Geothermics 70 (2017) 230–238

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Fuzzy control of calcium carbonate and silica scales in geothermal systems

Fusun Tut Haklidir[a,*], Mehmet Haklidir[b]

[a] Istanbul Bilgi University, Department of Energy Systems Engineering, Eyüp, Istanbul, Turkey
[b] TUBITAK BILGEM, Gebze, Kocaeli, Turkey

ARTICLE INFO

Keywords:
Scaling
Geothermal systems
Fuzzy control

ABSTRACT

Calcium carbonate scaling and silica scaling are critical challenges directly affecting the efficiency of production during operational periods for geothermal power plants or geothermal district heating systems. Although their precipitation mechanisms are different from each other, both can be observed in varied proportions in production and reinjection wells as well as surface equipment in geothermal systems. Thus, scale prevention and control systems are essential, as abatement of scaling is more efficient than removal from wells and equipment after precipitation in a geothermal system. There are a few methods for control of silica and calcium carbonate precipitation in geothermal wells and surface equipment. Most production and reinjection wells require the implementation of a silica/calcium carbonate inhibition system to prevent silica/calcite precipitation inside casings, pipes, separators and other surface equipment in geothermal power systems. Installation of inhibitor systems are the most effective and practical solution for prevention of scaling problems and production loss, if the optimum inhibitor dosages are determined and applied effectively in geothermal systems. Less than optimum ratios of inhibitors may result in product overfeed, increased costs, and in some cases, inhibitor-induced fouling. The system is nonlinear and has multiple dependent and independent variables thus, it is difficult to obtain a mathematical model that describes the relation of geothermal fluid characteristic and inhibitors and with this reason, a fuzzy controller may be good option to resolve it in geothermal systems. Fuzzy control may replace the role of the mathematical model in conservative controllers, substituting it with a different model that is built from a number of smaller rules that only describe a sub-section of the complete system. In this study, two fuzzy logic controllers have been designed to control precipitation of silica and calcium carbonate by using scale inhibitors.

1. Introduction

Geothermal energy is a renewable and sustainable energy source. The total installed capacity of geothermal power plants reached 14 GWh around the world in 2017. It is an attractive energy source with high capacity factors (80–95%) for geothermal power industry investors.

Geothermal power systems can be mainly classified into flash-binary types for water-dominated geothermal reservoirs (such as Kizildere and Germencik in Turkey) and dry steam power plants for steam-dominated geothermal reservoirs (such as Geyser in the USA and Larderello in Italy).

Potential scaling and corrosion concerns can be observed in the operation of geothermal power plants for medium-high temperature geothermal systems. Actually, both are serious challenges to power production, and both may increase the total cost of operation for a geothermal investor. Corrosion may be solved to some extent with selection of higher quality materials such as steam stainless steel; for example, Inconel-625 and Hastelloy C-276 consist of Ni-Cr-Mo alloys (Kaya, Hoşhan, 2005). However, the second concern, scaling, cannot be solved by only material selection because the problem directly depends on thermodynamic changes of fluid in the system. Brine (hot water) has high amounts of dissolved minerals and these minerals can be stable or unstable at different temperature (T) and pressure (P) conditions. It means that the highly dissolved mineral content tends to result in scaling and deposition as a result of P, T changes to the physical and chemical properties of the brine from depth to surface condition. The depths of deep geothermal production wells generally vary between 1000 and 4000 m, as water-rock interaction water has significant mineral deposition and changing P, T conditions lead to different scale types such as calcium carbonate (calcite), silica minerals, and sulfide minerals. If the fluid oversaturated with minerals and no well intervention is installed on wellhead, the first mineral can start to precipitate as calcite in borehole. Similarly, depending on the operating condition, calcite, sulfide minerals, silica minerals can be precipitate on surface equipment, re-injection lines and wells in the plant. These mineral

* Corresponding author.
E-mail addresses: fusun.tut@bilgi.edu.tr (F. Tut Haklidir), mehmet.haklidir@tubitak.gov.tr (M. Haklidir).

http://dx.doi.org/10.1016/j.geothermics.2017.07.003
Received 12 April 2017; Received in revised form 20 June 2017; Accepted 4 July 2017

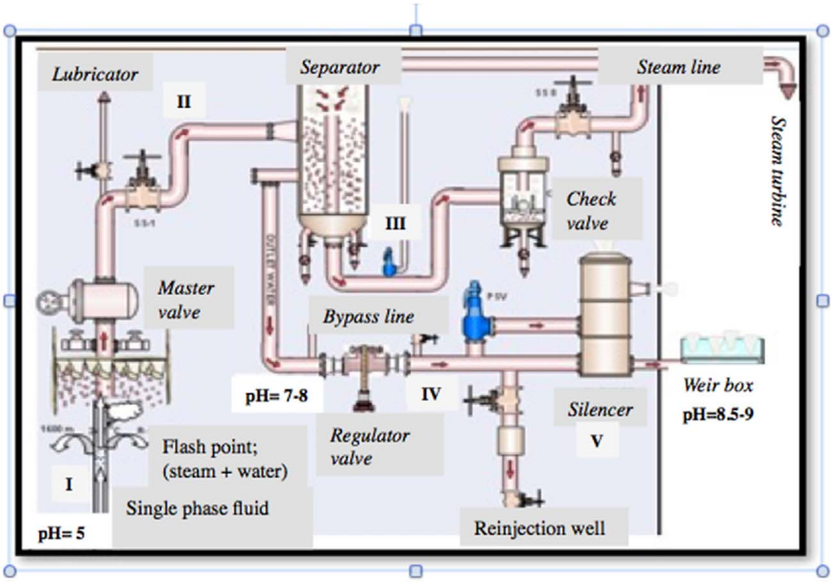

Fig. 1. Possible precipitation points and pH changes of water phase for a single flash geothermal power plant (I, II, III, IV certain pressure drop points in a geothermal power system; modified from Haklidir Tut et al. (2011)).

