SCALING POTENTIAL DURING PRODUCTION IN HVERAHLÍD FIELD, HENGILL HIGH-TEMPERATURE GEOTHERMAL AREA, SW-ICELAND

Kennedy Mativo Kamunya
Kenya Electricity Generating Company - KenGen
P.O. Box 785-20117, Naivasha
KENYA
kennedy.mativo@gmail.com, kkamunya@kengen.co.ke

ABSTRACT

Hverahlíd high-temperature geothermal field is one of four high-temperature geothermal fields of the Hengill geothermal area. It is located southeast of the Hengill central volcano. It has not been developed yet, but it shows a field capacity of 90 MWe. Scaling potential with respect to amorphous silica, calcite and anhydride was assessed for the Hverahlíd system through processes of adiabatic boiling and conductive cooling of the deep aquifer fluid, during steam production, utilization, separation and reinjection. The scaling potential was studied based on mineral saturation. The calculations were conducted using the WATCH program. Amorphous silica scaling shows a potential to occur in well fluids upon boiling at temperatures below 205°C in production wells, during utilization, in reinjection wells and in aquifers receiving the reinjected fluid. Calcite has the potential to cause scaling in production wells upon extensive boiling but is not considered a risk during utilization at lower temperatures in reinjection and the receiving aquifer. Anhydrite poses no risk of scaling for any of the processes of boiling and conductive cooling that were considered.

1. INTRODUCTION

Utilization of high-temperature geothermal resources usually comes with challenges. Among these challenges is mineral scaling in production and injection wells as well as in pipes transporting the geothermal brine. Potential scaling formation is largely governed by the concentrations of dissolved components in the geothermal fluids and changes in fluid chemistry upon boiling, cooling and mixing as well as by temperature and pressure dependent minerals and other solids' solubility. Mineral formation kinetics also plays an important role. It has been concluded that the concentration of major elements in geothermal fluids at depth is controlled by the close approach to equilibrium with common geothermal minerals (e.g. Giggenbach et al., 1980, 1981; Arnórsson et al., 1982). However, during utilization of geothermal fluids, the fluids are brought to the surface. This results in changes in the physical state of the fluid including temperature and pressure drop and fluid phase separation into water and steam. In turn, these changes disrupt the equilibrium conditions, potentially causing chemical reactions including mineral precipitation.

Scaling potential assessment for a production field prior to production is important. Through such an assessment, a potential scaling problem may be overcome by changing the P-T conditions of utilization

or fluid handling of mineral supersaturated geothermal brine. The three processes that may cause mineral scaling during geothermal fluid utilization are boiling, cooling and mixing. Depressurization boiling and the removal of steam from a geothermal fluid increases the concentration of non-volatile dissolved constituents in the residual boiled water as the same amount of solutes are dissolved in less amounts of water. Removal of heat through the heating of a secondary fluid leads to lowering of the temperature of the geothermal brine. The solubility of certain dissolved components like silica is related to the temperature of the fluid. Scales of various types form during exploitation. These include sulphides, calcite, silica, dolomite, and clays among others. Scales of greatest concern on surface installations and injection wells are sulphide and silica scales and calcite in production wells and the pressure reduction zones around them.

The extent to which utilization of high-temperature geothermal fluid can be put to use is mostly limited by the saturation state of silica in the fluid (Gunnarsson et al., 2010; Brown, 2011). Dissolved silica and pH value set the lower temperature at which a geothermal fluid can be safely used without the risk of silica scaling. This can set a limit to the amount of heat that can be extracted from the geothermal fluid and, therefore, the efficiency of the geothermal power plant. If set at a lower temperature, silica precipitation can clog valves, transport pipes (and other surface installations), reinjection wells and the receiving aquifer of the re-injected, spent geothermal waters. The solubility of quartz controls the amount of silica dissolved in the fluid in most geothermal systems (Fournier, 1982) and hot geothermal water extracted from geothermal systems corresponds to the solubility of quartz at reservoir temperature (Bohlman et al., 1980; Brown, 2011). Quartz precipitation has very slow kinetics in temperatures below 300°C (Bohlman et al., 1980) and, because of this, it is not readily precipitated from solutions upon utilization of the geothermal fluid.

If heat is extracted from the geothermal fluid beyond the point of amorphous silica solubility by second stage boiling or conductive cooling, the fluid becomes silica supersaturated. Two processes have a tendency to take place in silica supersaturated solutions. One is direct deposition of monomeric silica on an existing surface and the other is a homogenous formation of silica polymers (Gunnarsson and Arnórsson, 2005). Depending on the chemical composition of the fluid, these polymers either stay in solution or settle out of solution to form scales (Gallup 2011; Brown 2011). If the salinity of the fluid is low, the silica polymers stay in solution; the net outcome of polymerization is lowering the risk of silica scaling (Gunnarsson and Arnórsson, 2005).

Upon boiling of geothermal fluids, volatile components partition fully or partially into the steam phase. Among these volatiles are CO_2 and H_2S that are generally the two main acids in geothermal fluids. The loss of acid from the water to steam phase results in a pH increase of the boiled water which may trigger mineral precipitation of carbonates. Indeed, calcite scaling often takes place upon boiling. Chemical inhibitors have been used to prevent such scaling (Ngothai et al., 2010). Also, high wellhead pressures have to be maintained at the wellhead to prevent boiling within the production wells and to prevent scaling (Mroczek and Graham, 2001).

Anhydrite ($CaSO_4$) is precipitated from solution upon a drop in temperature. It exhibits retrograde solubility. Ca and SO_4 are both non-volatiles and their concentrations increase in the water phase upon boiling, possibly leading to supersaturation.

In this report, potential scaling associated with geothermal fluids from the Hverahlíd geothermal field of Hengill geothermal area, SW-Iceland, was investigated. Hverahlíd is a high-temperature geothermal field that is at production drilling stage. Several wells have been drilled and the field shows good potential for further development. The scaling potential was assessed in the production wells. Also, scaling potentials upon fluid mixing and phase separation (boiling) to form steam and waste water were carried out; scaling potentials upon re-injection, after electricity production treatment of the separated waters to enhance heat extraction after separation, were done for other low pressure uses. Modelling for scaling in spent water for reinjection was carried out and potential for scaling in the reinjection wells and receiving aquifer was assessed.

2. HENGILL GEOTHERMAL SYSTEM

2.1 General settings

The Hengill geothermal system is situated ~30 km east of Reykjavík in SW Iceland (Figure 1). It hosts four high-temperature geothermal fields: Hverahlíd, Hellisheidi, Nesjavellir, and Bitra. It is one of the most important geothermal fields in Iceland for district heating and electricity for Reykjavík city. As of today, of the four, Hellisheidi and Nesjavellir have been developed whereas Hverahlíd and Bitra have not. The production capacity at Nesjavellir power plant is 300 MWt and 120 MWe and at Hellisheidi the capacity is 133 MWt and 303 MWe. Four wells have been drilled in Hverahlíd and there is a plan to drill more wells (Níelsson and Franzson, 2010).

High-temperature geothermal resources in Iceland are associated with the North Atlantic Ridge and a mantle plume (Ágústsson and Flóvenz, 2005; Hardarson et al., 2009). The mantle plume has migrated over the course of geological history to the southeast relative to the North Atlantic Ridge, and a subsequent movement to the east. This caused shifts in the spreading axis over Iceland towards the


FIGURE 1: Location of Hverahlíd geothermal field; the NE-SW line are faults conforming to the Iceland neovolcanic zone that hosts high-temperature resources in the country (Gunnarsson et al., 2010)

east. In the Hengill area, the spreading axis is joined by a minor transform component, forming a triple junction. Micro seismic events occur in this transform component and may be influential especially on keeping permeability structures open (Hardarson et al., 2010).

