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Krafla geothermal system, northeastern Iceland: Performance assessment of alternative plant configurations

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ABSTRACT

This paper deals with the Krafla geothermal field, northeastern Iceland, and illustrates how the upgrade of high enthalpy geothermal plants can be effective and lead to increased power production. The aim of this paper is to examine ways of improving the thermodynamic performance of the power plant at Krafla in light of the recent wells. Starting with an energetic and exergetic characterization of the geothermal site, the evolution over time and space was analyzed for the main geothermal parameters and the current energy potential.

In light of several newly drilled wells with different characteristics from the previous wells, a number of alternative energy conversion systems are proposed for that installation, analyzing their performances with respect to the current system. The possibility of adding an extra pressure level to the current steam plant was analyzed along with the use of bottoming Organic Rankine Cycles (ORC).

For the most promising alternatives, a thorough energy and exergy analysis was carried out including a thermodynamic optimization, in particular identifying a solution that would achieve a significant increase in both total electrical power producible and efficiency. The results are presented in tables and graphs and constitute a useful starting point for a potential reconfiguration for the Krafla power plant.

1. Introduction

Evolution of geothermal power plants in the last decades has transitioned from the simple use of dry steam towards more complex systems based on multi-flash processes, binary cycles and hybrid systems. Plant complexity implies high investment costs, often in the face of modest efficiency increases. By contrast, the near-term evolution of fossil-fueled power plants has led to higher efficiency. In power plants based on combustion processes, the high temperatures involved, both of the heat source (flue gases) and the working fluid (steam), give an exergetic potential much larger than that of geothermal plants, which are confined to modest pressures and temperatures of geofluids. Nevertheless, for geothermal plants, because the values of efficiency are modest, a gain of only a few percentage points can result in a significant percentage increase in efficiency and produced power. Furthermore, the fact that the geothermal resource is usually continuously available and sustainable, if not absolutely inexhaustible, encourages optimizing the efficiency of geothermal plants, especially in the case of high-enthalpy reservoirs. For both high- and low-enthalpy geothermal systems, integration with other renewable sources such as biomass and solar energy (Amoresano et al., 2013; Thain and DiPippo, 2015) can be an interesting way to upgrade, as well.

Among the main areas of geothermal interest in the world, Iceland plays a major role, thanks to the high temperature of its underground geologic formations. This study regards the area of Krafla in northern Iceland and illustrates how the upgrade of high-enthalpy geothermal plants can be effective and lead to increased power production.

The Krafla geothermal field was the site of the first large-scale commercial geothermal power plant in Iceland. The 30 MW double-flash Unit 1 came online in 1978, preceded in 1969 by the 3.2 MW back-pressure wellhead unit at nearby Namafjall, about 7.5 km to the south. Located within a highly active volcanic zone, the plant and field have experienced unique events that have challenged the skills of the engineers and scientists associated with the project. Relatively young volcanic eruptions have created hazards for the operation of the facility and altered the reservoir resulting in several zones with markedly different characteristics. Wells in these diverse zones produce geofluids with strikingly different thermodynamic and chemical properties (Weisenberger et al., 2015). Integrating these wells into the current energy conversion system is a challenge. Given that the power plant

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Nomenclature

C	Condenser
CP	Condensate pump
CW	Cooling water
$\dot{E}$	Rate of exergy: $= \dot{m}ee$
EV	Evaporator
e	Specific exergy: $= h - h_o - T_o(s - s_o)$
G	Generator
h	Specific enthalpy
HP	High pressure
LP	Low pressure
$\dot{m}$	Mass flow rate
MR	Moisture remover
NCG	Noncondensable gases
ORC	Organic Rankine cycle
P	Pressure
q	Heat
$\dot{Q}$	Thermal power
S	Separator
s	Specific entropy
SJE	Steam jet ejector
T	Temperature
T	Turbine
VHP	Very high pressure
$\dot{W}$	Rate of work or mechanical power
WCT	Water cooling tower
x	Quality: mass fraction of vapor in liquid-vapor mixture

Greek symbols

η_u	Utilization or Second Law efficiency: $= \dot{W}/\dot{E}$
η_{th}	Thermal efficiency: $\dot{W}/\dot{Q}$

Subscripts

hp	High pressure
in	Input
lp	Low pressure
o	Dead state reference for exergy
out	Outlet
p	Pump
R1	Reservoir state
t	Turbine
th	Thermal
u	Second Law net utilization
vhp	Very high pressure
wh	Wellhead

was designed nearly 40 years ago for the wells that existed then, it may be possible to modify the current configuration to take better advantage of the newly drilled wells.