precipitations can reduce steam, power production and affect performance of a power plant as well as increase the operating costs for a geothermal power plant (Fig. 1).

To reduce risks associated with mineral scaling, the most effective application is to use chemical scale prevention inhibitors in geothermal power plants. Applied dosages are determined by short-term tests in the field, with dosages between 3 and 6 ppm viewed as acceptable in a geothermal system. Although using these inhibitors are the most effective solutions for water treatment, these are quite costly and require special inhibitor systems for geothermal power plants. For example, depending on water chemistry, normally one inhibitor dosage system may be sufficient to solve calcite scaling and dosing of inhibitor should be at the flash point at deep inside wellbore for a single flash geothermal power plant. However, if the water chemistry is hard (high Cl-anions or other minerals) or the geothermal power system is multi-flash, more than one dosage point can be determined for monitoring scaling occurrence in the system. This one of the highest cost items for the operation period budget for each geothermal power plant, and in order to reduce inhibitor consumption, some controller systems have been designed for this purpose.

The aim of this study is to design a control system to determine the best scale inhibitor doses required for optimum plant protection by using a human operator's experiments. Fuzzy logic is used to convert heuristic control rules stated by a human operator into an automatic control strategy (Mamdani, 1975). Thus, in the study, two fuzzy logic controllers are designed to control the precipitation of silica and calcium carbonate by using scale inhibitors. The simulation results are presented and discussed in this study.

2. Main scaling types in geothermal systems: calcite and silica scaling

Generally, scaling is a major problem in water-dominated geothermal system, especially if it occurred inside the production wellbore and reduces the flow rate, resulting to decreased net energy production day by day (Haizlip Robinson et al., 2012). Scaling is a precipitation of some minerals in geothermal waters accompanied by change in thermodynamic conditions such as pressure and temperature. A change in pH value also affects the stability of minerals in geothermal waters.

Geothermal fluids consist of hot water, gas and steam in liquid-dominated systems. The water phase contains dissolved minerals and dissolved gases at high pressure and temperature conditions at depth in a geothermal system. Under dynamic reservoir conditions, when measured total pressure lower than $P_{gas} + P_{liquid}$, flashing process starts at depth (Haizlip Robinson et al., 2012). As fluids travel from deep to surface through the production wellbore, a change in thermodynamic conditions can result to this boiling process which release dissolved gases and shift the pH to a more alkaline value. This essentially leads to precipitation of calcite and some metal sulfides that can deposit very hard scale inside of production well casings and also inside the surface equipment. When the two-phases geothermal fluid is flashing to lower separator pressure in the plant, the separated water phase will become oversaturated with respect to amorphous silica as its solubility decreases with lowering of the temperature. At this condition, without any process intervention, silica is expected to precipitate in re-injection lines and re-injection wells.

2.1. Silica scaling

Geochemistry of silica mineral and thermodynamics of silica solubility

Silica scaling is one of the most challenging scale types to treat in brine (water phase). The silica scale can be generally observed in the form of amorphous silica at medium to high temperature geothermal systems but can also exist as metal silicate such as iron silicates and aluminum silicate (Haklıdır Tut and Şengün, 2016; Thorhallsson, 2005; Ocampo-Díaz et al., 2005).

Silica is one of the soluble minerals in geothermal fluids at high temperature reservoir conditions. The dominant form of dissolved silica is mono-silicic acid; $Si(OH)_4$. Silica solubility is generally controlled by the polymorph quartz when the reservoir temperatures above 185 °C (Fournier and Rowe, 1977; Mahon, 1966) and it may be controlled by polymorph chalcedony which is more soluble than quartz, if reservoir temperature is less than 185 °C (Fig. 2). Thus, chalcedony form can substantially increase the amount of dissolved silica in lower temperatures above that expected from quartz equilibrium in silica scaling potential. Silica mineral saturation is reached with respect to amorphous silica between 100 °C–200 °C, generally indicating re-injection temperatures for geothermal systems (Gurnarsson and Arnorsson, 2005).

At high temperature reservoirs, the temperature of the brine at the wellhead is usually between 160 °C and 250 °C, depending on the wellhead pressure and during cooling process after production, saturation is compared to amorphous silica. Because of relatively rapidly precipitation rate of amorphous silica (Gunnarsson and Arnorrsson, 2005), there exists potential deposit buildup in reinjection pumps, reinjection lines and reinjection wells (Haklıdır Tut and Şengün, 2016).