The Hengill geothermal system comprises the Hengill central volcano, fissures swarms and lava flows. The system is in a graben with a NE-SW strike, extending up to 40 km NE of Hengill Mountain and a width of 3-5 km. It has a throw of 300 m to the west of Hengill. The same amount of throw is thought to occur in the east, though this is not apparent (Franzson et al., 2010). It is thought that the throw to the east may be in a series of small normal step faults. Within this graben is a series of dyke swarms and faulting with Hengill volcano as the loci of highest volcanic accumulation (Hardarson et al., 2009). The age of the Hengill system has been placed at 300,000 years from geologic studies in wells in the Nesjavellir field in the north, though studies in the south at Hellisheidi revealed an age of 400,000 years. The age at Hellisheidi has been placed as the maximum age of the geothermal system (Franzson et al., 2005).

The Hengill Mountain is built up of hyaloclastites and lava flows with the lava flows occurring in the interglacial periods. Hyaloclastites are rocks erupted in the base of glaciers allowing them to accumulate and form the highlands. The hyaloclastites are of limited extent and because of this they do not serve as good marker horizons for geological correlation. Felsic rocks can also be found to the southwest of the mountain; these are more evolved rocks. During interglacial periods, lava flows from the central volcano flowed to the surrounding lowlands. Basaltic fissure eruptions have occurred since the last glacial period of Holocene. Dates of these post glacial eruptions have given rise to three ages of 9, 5 and 2 thousand years ago for the lava flows (Níelsson and Franzson, 2010). Hverahlíd lies in the lowlands southwest of Hengill and outside of the central volcano. Although there is no seismic evidence
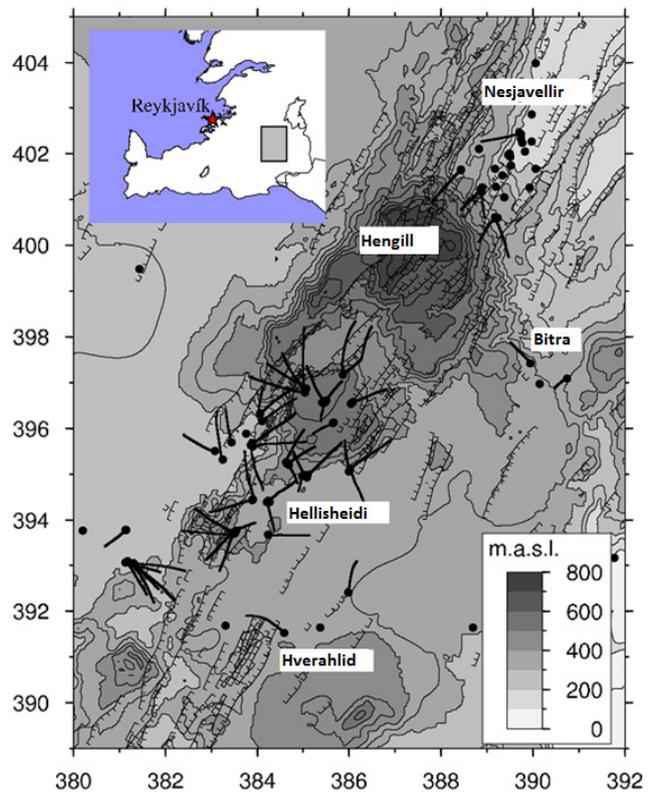
of a magma chamber underlying the root of Hengill central volcano (Franzson et al, 2010), periodic injections of shallow crustal magma chambers or dyke swarms are thought to be the source of heat driving the system (Hardarson et al., 2010).

2.2 Hverahlíd geothermal field

Hverahlíd field is located southeast of Hengill volcano and associated with the NE-SW structures of the Hengill system. Surface manifestations are reported there (Níelsson and Franzson, 2010) and are manifested in a structure that is a few metres wide, stretching 400 m with a strike in a NE-SW direction. The first well drilled in this field, HE-21, was drilled to target structures feeding the surface manifestations. Injection tests, carried out later for this first well, induced micro-seismic events in the area to the west. Well HE-36 was sited 1 km west of Well HE-21 to test the structures to the west of the field. Other wells have been drilled to test various structures in the field. They are vertical and direction wells.

Information on the geology and subsurface mineral alteration obtained from the analysis of drill cuttings taken at 2 m intervals are considered in this section. Studies from well cuttings for Well HE-36 reveal the geology of Hverahlíd. It shows post glacial lavas are found at the top 100 m with a pillow basalt formation below that. Below the pillow basalts are tuffaceous formations extending to a depth of 450 m below sea level. Lava formations continue from the base of the tuffaceous formation to 1000 m b.s.l. This has been interpreted as the base of the Hengill volcano (Níelsson and Franzson 2010). There are intrusive bodies at depth that have been identified in the well cuttings. These are of basaltic and andesitic composition and they are identified from their compact nature and the alteration in their margins.

Permeable zones have been interpreted as occurring where there is a loss of circulation during drilling, from temperature logs and hydrothermal alteration mineralogy. Well HE-36 shows feed zones at 750-950 m b.s.l. (Níelsson and Franzson, 2010). Though pillow basalts are highly porous, they have rather poor permeability, especially when they are altered (Franzson et al., 2005).

Alteration mineralogy encountered in wells drilled in Hverahlíd show a suite of alteration from low-temperature zeolites to amphibole at high temperatures. Major alteration horizons are marked by the appearance of quartz at temperatures of 180°C, epidote at temperatures above 250°C and amphibole above 280°C. Comparison of alteration mineralogy with present day formation temperature reveal recent heating in some parts of the field as observed in temperature reversal with depth for Well HE-36.

From studies of the Hengill geothermal field, the wells discharge water of Na-Cl-HCO$_3$ composition with considerably low chloride content of below 200 ppm (Scott, 2011). The source of the fluids for Nesjavellir has been inferred to come from Langjökull glacier while that of Hellisheidi is from local precipitation from isotope studies (Mutonga et al., 2010). Waters from Nesjavellir and Hellisheidi plot mostly on the partial equilibrated waters on the Na-K-Mg ternary plot but within mature waters on a Cl-SO$_4$-HCO$_3$ ternary plot.

3. METHODS AND RESULTS

3.1 Sampling and analysis of geothermal water and steam

The samples from Hverahlíd used in this report were obtained from Wells HE-21, HE-36, HE-53 and HE-54. The sampling methods have been outlined in detail by Arnósson et al. (2006). Steam and water from two-phase well discharges were separated using a Webre separator. It is important that the separator is well insulated to prevent steam condensation. Pressure and/or temperature of separation need to be measured. Sampling of high enthalpy fluids poses a particular challenge due to the high

steam to water ratio and problems of steam condensation in the water phase. The water phase was cooled using a stainless steel coil. A liquid water phase, free of steam contamination, was collected by ensuring that there were no gas bubbles in the liquid after cooling.

The pH of the water phase was measured on site and samples for the determination of dissolved inorganic carbonate (DIC) were collected into air tight amber glass bottles for later determination in the laboratory. Samples for H_2S analysis were collected in a similar way for on-site analysis. Samples for determination of major cations including Si, B, Na, K, Mg, Ca, Al, and Fe were filtered through a 0.2 µm pore cellulose acetate membrane into high density polyethylene plastic bottles and acidified to 0.5% using Suprapur HNO_3. Samples for F and Cl determination were filtered as described above but not further treated. Samples for SO_4 analysis were also filtered as described above, followed by the addition of 2 ml of 0.2 M Zn-acetate in order to precipitate H_2S out of solution. A further sample for SiO_2 analyses was collected; this sample was not filtered and was diluted on site with deionized water at a 1:10 ratio.

