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Power production from a moderate temperature geothermal resource with regenerative Organic Rankine Cycles

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ABSTRACT

Much remains to be done in binary geothermal power plant technology, especially for exploiting low-enthalpy resources. Due to the great variability of available resources (temperature, pressure, chemical composition), it is really difficult to "standardize the technology".The problem involves many different variables: working fluid selection, heat recovery system definition, heat transfer surfaces sizing and auxiliary systems consumption. Electricity generation from geothermal resources is convenient if temperature of geothermal resources is higher than 130 °C. Extension of binary power technology to use low-temperature geothermal resources has received much attention in the last years. This paper analyzes and discusses the exploitation of low temperature, water-dominated geothermal fields with a specific attention to regenerative Organic Rankine Cycles (ORC). The geothermal fluid inlet temperatures considered are in the 100–130 °C range, while the return temperature of the brine is assumed to be between 70 and 100 °C. The performances of different configurations, two basic cycle configurations and two recuperated cycles are analyzed and compared using dry organic fluids as the working fluids. The dry organic fluids for this study are R134a, isobutane, n-pentane and R245fa. Effects of the operating parameters such as turbine inlet temperature and pressure on the thermal efficiency, exergy destruction rate and Second Law efficiency are evaluated. The possible advantages of recuperated configurations in comparison with basic configurations are analyzed, showing that in a lot of cases the advantage in terms of performance increase is minimal but significant reductions in cooling systems surface area can be obtained (up to 20%).

Introduction

Moderate-temperature water-dominated systems, with temperatures below 130 °C, account for about 70% of the world's geothermal energy potential (Barbier, 2002). The distribution of geothermal energy as function of the resources temperature and the technical resource potential has been evaluated recently by Stefansson (2005), starting from a general correlation between the existing geothermal high temperature resources inferring a total geothermal potential of 200 GWe.

Binary technology allows the use of low temperature water dominant reservoirs and makes geothermal power production feasible even for countries lacking high enthalpy resources at shallow depth. For binary plants two different systems currently are state of the art, the Organic Rankine Cycle (ORC) and the Kalina cycle.

The binary power plants have the least environmental impact due to the "confinement" of the geofluid. In a binary cycle power plant the heat of the geothermal water is transferred to a secondary working fluid, usually an organic fluid that has a low boiling point and high vapor pressure when compared to water at a given temperature. The cooled geothermal water is then returned to the ground by the re-injection well to recharge the reservoir (DiPippo, 2008).

Such a geothermal plant has no emissions to the atmosphere except for water vapor from the cooling towers (only in case of wet cooling) and any losses of working fluid. Thus, environmental problems that may be associated with the exploitation of higher temperature geothermal resources, like the release of greenhouse gases (e.g. CO_2 and CH_4) and the discharge of toxic elements (e.g. Hg and As) are avoided.

Another advantage of the binary technology is that the geothermal fluids (or brines) do not contact the moving mechanical components of the plant (e.g. the turbine), assuring a longer life for the equipment. Binary plants have allowed the exploitation of a large number of fields that may have been very difficult (or uneconomic) using other energy conversion technologies (Schochet, 1997; DiPippo, 2004; Bronicki, 2007).

Of the about 10,700 MW of geothermal plants installed worldwide, more than 1170 MW use ORC or steam/ORC combined cycles (Bertani, 2010). There exist a great number of studies addressing both the different characteristics of geothermal fields and the various types of power plants that could be used in their exploitation for electricity production; Barbier (2002), Bertani (2005), Lund (2007) and DiPippo

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Nomenclature

e	specific exergy (J kg^{-1})
Ex	exergy flow (W)
h	specific enthalpy (J kg^{-1})
H	enthalpy flow (W)
I	exergy loss flow (W)
$K(Q_{cond})$	function defining the heat transfer performance of condenser (W K^{-1})
m	mass flow rate (kg s^{-1})
p	pressure (bar)
Q	heat flow rate (W)
S	heat transfer surface (m^2)
s	specific entropy (J kg^{-1} K^{-1})
T	temperature (°C)
T_o	reference temperature (K)
v	specific volume (m^3 kg^{-1})
x	steam quality
W	power (W)

Greek symbols

β	specific brine consumption (kg MJ^{-1})
ΔT	temperature difference (°C)
Δp	pressure drop (bar)
η	efficiency
η_I	First Law efficiency
η_{II}	Second Law efficiency

