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Reducing Silica Deposition Potential in Waste Waters from Nesjavellir and Hellisheiði Power Plants, Iceland

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ABSTRACT

Silica deposition from spent geothermal water can be problematic. Correct fluid handling of amorphous silica supersaturated geothermal waters is very important for successful disposal of the water. In this contribution, treatment of spent geothermal water prior to injection from the Nesjavellir and Hellisheiði Power Plants are described. Utilization on the surface makes the separated geothermal waters supersaturated with respect to amorphous silica. Before disposal in Nesjavellir the waters are retained in a tank or pipe where the silica polymerizes and supersaturation with respect to amorphous silica is reduced from 411 ppm to 168 and 199 ppm SiO_2 when the flow rate of separated water is 106 and 163 l/s. Mixing with condensed steam after the retention tank in Nesjavellir further reduces the supersaturation to 63 and 94 ppm SiO_2 for the two flow rates. In Hellisheiði Power Plant silica supersaturation with respect to amorphous silica is reduced in a pipe from 206 to 136 ppm SiO_2 in the separated water before re-injection. This handling of separated water has been successful in Nesjavellir Power Plant where lower temperature of the separated water compared to Hellisheiði power station result in higher proportion of polymerized silica in the injection water.

1. INTRODUCTION

Scaling problems of spent high temperature geothermal waters often put limits on to what extent heat can be extracted from geothermal waters. When the waters cool down they often become supersaturated with respect to secondary minerals and their deposition makes fluid handling difficult. Geothermal waters in Nesjavellir and Hellisheiði geothermal areas are 250°C -320°C low salinity fluid. The main scaling problem from the geothermal fluids at Nesjavellir and Hellisheiði is the deposition of silica as the fluid cools down either by boiling or conductive cooling. Several methods have been proposed to reduce the risk of silica scaling. They include decreasing or increasing the pH of the waste water (Gill, 1993; Gudmundsson and Einarsson, 1989), mixing the waste water with water with low silica concentration (Gallup and Featherstone, 1985), adding organic inhibitors (Gallup, 2002, Candelaria et al., 1996), controlled precipitation by addition of silica gel (Sugita et al., 1998 and 1999), or cationic reactant to trigger silica deposition (Ueda et. al., 2000 and 2003) and storage in a retention pond (Yanagase et al., 1970). These methods have proven successful in individual geothermal areas but no universal method has been developed to prevent silica scaling.

When geothermal waters become supersaturated with respect to amorphous silica two kinds of processes have the tendency to take place. One is deposition of monomeric silica directly onto available surface and the other is polymerization of monomeric silica to form silica polymers. Which process takes place in spent high temperature geothermal waters depends to some extent on the waters environment. If the waters are in turbulent flow where there is surface available for monomeric deposition onto the surface silica scaling is likely to take place, but if the waters are placed in quiet environment silica polymerization is the favorable process. Many studies have been performed on the rate of silica polymerization (Weres et al., 1981; Rothbaum and Rhode, 1979; Crerar et al., 1981; Gunnarsson and Arnórsson, 2003, 2005 and 2008) and the rate has proved to be affected by pH-value, ionic strength, temperature and the degree of supersaturation with respect to amorphous silica. Despite many studies the mechanism of silica polymerization is not completely understood and reaction orders between 1 and 8 have been reported (Chan, 1989).

Silica polymerization is used to lower silica scaling potential in separated waters form Nesjavellir and Hellisheiði Power Plants, Iceland. The separated waters are aged in a retention tanks or a pipes allowing the monomeric silica in excess of amorphous silica solubility to polymerize. In this contribution we introduce the effectiveness of this method to lower amorphous silica supersaturation prior to re-injection.

2. INJECTION HISTORIES

2.1 Nesjavellir Power Station

The Nesjavellir Geothermal field is located within the Hengill Central Volcano in southwestern Iceland. Power generation started in Nesjavellir power station in 1990 with the production of 100 MW_t for district heating in Reykjavík. Hot water production has since been increased in several steps and was in 2005 290 MW_t. Electricity production started in 1998 with two 30 MW_e turbines. The third 30 MW_e turbine was added in 2001 and the fourth in 2005. Currently Nesjavellir Power station is producing 290 MW_t and 120 MW_e.