Steam samples were collected into pre-evacuated gas bulbs containing 10-15 mL 50% KOH solution. During sampling, the gas-bulb was continuously cooled to condense the steam. In addition, H_2S and CO_2 were dissolved into the alkaline steam condensate whereas the other non-condensable gases including N_2, H_2, CH_4, Ar and O_2 were enriched in the gas phase.

The chemical analyses were carried out according to standard methods for geothermal fluid analysis. For the water phase, the H_2S concentration was determined on-site using Hg-acetate titration (Arnórsson et al., 2000; Arnórsson et al., 2006). Other chemical analyses were carried out in the laboratory. The pH was analysed using a combination glass electrode and the DIC concentration was determined using modified alkalinity titration (Arnórsson et al., 2000; Stefánsson et al., 2007) within 1-2 days of sampling. The major cations, Si, B, Na, K, Mg, Ca, Al, and Fe, were analysed using ICP-OES, whereas the major anions Cl and F were determined in filtered and untreated samples, SO_4 in filtered samples and Zn-acetate treated samples by using ion chromatography.

The concentration of H_2S and CO_2 in steam samples was analysed in the steam condensate using Hg-acetate and modified alkalinity titration, respectively (Arnórsson et al., 2000). The non-condensable gases were analysed using gas chromatography.

3.2 Calculation of aquifer fluid composition

Fluid composition was calculated beyond the level of boiling from the samples of two-phase well discharges collected at the surface. In addition, the fluid composition was simulated upon boiling and mixing from the parent aquifer fluids. These calculations were carried out using the WATCH program (Arnósson et al., 1982; Bjarnasson, 2010). For these calculations, conservation of enthalpy and mass was assumed. For conservation of enthalpy we have:

$$h^t = Xh^v + (1 - X)h^l \tag{1}$$

and

$$X = \frac{h^t - h^l}{h^v - h^l} \tag{2}$$

Where h^t is the total enthalpy of the fluid, h^v is the enthalpy of the vapour phase, h^l is the enthalpy of the liquid water and X is the steam fraction.

Similarly, the conservation of mass for the i-th component may be defined:

$$m_i^t = Xm_i^v + (1 - X)m_i^l \tag{3}$$

where m_i^t is the concentration of the *i*-th component in the total fluid, m_i^v is the concentration of the *i*-th component in the steam phase and m_i^l = the concentration of the i-th component in the liquid water phase.

For non-volatiles that do not enter into the steam phase upon boiling, m_i^v is equal to zero and the concentration in the total aquifer fluids becomes:

$$m_i^t = (1 - X)m_i^l \qquad (4)$$

where X is the steam fraction of the discharge fluids at sampling.

For volatile components that only partition in the steam phase we have:

$$m_i^t = m_i^v x \qquad (5)$$

Some components partition both in the water and the vapour phase. These are usually gases (CO_2 and H_2S). An equation for calculating the concentration of the two phases is given by:

$$D_s = \frac{n_v^S}{n_l^S} \qquad (6)$$

where D_s is the distribution coefficient for water and steam phase, n_v^S is the molal concentration of the gas in the steam fractions and n_l^S = the molal concentration of the gas in the water fractions.

The calculations of aquifer fluid composition beyond the level of boiling require the selection of an aquifer temperature. In the present study, the aquifer temperatures were calculated assuming equilibrium with quartz, i.e. using the quartz geothermometry temperature. Alternatively, the measured temperatures of the producing aquifers may be used when available.

3.3 Aqueous speciation and mineral saturation

Aqueous speciation and mineral saturation were calculated with the aid of the WATCH program (Arnórsson et al., 1982; Bjarnasson, 2010).

The mineral saturation index (SI) is defined as the logarithm of the ratio of the reaction quotient (Q) to the equilibrium solubility (*K*) of a particular mineral reaction:

$$SI = \log(Q/K) \qquad (7)$$

where *Q* is defined as the activity product of the respective water,

$$Q = \prod a_i^v \qquad (8)$$

where a_i is the activity of the aqueous species to the stoichiometric power for the reaction. The stoichiometric power is negative for reactants and positive for products.

The three major mineral reactions considered in this study are silica, carbonate and anhydrite scaling. The dissolution for solid silica is defined according to:

$$SiO_{2(s)} + H_2O = H_4SiO_{4(aq)} \qquad (9)$$

The equilibrium constant for this reaction may be defined for various polymorphs of silica including amorphous silica, chalcedony and quartz (Gunnarsson and Arnórsson, 2000). The reaction quotient for the reaction is defined as:

$$Q = aH_4SiO_{4(aq)} \qquad (10)$$

For calcium carbonate, the dissolution is defined according to:

$$CaCO_{3(s)} = Ca^{2+} + CO_3^{2-} \qquad (11)$$

and the reaction quotient is defined as:

$$Q = aCa^{2+} \, aCO_3^{2-} \tag{12}$$

For anhydrite, the dissolution is defined according to:

$$CaSO_{4(s)} = Ca^{2+} + SO_4^{2-} \tag{13}$$

and the reaction quotient is defined as:

$$Q = aCa^{2+} aSO_4^{2-} \tag{14}$$

The equilibrium solubility of calcite and anhydrite was taken from Arnórsson et al. (1982).

From the activities of the respective species and the mineral solubilities, the mineral saturation states may be determined. At equilibrium SI = 0, whereas if SI>0, the fluids are supersaturated with respect to the mineral and if SI<0 the fluids are undersaturated with respect to the mineral.

3.4 Boiling, mixing and mineral scaling

The potential calcite and silica scaling were assessed in this study along the production line from the data on aquifer fluids and well discharges. After the steam separation pressure for the field was chosen, the steam fraction at the separation pressure was obtained and used to calculate the liquid fraction. The discharge rate for each well was used to compute the water discharge rate after separation. The separated water was then boiled to 2 bars absolute and conductively cooled to 60°C. This water was subsequently diluted with condensate. The chemistry of the condensate was obtained from experience in the other fields of Nesjavellir and Hellisheidi in Hengill geothermal area. Mixing ratios for the separated water was done with the condensate from 90% separated water and 10% condensate to 30% separated water and 70% condensate. The mixture was then heated to 250°C to simulate re-injection. For each step the SI for amorphous silica, calcite and anhydride were computed using the same method described above for amorphous quartz, but the SI for calcite and anhydrite was computed by the program using log K and log Q.

Some analysis was done in the lab to measure the total concentration of the component in the solution. Another analysis was made of the active part of the component that was sensitive to the method applied. The components, however, for example C and Si in a geothermal fluid, can exist in several forms in solution which are $H_2CO_3^0$, HCO_3^- or CO_3^{2-} for carbon and $H_4SiO_4^0$, $H_3SiO_4^-$, and $NaH_3SiO_4^0$ for silica. The distribution of various species in a geothermal fluid is a function of pH, the ionic strength and redox potential of the fluid. As a result, care must be taken in the measurement of the pH as pH is a function of temperature for calculations in other temperatures. The sum of the ions of weak acids was taken to be constant at all temperatures (Arnórsson et al., 1982). The sum of the ions of weak acid can be used to derive the pH at a different temperature deduced from that of measured pH. The sum of weak acid used in this report was calculated as follows:

$$\sum weak\ acids = mOH^- + mH_3SiO_4^- + 2mH_2SiO_4^{2-} mH_2BO_3^- + mHCO_3^- + 2mCO_3^{2-} + mHS^- \\ + 2mS^{2-} \tag{15}$$

where *m* is the *molal* concentration of the charged species contributing to the weak acids in the fluid.