The aim of this paper is to examine ways of improving the thermodynamic performance of the power plant at Krafla in light of the recent wells. Many other geothermal plants have undergone similar modifications after the initial installations had completed several years of operation. To cite only a few, in Mexico the Cerro Prieto I plant added a 30 MW double-flash fifth unit in 1981 to the original four 37.5 MW single-flash units (MHI, 2000); in New Zealand the Wairakei plant added a 2 × 7 MW bottoming binary unit to the flash units in 2005 (Montague et al., 2013); and in the United States a 5 MW bottoming binary unit was added in 2011 to the Dixie Valley 60 MW double-flash plant (McDonald, 2010); many more could be mentioned (DiPippo, 2016a).

Likewise, after an extended period of plant operation and expansion of the resource by step-out wells, it is appropriate to reexamine the reservoir model with the goal of maintaining as efficient an operation as possible for the foreseeable future. For example in Italy, Larderello — the first field to be developed for geothermal power generation — has been under continuous study for over 100 years, and the results have led to a greater understanding of the depth and breadth of the productive reservoir regions (Cappetti et al., 2005). Furthermore, innovative energy conversion systems have been designed to maintain generation, including a novel biomass-geothermal hybrid power plant (DiPippo, 2016b).

In Section 2 the geological setting of Krafla is presented and the main parameters of the geothermal field are analyzed. In Section 3 several new conceptual options are explored for the power plant in light of the new wells and their characteristics. In Section 4 the results are shown for quantitative analyses carried out on the most promising of the alternative designs. The conclusions are presented and discussed in Section 5.

2. Geological and geothermal framework of the Krafla system

2.1. Geological overview

The Krafla high-temperature geothermal system is located within the Krafla caldera, in the neo-volcanic zone of NNE-trending axial rifting in northern Iceland (Fig. 1). The geology of the area is characterized by an active central volcano including the caldera and a N–S trending fissure swarm. The fissure swarm that intersects the Krafla caldera formed about 100,000 years ago and is 5–8 km wide and about 100 km long (e.g., Saemundsson, 1983). The oldest exposed rocks in the Krafla central volcano are hyaloclastites from the second-to-last glacial age (younger than 200,000 years). At the end of the last interglacial, about 100,000 years ago, a large (some km^3), explosive rhyolitic eruption resulted in the formation of the Krafla caldera, which is 8 km by 10 km in diameter (Fig. 1). During the last glacial period the caldera was filled with volcanics and subsided about 100 m. Furthermore, the fissure swarm crossing the area widened by some decimeters every 10,000 years, resulting in the elliptical shape of the caldera (Saemundsson, 1991). During the Holocene, extensive volcanic activity took place inside the caldera, especially within the presently active fissure swarm (Fridleifsson et al., 2006). The activity was characterized by fissure eruptions and lava flows outside the geothermal fields and magma-phreatic explosive activity within the geothermal area. It was during this period of activity (early Holocene, about 9000 years ago) that the Hveragil explosive fissure erupted (Fig. 1a–b). It was formed from a series of explosion craters and currently serves as the main recharge or hydrothermal up-flow zone (Saemundsson, 1991).

Post-glacial volcanism in the Krafla area was divided into two periods. The first one was in early post-glacial times and ended about 8000 years ago. The second period started about 3000 years ago and is ongoing (Saemundsson, 1984). Since the beginning of post-glacial time, the volcanic activity at Krafla has been episodic, and 20 eruptions have taken place within the caldera; six of them belong to the second period and occurred at 250–1000 year intervals.

The explosive crater Viti (Fig. 1a–b) was formed in 1724 at the beginning of a 5-year volcanic episode known as the “Myvatn Fires.” It is the youngest eruptive formation within the Krafla system. Due to the formation of explosive craters, pyroclastic material covers the surface of the caldera (e.g., Armannsson et al., 1987). The Daleldar crater row and lavas on which the Krafla power plant is built (Fig. 1b) is the second youngest eruptive product in the area, about 1100 years old. The third youngest eruptive products of the field are the eruptions and volcanic fissures of Holseldar (Fig. 1b), about 2000 years old.