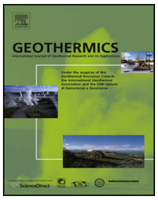
Geothermics 51 (2014) 445–459

Contents lists available at ScienceDirect

Geothermics

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



Silica scaling in geothermal heat exchangers and its impact on pressure drop and performance: Wairakei binary plant, New Zealand

Sadiq J. Zarrouk[a,*], Blair C. Woodhurst[a], Chris Morris[b]

[a] Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland, New Zealand
[b] Contact Energy Ltd., Wairakei Power Station, Private Bag 2001, Taupo 3352, New Zealand

ARTICLE INFO

Article history:
Received 14 March 2013
Accepted 7 March 2014
Available online 7 April 2014

Keywords:
Geothermal heat exchanges
Fouling
Silica scaling
Binary
Wairakei
New Zealand.

ABSTRACT

Scaling (fouling) has a dramatic impact on the long term operational performance of geothermal heat exchangers. Scaling affects both the flow hydrodynamics and the heat transfer resistance. A review of reported scaling problems in geothermal heat exchangers shows that silicate (pure silica and metal silicate) is the main deposited mineral. Scanning electron microscope images show that: silica deposition at the Wairakei binary plant is very dense as result of molecular (monomeric) deposition. This work attempts to characterize this impact on the binary plant, using long term production data. The geothermal brine flow rate and pressure drop within the plant are useful to assess the plant performance. These are interdependent quantities hence taken alone do not allow a proper understanding of the impact of silica scaling on performance. A new simple model was proposed to quantify the performance impact (resistance) of scaling. The available chemistry data showed that the recent (late 2009) increase in scaling rate and flow resistance is mainly related to the introduction of new wells with high silica content to the production system. Recommendations were given to maintain silica saturation index to less than two and use scaling inhibitors.

1. Introduction

The deposition of scale in wells, separators, pipes, turbines and heat exchangers is one of the main problems that hinder the wide utilization of geothermal resources. The flow of geothermal brine in production equipment is often affected by scaling. It not only decreases the amount of extracted energy, but leads to the loss of power generation due to shutdowns and additional expenses for solid/deposits removal and disposal (Kashpura and Potapov, 2000). Therefore, scaling prevention is one of the main reasons for the relatively low conversion efficiency of geothermal power stations (Zarrouk and Moon, 2014).

Deposition or precipitation of solids on the surfaces of heat exchanger tubes is a well reported problem commonly known as fouling (Bott, 1995; TEMA, 2007). Fouling increases the thermal resistance as it has lower thermal conductivity than the heat exchanger tubes, reducing the overall heat transfer coefficient of the heat exchanger (TEMA, 2007) which reduces the performance of the heat exchanger. Fouling also reduces the flow cross section of the heat exchanger tubes. This causes an increase in the pressure drop and/or reduction to the fluid flow rate through the heat exchanger, which effectively further reduces the performance/efficiency of the heat exchanger. Therefore, the common industry practice when designing heat exchangers is to have a fouling allowance by oversizing the heat transfer area.

The fouling layer is known to increase in thickness (with time) as the heat exchanger is in service. This will mean operating the heat exchanger until the lost performance from scaling/fouling justifies shutting down the system for cleaning (TEMA, 2007).

Two types of heat exchangers are found in use in geothermal applications. They are mainly; plate type for both low temperature and pressure in direct use applications, and shell and tube type for the high temperature and pressure associated with power generation and some of the higher temperature direct use. Geothermal shell and tube heat exchangers are all designed to have the geothermal (primary) fluid flowing inside the tubes, while the other (secondary) clean fluid flows on the shell side. This is to facilitate heat exchanger cleaning from the precipitation of solids and mineral deposition. This is also the main reason for not using U-tube heat exchanger type which would be too difficult to clean.

Mineral scaling from geothermal brine within wells, steamfield and power generating equipment is a common problem in almost all geothermal power production. Characterizing its impact

---

[*] Corresponding author. Tel.: +64 9 373 7599x85542; fax: +64 9 373 7468.
E-mail addresses: s.zarrouk@auckland.ac.nz, sadiqzarrouk@gmail.com (S.J. Zarrouk).

http://dx.doi.org/10.1016/j.geothermics.2014.03.005
0375-6505/© 2014 Elsevier Ltd. All rights reserved.

on performance is of major design and operational importance. Unfortunately, such a characterization may be difficult as the nature of scaling is affected by a host of variables from brine chemistry to process design.

Both qualitative and quantitative aspects of deposition are important; whereas the amount of deposition may be estimated, the mechanism, form and chemistry of the mineral deposited can be just as important with respect to equipment performance.

Geothermal scales may deposit uniformly around the interior of a pipe as a low-density friable mass or it might form as a rough hard scale, both will have different impacts on the performance of the system in terms of pressure drop and flow velocity. When the pipe system in question is part of a heat exchanger, the operationally relevant impact of differences in scaling morphology can include such complicated phenomena as intra-fluid-mixing and the heat transfer properties of heat-exchange surface.

An example of the impact that peculiarities in scaling morphology can have on pipe system performance is the case of the heat exchangers in the binary power plant at the Wairakei geothermal power station. In this system, heat is extracted from silica laden geothermal brine by means of an Organic Rankine Cycle with a system of shell and tube heat exchangers, within which a secondary working-fluid is evaporated and used to drive turbines to generate electricity. Because silica solubility is temperature dependant, as the brine passes through these heat exchangers and cools, silica is inclined to precipitate and form a scale on the inside of the pipes it is flowing through. Though this is a basic mechanism by which scale might form in any heat exchanger, the scale that forms by this process in the heat exchangers at Wairakei is relatively thin but is remarkable in its extreme roughness.