3.5 Results

3.5.1 Sampled fluid composition

The results of chemical analysis for Hverahlíd wells carried out in the lab are presented in Table 1. The waters show typical composition of high-temperature geothermal waters that have undergone boiling.

The pH is alkaline and major elements in the water phase include SiO_2, Na and Cl, whereas the major gases in the vapour phase include CO_2, H_2S and H_2.

3.5.2 Aquifer fluid calculations

The composition of deep aquifer fluid beyond the zone of boiling was calculated for individual wells based on the chemical composition of the water and vapour at the wellhead. The calculations were carried out with the aid of the WATCH speciation program. The temperatures were calculated assuming equilibrium with quartz, i.e. the quartz geothermometry temperatures were used, and deep liquid enthalpy was used to estimate possible aquifer steam fraction and aquifer vapour composition. The results are listed in Table 2. The aquifer fluids discharged by various wells at Hverahlíd show very similar composition for non-volatiles, including Na, Cl and SiO_2 with the expectation of Well HE-36 being much lower in SiO_2 than the other wells. However, the volatile concentration is somewhat variable. The main reason for this is considered to be the difficulties in calculating the exact mass of the aquifer vapour; the volatile concentrations are very sensitive to aquifer vapour fraction.

TABLE 1: Well discharge fluid composition of Hverahlíd geothermal field

Well	HE-36	HE-21	HE-54	HE-53
Well head pressure	19	25	30.2	35
Sample no.	08-5119	11-5096	11-5185	11-5062
Sampling pressure	7.2	5.1	18.8	8
Water (ppm)				
pH/°C	9.31/23	7.87/24	8.06/24	7.87/19
CO_2	3.10	34	30.4	3.79
H_2S	77.4	6.63	21.6	15.6
B	0.863	2.13	1.22	1.30
SiO_2	557	1035	964	1071
Na	220	276	245	266
K	33.8	65.4	65.7	66.0
Mg	0.030	0.019	0.007	0.001
Ca	2.03	0.596	0.569	0.513
F	1.48	0.965		0.833
Cl	252	448	378	430
SO_4		6.49	3.26	3.80
Al	1.52	1.25	0.972	1.17
Fe	0.060	0.069	0.015	0.007
Vapour				
L gas/kg condensate			0.172	0.399
CO_2 (ppm)	1572	4199	2966	1472
H_2S (ppm)	1180	355	792	630
H_2 (%)			60.54	71.25
N_2 (%)			38.75	26.40
CH_4 (%)			0.70	0.52
O_2 (%)				0.1

4. DISCUSSION

Utilization of geothermal fluids poses several challenges. Among these challenges is scaling. Scaling is the precipitation of minerals from the fluid which coat the surfaces inside equipment in geothermal installations, from the well bore casing inside the well, steam gathering systems, feeding separator stations, in separator stations and in pipes carrying separated water to reinjection wells. Scaling inside wells leads to a reduction in output of production wells; there may be a sharp decline or a gradual fall in output. Spent geothermal fluids are re-injected in many geothermal fields in the world today. Re-injection wells and the receiving aquifer may suffer scaling and mineral precipitation. The potential for scaling in geothermal fluid can be evaluated through speciation programs.

4.1 Scaling potential evaluation of Hverahlíd during production

Evaluation for scaling was taken in steps from production wells to reinjection. The processes that contribute to the processes of scaling that were looked at in this evaluation include adiabatic boiling and conductive cooling. For evaluation of scaling potential in production wells, stepwise adiabatic boiling

of individual well aquifer fluids was done. The boiling process assumed conservation of mass and enthalpy. At each temperature step, the solubility quotient of amorphous silica, calcite and anhydrite was obtained. Similarly, the solubility constant for the 3 minerals was obtained. The saturation index (SI) for each mineral was calculated according to Equation 7.

4.1.1 Amorphous silica saturation state

Evaluation for scaling was taken in steps from production wells to reinjection. The processes that contribute to the processes of scaling that were looked at in this evaluation include adiabatic boiling and conductive cooling. For evaluation of scaling potential in production wells, stepwise adiabatic boiling of individual well aquifer fluids was done. The boiling process assumed conservation of mass and enthalpy. At each temperature step, the solubility quotient of amorphous silica, calcite and anhydrite was obtained. Similarly, the solubility constant for the 3 minerals was obtained. The saturation index (SI) for each mineral was calculated according to Equation 7.

The saturation index of amorphous silica in production wells in Hverahlíd is shown in Figure 2. In all cases, the fluids are undersaturated at aquifer conditions. The degree of undersaturation is, however, variable. It is lower in Well HE-36 compared with Wells HE-21, HE-53 and HE-54. Consequently, the fluids became amorphous silica saturated at a much lower temperature for Well He-36 or at 122°C compared to the other three wells which became saturated with amorphous silica as follows: Well HE-21 at 198°C, Well HE-54 at 201°C and Well HE-53 at 204°C. In order to avoid amorphous silica saturation and prevent scaling, a separation temperature was chosen above these temperatures or at 205°C. This

TABLE 2: Aquifer fluid chemistry of Hverahlíd geothermal field for wells

|	HE-36	HE-21	HE-54	HE-53
Temperature (°C) (T^{qtz})	247	304	312	315
Liquid phase (ppm)				
pH	7.40	7.21	7.37	7.08
B	0.717	1.42	0.911	0.887
SiO_2	463	692	721	729
Na	183	185	183	181
K	28.1	43.8	49.1	44.9
Mg	0.025	0.013	0.005	0.001
Ca	1.69	0.40	0.43	0.35
F	1.23	0.649		0.565
Cl	209	300	283	293
SO_4		4.34	2.44	2.59
Al	1.26	0.838	0.727	0.794
Fe	0.050	0.046	0.011	0.005
CO_2	44.6	204	160	76.4
H_2S	140	41.3	100	74.2
H_2			0.13	0.37
O_2			0	0.01
CH_4			0.01	0.02
N_2			1.02	1.62
Vapour phase (ppm)				
CO_2	3672	6713	4327	1998
H_2S	2339	523	150	813
H_2			13.2	33.2
O_2				0.74
CH_4			1.21	1.85
N_2			118	171
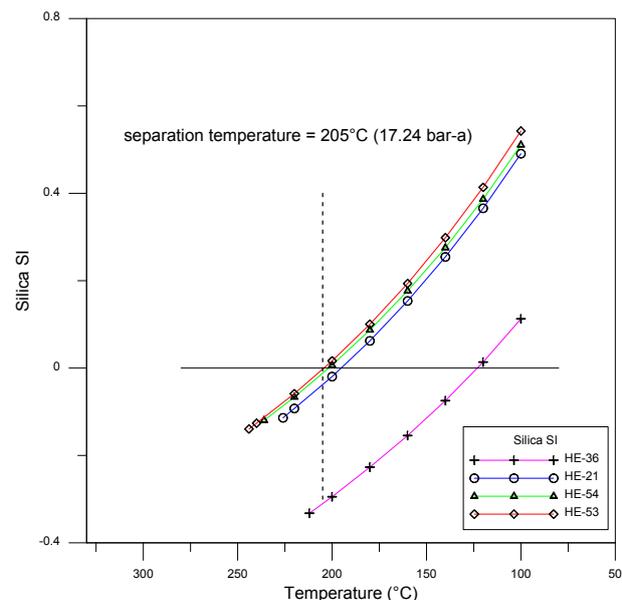
FIGURE 2: Amorphous silica scaling potential of Hverahlíd production wells upon boiling of aquifer fluid

temperature corresponds to the liquid and steam pressure value of 17.24 bars absolute.