Until 2004 separated waters were disposed of on the surface into the Nesjavellir stream which flows by the power plant and disappears into the lava north of the power station. Condensed steam was until then injected into shallow drillholes north of the power station. The wastewaters mix with the local groundwater which flows through the lava bedrock into lake Þingvallavatn. This causes increase in temperature and concentration of dissolved elements in the local ground waters and in springs appearing on the south shore of lake Þingvallavatn. Injection tests were performed with a 40°C mixture of separated water (30%) and condensed steam (70%) in 1992 and 1993. Flow into the injection drill hole reduced by 50% probably due to precipitation of minerals in the drill hole or aquifers receiving the water (Gíslason, 1995).

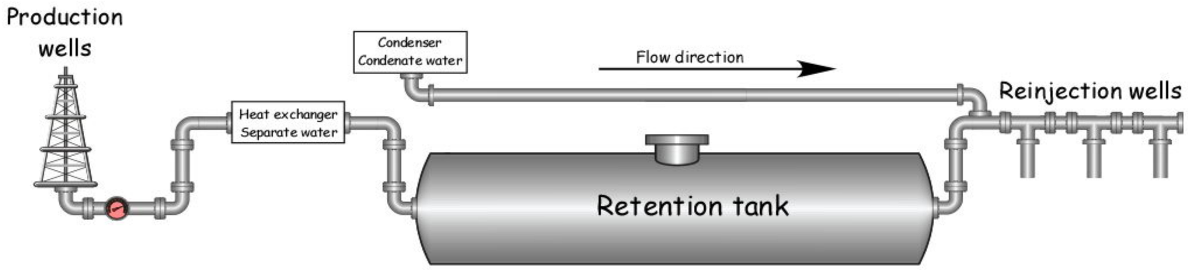

Figure 1: Simplified schematic flow diagram of the separated water in Nesjavellir Power Plant.

Followed by increase in production in 1998 thermal and chemical contamination increased the spring on the shore of Lake Þingvallavatn and Grámelur, the area for fresh water uptake for the district heating system. Subsequently more emphasis was put on re-injecting waste waters from the power plant. New injection drillholes were drilled and extensive experimental work done on ways to prevent silica scaling from the waste waters (Gunnarsson et.al. 2002). One of the main results from that work was that ageing the separated water for two hours at 80°C considerably reduces the concentration of monomeric silica and as a result lowers the silica scaling potential of the waters (Gunnarsson et.al. 2002).

In 2004 a retention tank was build to retain the separated waters prior to injection (Fig. 1). The retention tank is a 144m long horizontal pipe 2,39 m in diameter. Total volume is 649 m3. It is designed to retain 90 l/s of 80°C separated water for 2 hours. Injection of 40 l/s separated water started in 2004 in an injection borehole approximately 300 m north-east of the power plant. Since then injection has increased following drilling of new injection boreholes approx. 700 and 900 m northeast of the power station. Currently most of the separated water is being reinjection into these boreholes. In 2006 the mixing of the separated water after the retention tank with condensed steam started. The condensed steam contains no dissolved element except CO_2 and H_2S and therefore dilutes the concentration of all other dissolved elements in the separated water.

2.2 Hellisheiði Power Station

The Hellisheiði Power Plant is located in the Hengill Central Volcano in southwestern Iceland. Power production started in 2006 with the installment of two 45 MWe turbines. In 2007 a 33 MW_e low pressure turbine was started and two additional $45MW_e$ turbines were started in 2008. Currently 213 MW_e are being produced. Since the beginning of power production in Hellisheiði power plant majority of the waste water has been injected. Majority of the separated waters or around 180 l/s are injected into the Gráuhnúkar area, approx 3 km southwest of the power station, around 30 l/s are injected in the Húsmúli faults approx. 1 km northeast of the power station. Excess separated waters that don’t go in to these two injection sites go into shallow drillholes around 1 km northwest of the power station. The pipe going to the Gráuhnúkar injection site is 3,3 km long and 1 m in diameter. The aquifers receiving the waters in the Gráuhnúkar site are between 270° and 300°C.

3. SAMPLING AND ANALYSIS

In order to evaluate the silica scaling potential of the injection waste water from Nesjavellir and Hellisheiði Power Plants, and the effectiveness of the retention tank and pipe the waters were sampled for monomeric and total silica as well as analyzed for all major elements.