As a result of this roughness, pressure drop across the heat exchanger system is increased, yet operational constraints require the drop across the system to be held at about 3.5 bar. Therefore this drop in pressure must be counteracted by decreasing flow through the system. Hence, there are two major operational impacts of this scaling process. It imposes the need for frequent cleaning of the heat exchanger tube system and because of the decrease in flow through the system decreases the amount of power that can be generated.

The objectives of this work:

(A) Make use of production (operational) data from the Wairakei binary power plants to assess the impact of silica scaling on plant performance and the effectiveness of cleanings at restoring output.
(B) Investigate the microscopic nature of the scale in the Wairakei heat exchanger tubes and compare that with reported cases.
(C) Develop a simple method for assessing the impact of scaling on the heat exchanger performance.

2. Scaling from geothermal fluid

Many chemical species (minerals) can be present (dissolved) in geothermal fluid which are dissolved from the surrounding rock into solution under the high temperature conditions of the geothermal reservoir and come into equilibrium with the host rock. These minerals (mainly carbonates and silicates) are produced with the geothermal fluid and can deposit/precipitate on the surfaces of different equipment in many forms. Carbonate (calcite $CaCO_3$) and anhydrite ($CaSO_4$) has retrograde solubility and are not anticipated to deposit in heat exchangers. Silicates (pure silica and metal silicate), has a solubility that reduces with temperature (prograde solubility) and is expected to deposit in heat exchangers. Silicates scaling has been reported in most geothermal power developments and in several geothermal heat exchangers, but the chemistry of the scale, rate of deposition and mechanical properties vary from field to field.

Significant silica (SiO_2) scaling in heat exchangers of binary geothermal power stations has been encountered in; Rotokawa and Ngawha, New Zealand (Wilson et al., 2007), Blundell, Utah (Gallup, 2011), two fields in the Imperial Valley, California (Gallup, 2011) and most likely many other plants around the world. One of the main contributors is that binary plants generally operate at lower geothermal fluid rejection temperatures than flash plants (Zarrouk and Moon, 2014) with a correspondingly higher silica saturation index.

The mixing of separated brine with steam condensates has been proven to retard/reduce silica scaling. However, with the lower pH of the brine and condensate mixture, stibnite (Sb_2S_3) scaling has been observed in the heat exchanger units of several New Zealand binary plants. It was found that pH decrease was the principal cause of stibnite scaling in Rotokawa while temperature decrease was the more significant cause of this type of scaling in Ngawha (Wilson et al., 2007). Silica and stibnite are both covalent solids which pose particular difficulties because inhibitors developed against carbonates and silicates (which are ionic solids), have limited effect on silica and stibnite (Stapleton and Weres, 2011).

Metal silicate or metal rich silicate can form in metal rich geothermal fluid. Some of the commonly reported metals are aluminium (Al), magnesium (Mg) and iron (Fe) (Gallup, 2011; Gunnarsson and Arnórsson, 2005b; Hauksson et al., 1995; Inanli and Atilla, 2011; Kristmannsdóttir et al., 1989). Metal silicate has a much lower solubility than pure silica, complicating the cleaning and prevention process (Gallup, 2011).

Inanli and Atilla (2011) reported metal silicate in the heat exchangers of the Tuzla geothermal binary plant in Turkey. Metal silicates form in more saline fluids rich in Magnesium and Iron (Mg/Fe). Magnesium silicates, or mixed Magnesium-Iron silicates, have very low solubility after steam separation from the brine and a decrease in temperature would cause metal silicates to precipitate. Although normally there are only small amounts of Magnesium in brine, they form tenacious, hard scales that are difficult to remove even if hydrofluoric acid (HF) is used. This scale can decrease the performance of heat exchangers, particularly in binary bottoming cycles (Stapleton and Weres, 2011). Magnesium silicates scaling has also been observed in shell and tube heat exchangers at several geothermal district heating systems in Iceland (Gunnlaugsson, 2012; Hauksson et al., 1995; Kristmannsdóttir et al., 1989).

At lower temperatures (<100 °C), microorganisms (biological fouling) such as algae, fungi, slime and bacteria can grow on surfaces of geothermal heat exchangers, and can plug fluid passages (Datuin and Gazo, 1989). This is particularly the case if the geothermal fluid is aerated and/or reheated in some direct use applications (private communication with Mr Steve Walker, Polynesian spa, New Zealand). The microorganisms can also cause the deterioration of the heat exchanger walls through corrosion (Datuin and Gazo, 1989).

In some reported cases, the scale inside the heat exchanger breaks down (sheds/flakes) during plant shutdown as the pipelines and heat exchanger tubes cools down and shrinks in size (Inanli and Atilla, 2011; Steins and Zarrouk, 2012). However, most deposited minerals are very hard and can only be removed mechanically or chemically (Brown, 2011a).

2.1. Silica scaling

The chemical compound of silica (SiO_2), found ubiquitously in geothermal fluids, is present in the ground in a number of mineral forms; Quartz, chalcedony, α-cristobalite, Opal CT and Opal A (amorphous silica) (Brown, 2011a). Quartz is the least soluble of these forms, so it is the quartz solubility equilibrium that