4.1.2 Calcite saturation state

The potential for calcite scaling was assessed in a similar manner as for amorphous silica. For these calculations CO_2 degassing was assumed to be at equilibrium or less, i.e. degassing coefficients of 0.1, 0.5 and 1.0 were used. The results are shown in Figure 3. Calcite exhibits retrograde solubility as the temperature of water rises. Boiling enhances the removal of CO_2 from solution. At the same time, the main acids CO_2 and H_2S enter the vapour phase and the resulting boiled water becomes alkaline. This results in an increase of HCO_3^- and CO_3^{2-} species concentration. The combination of these effects lead to calcite supersaturation upon boiling. However, extensive boiling eventually leads to calcite undersaturation.
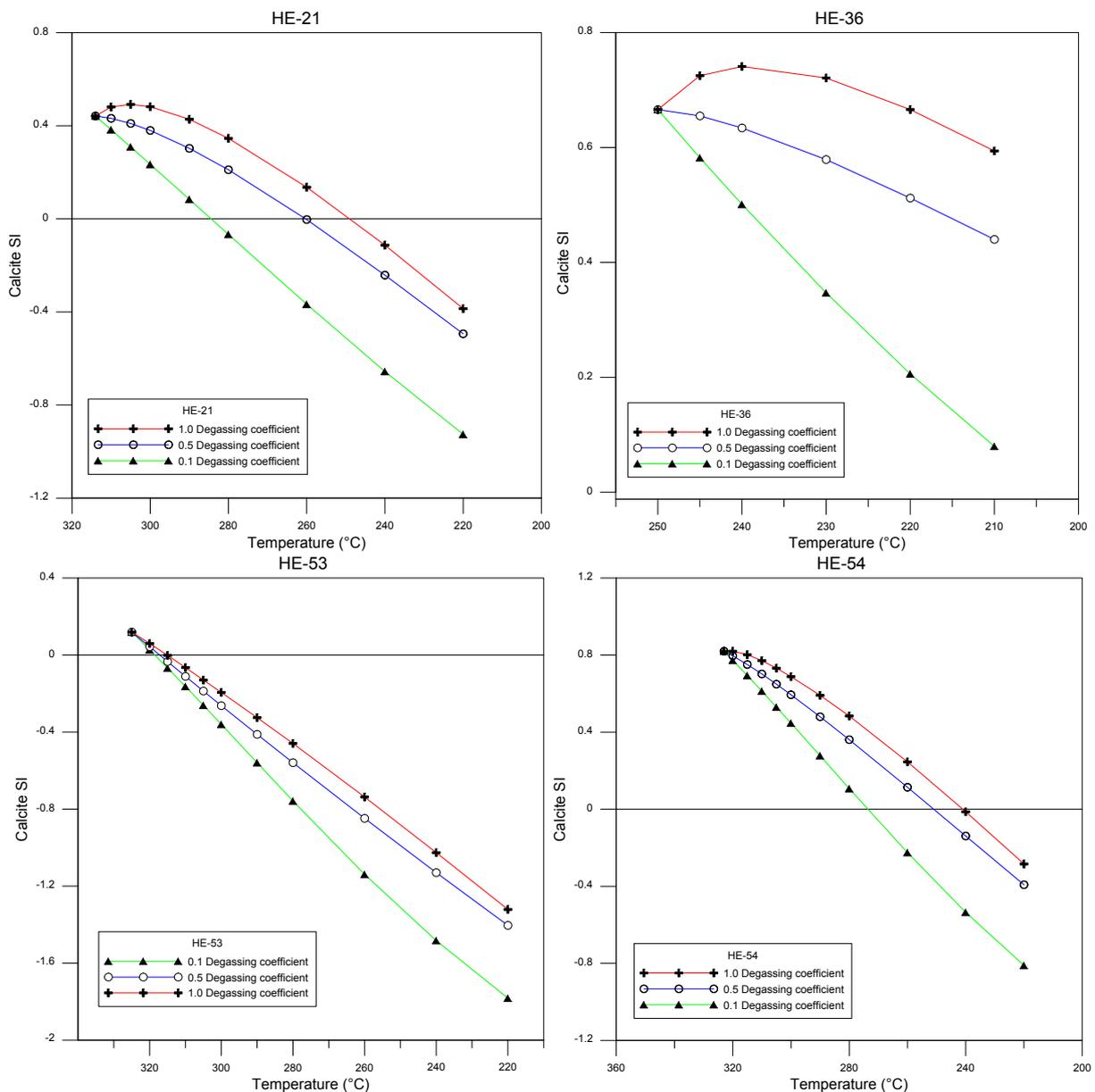
FIGURE 3: Calcite scaling potential of Hverahlíd production wells upon boiling of aquifer fluid

4.1.3 Anhydrite saturation state

All the wells considered for Hverahlíd show anhydride undersaturation with respect to the aquifer fluids and upon boiling. Anhydrite scaling in the production wells is, therefore, not considered a potential risk (Figure 4). The SI for anhydrite for Well HE-36 was not evaluated due to missing results for SO_4 analysis.

4.2 Mixing of production wells separated water

The composition of the separated water mixture was calculated based on the fluid discharge mass of each production well (Table 3). The steam fraction at the separation pressure for individual wells was subtracted from the total mass of the wells to obtain the water fraction. The water fractions from various wells was then added together to obtain the respective water mixture. The concentration of the various components in the mixture is given in Table 4. The pH for the mixture was modelled based on conservation of alkalinity. A model for the calculation of the pH for the separated well water mixture is shown in Figure 5.
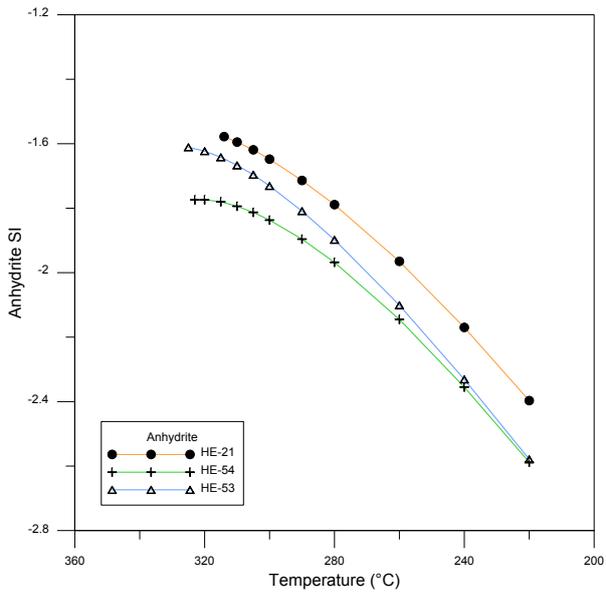
FIGURE 4: Anhydrite scaling potential in Hverahlíd production wells upon boiling of aquifer fluid

TABLE 3: Well discharge characteristics of Hverahlíd geothermal field

	HE-36	**HE-21**	**HE-54**	**HE-53**
Discharge Q (total) kg/s	22.9	59.5	85.1	46.5
Steam fraction separation (205°C/17.24 bar-a)	0.19	0.49	0.49	0.58
Water discharge (kg/s)	18.59	30.35	43.15	19.60

