperature resources, and binary power plants (or Organic Rankine Cycle units; ORC) are the best energy conversion systems to exploit lower temperature reservoirs, both from a technical and environmental points of view. Thus, we have focused on these ones.

The second issue related to the use of geothermal energy is to evaluate the ORC and the proper fluid. There are a number of recent studies in the literature [4–11]. Most of the studies are based on simple models for the Rankine cycle, comparing a number of fluids [4,8]. Other works focused on the optimization of the cycle using different approaches. Franco and Villani [10] proposed a heuristic methodology to optimize geothermal plants comparing several working fluids, refrigerants and hydrocarbons. Roy and Misra [9] performed a sensitivity analysis for the optimization of the cycle for one single fluid, refrigerant R123. Another typical refrigerant, R134, was evaluated by Sun and Li [6]. The authors developed a model based on first principles considering thermal efficiency for the different units such as the expander, the condenser, an air cooler, and the evaporator in order to optimize the power production. Simple thermodynamics is assumed as well as one single expansion. Wang et al. [7] compared a limited number of fluids,

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Nomenclature

c_p	brine heat capacity (kJ/kg °C)
f(t)	dimensionless time function for heat transfer
f	friction factor
fc_{brine}	brine flow rate (kg/s)
$fc_{(J,unit,unit1)}$	mass flow of component J from unit to unit1 (kg/s)
H_i	enthalpy of stage I in the diagram (kJ/kg)
$H_{b,(unit,unit1)}$	enthalpy of the stream at the state b from the stream from unit to unit1 (kJ/kg)
K	thermal conductivity (W·(m°C)$^{-1}$)
k	permeability (mDarcys)
$L_{yac,}$	depth of the source (m)
P_{yac}	pressure down the well (MPa)
P_{IN}	pressure at the production well entrance (MPa)
P_{head}	pressure at the production well head (MPa)
P_{turb}	pressure at the expansion (MPa)
r	internal radius of the well (m)
r_{yac}	influence radius of the reservoir (m)
$r_{\text{ well:}}$	external radius of the well (m) 0.120
$r_{\text{ int}}$	external radius of the well (m) 0.1133
$s_{b(unit,unit1)}$	entropy the stream at the state b for the stream from unit to uni1 kJ/kgK
$T_{(unit,unit1)}$	temperature of the stream from unit to unit 1 (°C)
T_{bh}	temperature down the well (°C)
T_o	temperature at the bottom when no fluid movement (°C)
T_{sat}	saturation temperature (°C)
Total Risk	risk of the design (yr^{-1})
U	brine velocity (m/s)
y	vertical distance from the bottom of the well to the surface (m) 3600

Symbols

α	temperature gradient (43.49E−3 °C/m)
∝	thermal diffusivity of the formation (10^{-6} m^{2}s^{-1})
μ	brine viscosity (poises) 0.0015854567
ρ_{yac}	density of the brine (kg/m^3) 922

Subindexes

Brine	hot brine from the well
s	isentropic
I	point in Fig. 2
COOL	cooling unit
Fluid	thermal fluid
Unit	equipment from the flowsheet
HX	heat exchanger
IW	injection well
Mix	mixer
Pump	pumps
PW	production well
Turb	turbine
Splt	splitter
SR	sands removal unit
Str	storage tank
Valv	valve

Subscripts (Fig. 2)

Stage 1	saturated liquid exiting the cooling superstructure, and reaching the storage tank Str1
Stage 2,s	compressed liquid exiting the pump PMP1, supposing ideal compression (efficiency of the process equal to 100%)
Stage 2	compressed liquid exiting the pump PMP1
Stage 3	saturated liquid exiting the heat exchanger HX1 and reaching HX2, as well as the pump PMP2
Stage 4,s	compressed liquid exiting the pump PMP2, supposing ideal compression (efficiency of the process equal to 100%)
Stage 4	compressed liquid exiting the pump PMP2
Stage 5	saturated liquid exiting HX3
Stage 6	saturated steam exiting HX4, which constitutes the feed of the first body of the turbine
Stage 7,s	overheated steam produced at the expansion of the first body of the turbine, supposing ideal expansion (efficiency of the process equal to 100%)
Stage 7	overheated steam produced at the expansion of the first body of the turbine
Stage 8	overheated steam produced at the mix of stages 7 and 9, at the inlet of the second body of the turbine
Stage 9	saturated steam exiting HX2, which constitutes the feed of the second body of the turbine
Stage 10,s	overheated exhausted steam produced at the expansion of the second body of the turbine, supposing ideal expansion (efficiency of the process equal to 100%)
Stage 10	overheated exhausted steam produced at the expansion of the second body of the turbine
Stage 11	saturated steam exiting HX5

mostly refrigerants, on the performance of a simplified Rankine cycle. The cycle is optimized following a pinch analysis approach embedded in a genetic algorithm. Yu et al. [12] presented a pinch-based method for the design of efficient ORC's to recover waste heat from different sources within a refinery. Most of the works considering detailed thermodynamics have used process simulators [11], otherwise simplified flowsheets for the Rankine cycle have been considered. Only lately Yu et al. [12] presented the design of a heat exchanger network for the optimal heat recovery form waste heat using detailed thermodynamics by implementing equations of state within the optimization for one fluid, n-pentane.

While in a previous work a fast screening procedure of fluids for the operation of Organic Rankine Cycles (ORC's) was carried out based on a multiobjective optimization approach considering economic, environmental and safety issues, but the process was oversimplified. Therefore, in this work we use a superstructure optimization approach for the mathematical optimal design and operation of Organic Rankine binary Cycles for the recovery of energy from medium and low geothermal sources. We focus on the three fluids that our previous study identified as the most promising from environmental, economic and safety points of view [13]. In particular, we develop a superstructure for the heat exchanger network to use the hot brine from a geothermal well allowing double and single extractions to optimally design the best cycle [14–16], where the thermodynamics of the fluids is included through surrogate models for the enthalpies and entropies instead of the more theoretical approach [17,18]. Two solutions are presented, the first one optimizes the energy output and a second one where economic, environmental and safety considerations are included in a normalized objective function to evaluate their effect on the selection of the cycle and on the operating conditions. Finally, the effect of the scale on the investment and production costs is evaluated. The paper is organized as follows. Section 2 describes the process flowsheet superstructure. Section 3 comments on the modelling aspects of all the units involved in the flowsheet. Section 4 presents the optimization procedure including