Subscripts and abbreviations

cond	condenser, condensation
CS	cooling system
el	of the electric system
env	environment
esp	of expansion
exp	of the expander
geo	of the geothermal brine
gross	gross power
in	at the inlet
is	isentropic
liq	of the liquid
max	maximum
net	net power
o	reference state
out	at the outlet
PL	pressure levels
pp	pinch point
pump	of the circulation pump
RAN	Rankine Cycle
RANSH	Rankine Cycle with superheater
RHE	recovery heat exchanger
rec	of the recuperator
rej	rejection
sat	saturation
sh	superheater
ST	steam turbine
wf	working fluid

(2008) provide analyses of the various technological solutions and of the state of the art. A geothermal binary power plant is characterized by high brine specific consumption and low plant efficiencies (5–10%); First Law efficiencies even Second Law efficiencies are typically in the 25 to 45% range and by the requirement for large heat transfer surfaces both for the heat recovery heat exchanger and for the condensation system.

The design of binary plants, although widely addressed in the literature (e.g. Gnutek and Bryszewska-Mazurek, 2001; Kanoglu, 2002; DiPippo, 2004; Hettiarachchi et al., 2007; Kaplan, 2007; Kose, 2007; Moya and DiPippo, 2007) is still an area of active research. The author in a recent paper has already analyzed the perspective and the thermodynamic performance of a lot of possible plant configurations, combining different available organic fluids and recovery cycles for different combination source temperature–reinjection termperature (Franco and Villani, 2009). Different analyses show the possible benefits, in terms of the extent of using the thermal energy of low-temperature geothermal water, that arise from utilizing hybrid and dual-fluid-hybrid power plants rather than ORC power plants (Borsukiewicz-Gozdur, 2010).

Reconsidering the technology of ORC plants, at present this is not at a stage of development capable of providing "standard machinery", and each installation is designed for the conditions at a given location by the big manufacturers in this field, like Ormat, Mafi Trench, Siemens and UTC/Turboden.

Only recently systematic attempts to standardize machinery have been made: for example UTC Power has proposed The PureCycle® Power System. This is an electric power generating system which runs off any hot water resource at temperatures as low as 90 °C. The hot water can be derived from a geothermal source or other waste heat source. Currently this ORC unit is sized at 280 kW (gross) of electrical power.

The flexibility of a modular approach in geothermal power technology is interesting because of employing small, off-the-shelf units, a plant that can be scaled to the local geothermal resource, energy demand and available financing.

Organic Rankine Cycles seem to be a promising technology in the perspective of a decrease in plant size and investment costs. They can work at lower temperatures, and the total installed power can be reduced down to the kW scale. The market for ORC's is growing at a rapid pace. Since the first installed commercial ORC plants in the 80's, an exponential growth has been seen in the past decade. The success of the ORC technology can be partly explained by its modular feature: a similar ORC system can be used, with little modifications, in conjunction with various heat sources. This success was reinforced by the high technological maturity of most of its components. Moreover, unlike with conventional power cycles, local and small scale power generation is made possible by this technology. Today, Organic Rankine Cycles are commercially available in the MW power range, while very few solutions are actually suitable for the kW scale.

Organic Rankine Cycle (ORC) raises considerable interest as it makes it possible to produce electricity from cooler geothermal sources, typically within the 100–130 °C temperature range, exceptionally down to 90–95 °C, often available from below 1000 m deep production well (a case of 75 °C is available too) increasing the number of geothermal reservoirs in the world that can potentially be used for generating electricity.

No high plant ratings can be expected for obvious thermodynamic reasons even if improvements should concentrate on cycle and plant efficiencies. One of the problems of geothermal binary plants is the rejection of heat at low temperature (thermal pollution). If no adequate water source is available, a dry cooling system must be used. Although such a system solves the problem of water supply, it raises many others. The parasitic power consumption is relatively high because of the need for forced ventilation; a dry cooling system can absorb from 10–12% of gross power (under ideal conditions), to as much as 40–50% if the ambient temperature is very close to the condensation temperature.

The capital cost is also quite high; 30–35% of the total capital cost of the geothermal project. A good review on the costs of small geothermal plants is available in the literature (Entingh et al., 1994;