TABLE 4: Separated water composition in ppm

Water pH/T (°C)	7.15/ 205
B	1.33
SiO_2	888
Na	239.7
K	57.5
Mg	0.01
Ca	0.76
F	0.60
Cl	365
SO_4	3.5
Al	1.11
Fe	0.03
CO_2	19.8
H_2S	34.5
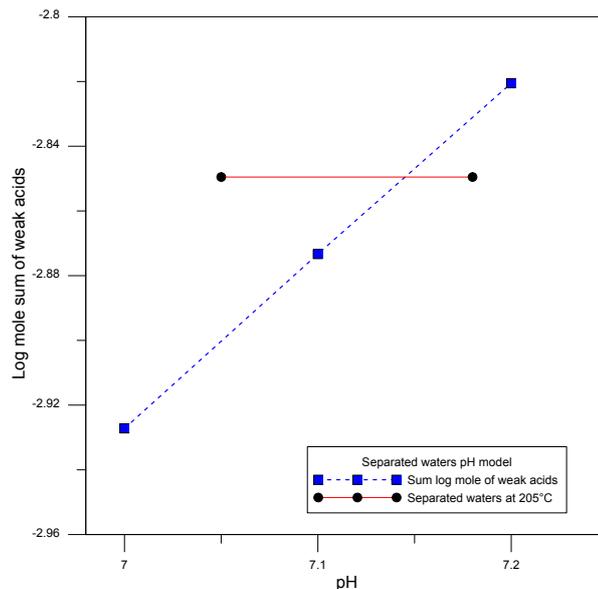
FIGURE 5: Log mole sum of weak acids calculated at 205°C at guessed pH values of 7, 7.1 and 7.2; Log mole sum of weak acids calculated for the separated water is fitted into this model to find the true pH of separated water

4.3 Scaling potential during reinjection

The fluid reinjection experience at Hengill area is that separated water reinjected at wells at high temperatures is more likely to cause scaling problems in the receiving aquifer, reducing its permeability due to silica scaling, than when reinjection is done for fluids at a lower temperature (Hardarson et al., 2010). As a result, the temperature of the separated waters was reduced through adiabatic boiling of the well mixture at 205°C. The separated water mixture at 17.24 bar-absolute was adiabatically boiled to 2 bar-a. The purpose of this was to maximise the usage of the heat from the water to run a possible low pressure turbine. The fluid was conductively cooled from 2 bar-a (Table 5) to 60°C. At each step of the two processes, scaling potential for all three minerals was evaluated. Figures 6, 7 and 8 show the saturation index of amorphous silica, calcite and anhydrite, respectively, upon boiling and conductive cooling.

TABLE 5: Separated water composition in ppm, adiabatically boiled to 120°C

Water pH/T (°C)	7.717/ 120
B	1.6
SiO_2	1068
Na	288
K	69.1
Mg	0.012
Ca	0.91
F	0.7
Cl	439
SO_4	4.16
Al	1.34
Fe	0.04
CO_2	0.8
H_2S	4.7
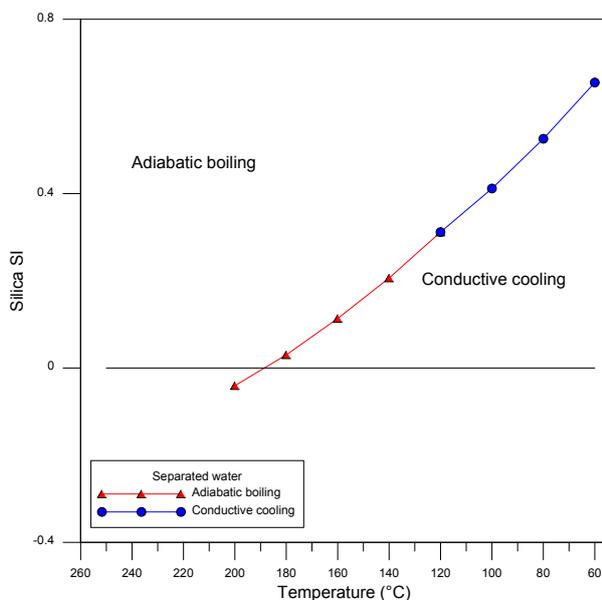
FIGURE 6: Amorphous silica saturation index of separated waters upon adiabatic boiling from 205°C to 120°C and subsequent conductive cooling to 60°C
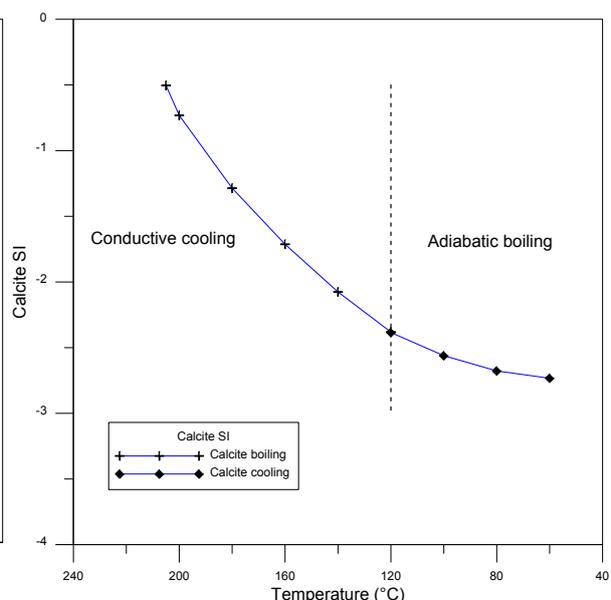
FIGURE 7: Calcite saturation index of separated waters upon adiabatic boiling from 205°C to 120°C and subsequent conductive cooling to 60°C

4.4 Dilution of separated water with condensate

To prevent possible scaling upon re-injection, steam condensate and separation water may be mixed with waste water. Condensate was added to the separated water mixture at various ratios. This was done at 7 ratios as follows: 90% separated water 10% condensate, to 30% separated water 70% condensate. The composition for each of the mixtures was then computed based on the ratio of the separated water to the condensate as described for the mixture after separation. The condensate essentially is steam condensed after expansion in the turbine and consequent cooling in the condenser and cooling tower in geothermal power stations and has no non-volatile components dissolved in it except for condensable gases (CO_2 and H_2S) at 1 ppm. The pH of each of the mixtures was then modelled as described above for separated water from production wells (Figure 9). Table 6 shows the
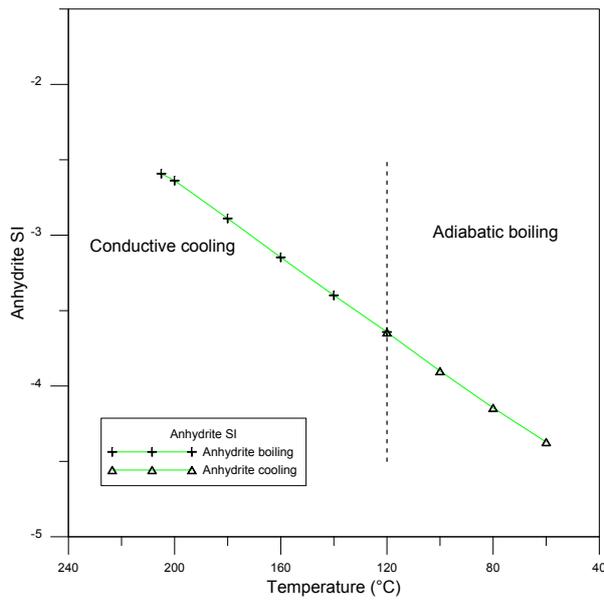
FIGURE 8: Anhydrite saturation index of separated waters upon adiabatic boiling from 205°C to 120°C and subsequent conductive cooling to 60°C
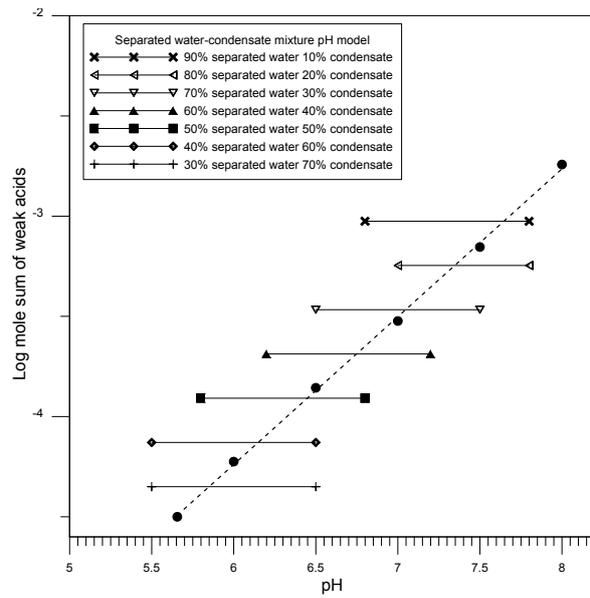
FIGURE 9: Log mole sum of weak acids calculated for separated waters-condensate mixture at 25°C with fits of actual sum log mole of weak acids for the mixture at various ratios

composition of the condensate-separated water at various ratios. The change in the saturation index of the minerals in the fluid upon mixing the separated water with condensate at the various ratios was evaluated. Figures 10, 11 and 12 show the saturation index of amorphous silica, calcite and anhydrite, respectively, upon this dilution.

TABLE 6: Separated water-condensate mixture composition at various mixing ratios in ppm

Separated water-condensate mixture	90% brine 10%cond.	80% brine 20%cond.	70% brine 30%cond.	60% brine 40%cond.	50% brine 50%cond.	40% brine 60%cond.	30% brine 70%cond.
pH/T (°C)	7.63/25	7.33/25	7.04/25	6.74/25	6.45/25	6.15/25	5.86/25
$T_{Mixture}$ (°C)	94.5	89	83.5	78	72.5	67	61.5
B	1.44	1.28	1.12	0.96	0.80	0.64	0.48
SiO_2	961	854	748	641	534	427	320
Na	260	231	202	173	144	115	86
K	62.2	55.3	48.4	41.5	34.6	27.6	20.7
Mg	0.01	0.01	0.008	0.007	0.006	0.005	0.004
Ca	0.82	0.73	0.64	0.55	0.46	0.36	0.24
F	0.65	0.58	0.51	0.43	0.36	0.29	0.22
Cl	395	351	307	263	220	176	133
SO_4	3.7	3.3	2.9	2.5	2.1	1.7	1.2
Al	1.2	1.1	0.9	0.8	0.7	0.5	0.4
Fe	0.03	0.03	0.03	0.02	0.02	0.01	0.01
CO_2	0.82	0.84	0.86	0.88	0.9	0.92	0.94
H_2S	4.34	3.97	3.60	3.23	2.86	2.48	2.11
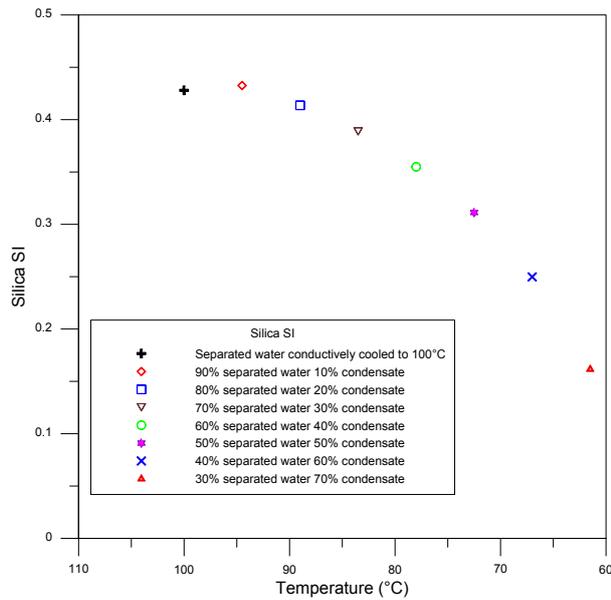
FIGURE 10: Amorphous silica saturation index of separated water after conductive cooling to 100°C and mixing with condensate at 45°C at various ratios of separated water to condensate
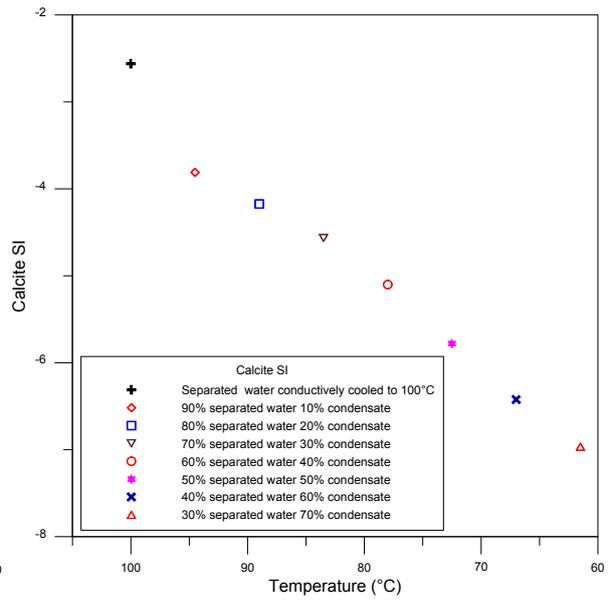

FIGURE 11: Calcite saturation index of separated water after conductive cooling to 100°C and mixing with condensate at 45°C at various ratios of separated water to condensate

4.5 Mineral saturation state in reinjection aquifer

To simulate for reinjection, the condensate separated water mixture was heated in steps of 25°C up to 250°C to simulate reinjection reservoir conditions. The calculations were carried out with the aid of the WATCH program (Bjarnason, 2010). Generally, calcite and anhydrite were undersaturated in the condensate mixture throughout and in the reinjection wells and with subsequent heating to 250°C (Figures 13 and 14). However, amorphous silica was found to be supersaturated at temperatures below 100-200°C, depending on the separated water to condensed steam mixing ratio (Figure 15).
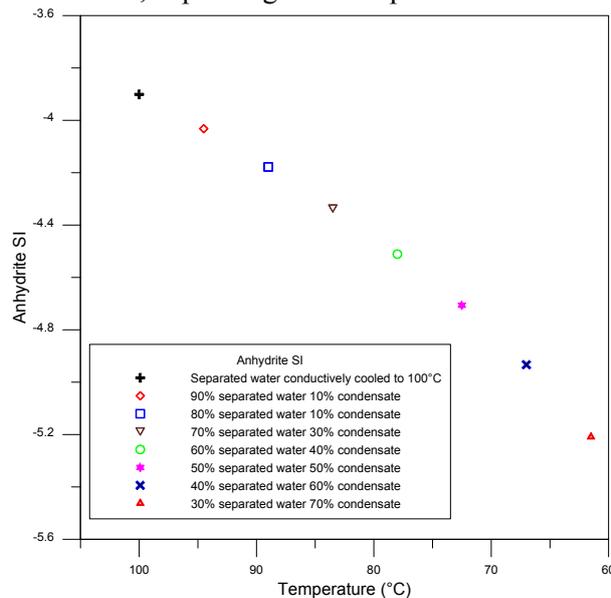
FIGURE 12: Anhydrite saturation index of separated water after conductive cooling to 100°C and mixing with condensate at 45°C at various ratios of separated water to condensate
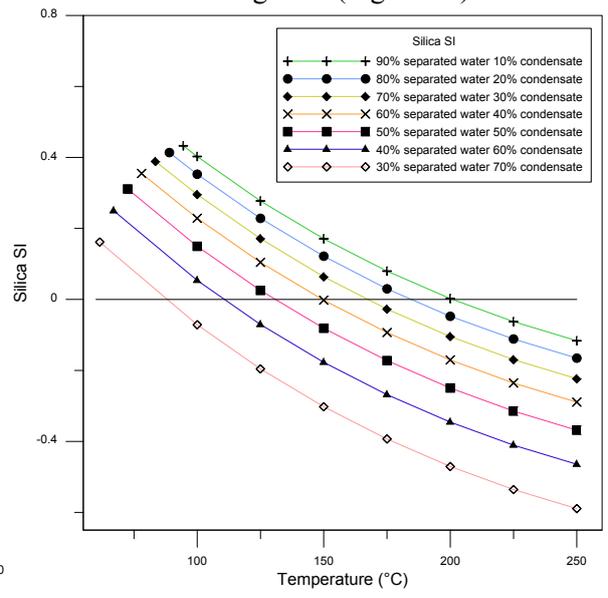
FIGURE 13: Amorphous silica saturation index of separated water-condensate mixture heated to 250°C to simulate heating at reinjection aquifer
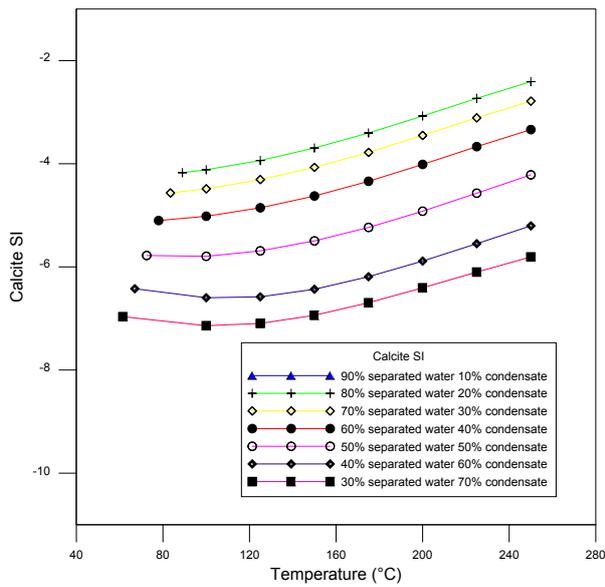
FIGURE 14: Calcite saturation index of separated water-condensate mixture heated to 250°C to simulate heating at reinjection aquifer
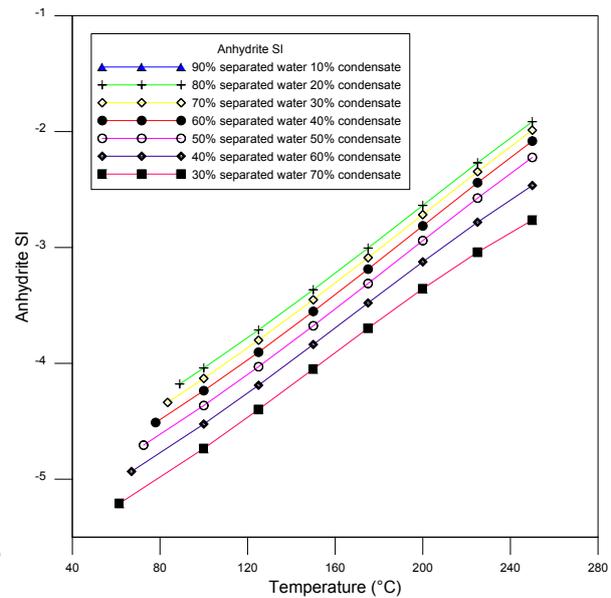
FIGURE 15: Anhydrite saturation index of separated water-condensate mixture heated to 250°C to simulate heating at reinjection aquifer

4.6 Summary

In summary, of greatest concern is silica scaling since it has the potential to occur in all the cases considered from production wells, separated water mixing and in reinjection. Figure 16 gives a summary of the silica saturation index at the various stages during utilization of the Hverahlíd fluids for the wells that were considered for this study.

Fluids with high dilution ratios of steam condensate were found to be less supersaturated than less steam diluted separated water.
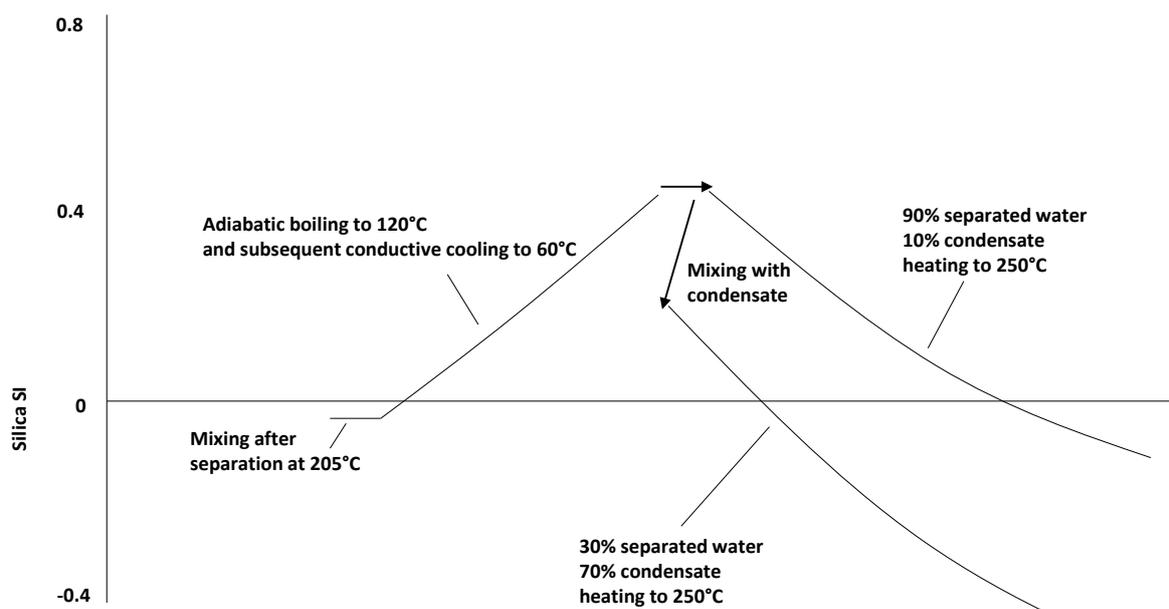
FIGURE 16: Silica saturation index of Hverahlíd high-temperature geothermal field from production wells, mixing of separated well fluids, utilization, dilution with condensate and reinjection

5. CONCLUSIONS

- Amorphous silica oversaturation was attained for the geothermal separated waters for Hverahlíd wells considered in this study. Steps should be taken to avoid silica scaling on surface installations upon use of the fluids after separation.
- There is a potential for downhole calcite scaling for Wells HE-21, HE-54 and HE-53. Monitoring for calcite scaling for the wells during production should be considered.
- There is no danger posed by anhydride scaling for any of the wells considered.
- The best reinjection composition for spent geothermal fluids is the composition of 30% separated water and 70% condensate. However, this may prove a challenge considering the availability of condensate water to meet the mixing ratio.

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