The separated water was sampled by passing it through a 1 meter long 1/8” ID cooling coil where it was cooled rapidly from 122° or 80°C to below 25°C. For the analysis of monomeric silica, an 0,25 ml aliquot was then pipetted into a 10,25 ml 0,18 N sulfuric acid. Reducing effects of H_2S was prevented by adding 1 drop of 0,1N iodide solution, the solution shaked, and excess iodide subsequently removed with 2 drops of 0,05 N thiosulphate solution. Finally, 1,25 ml 10% ammonium molybdate solution was added and after 10 minutes absorbance of the yellow molybdic silica complex measured at 410 nm in a UV-Vis spectrophotometer. Rapid cooling followed by hasty analysis of monomeric silica is important as temperature effects the rate of silica polymerization and the silica polymers in the sample to be analyzed can break down and interfere with the analysis of monomeric silica if the analysis is not performed on site. pH value of the separated water was measured on site at room temperature. Storage of pH-sample will increase the pH value because polymerization of silica affects the pH value of waters with pH higher that 8 (Gunnarsson and Arnórsson, 2005). Samples for total silica concentration where cooled and filtered through 0,45 µm filter paper. Total silica was analyzed in approx 10 times diluted samples after treatment with hydrofluoric acid to break down the silica polymers making all the silica reactive to the molybdic acid. Polymeric silica was calculated as the difference between total and monomeric silica. Major anions were analyzed with IC and major cations analyzed with ICP-AES.

4. RESULTS

4.1 Silica Polymerization in Separated Water from Nesjavellir and Hellisheiði Power Plants

The concentration of monomeric silica and total silica was measured in the separated waters from Nesjavellir and Hellisheiði power stations. Total silica was calculated as the difference between monomeric and polymeric silica. The results are shown in Table 1.

Sampling and analysis of the 80°C separated water was performed before and after the retention tank at Nesjavellir at two flow conditions, 106 and 163 l/s. At the inlet of the retention tank very little silica has polymerized (Fig. 2) . The time it take the separated water to flow from the outlet of the heat exchangers into the retention tank is approx. 2,5 minutes when the flow is 106 l/s and around 1,5 minutes when the flow is 163 l/s. At the outlet of the retention tank the concentration of monomeric silica has dropped to 487 and 519 ppm SiO_2 for 106 and 163 l/s flow. The supersaturation and therefore the potential for silica scaling have decreased considerably. After mixing with condensate the water cools from 80°C to 75°C and the concentration of monomeric silica drops to 321 and 376 ppm SiO_2 for each flow, respectively.

The concentration of monomeric and total silica in the pipe going to Gráuhnúkar, Hellisheiði, is shown in fig. 3. After the low pressure boiler, where the separated waters boils from 180°C to 120°C to produce steam from low pressure turbine, the concentration of monomeric silica is 766 ppm SiO_2. After 1 and 3 km along the pipe the monomeric silica concentration has dropped to 720 and 731 ppm SiO_2. The total silica concentration is in all cases close to 800 ppm SiO2. The variation in concentration of total silica is within the 3% analytical error for silica.

4.2 Saturation State of Amorphous Silica in Separated and Injection

Saturation state of amorphous silica was calculated in the separated water and injection water from Nesjavellir and Hellisheiði Power Plants with the aid of the WATCH program (Arnórsson, et al. 1982; Bjarnason 1996).

Table 1: Concentration of monomeric, polymeric and total silica in separated water from Nesjavellir and Hellisheiði power stations, Iceland. Concentrations are in ppm SiO_2.

	$SiO_{2,m}$	$SiO_{2,t}$	$SiO_{2,p}$
Nesjavellir Power Plant			
Flow 106 l/s			
Before retention tank	722	726	4
After retention tank	487	738	251
After mixing with condensate	321	509	188
Flow 163 l/s			
Before retention tank	730	745	15
After retention tank	519	732	212
After mixing with condensate	376	517	141
Hellisheiði Power Plant			
Flow 175 l/s			
After low pressure boiler	766	811	45
Pipe to Gráuhnúkar 1 km	720	789	69
Pipe to Gráuhnúkar 3 km	731	784	53

$SiO_{2,\,m}$: Monomeric silica
$SiO_{2,\,t}$: Total silica
$SiO_{2,\,p}$: Polymeric silica

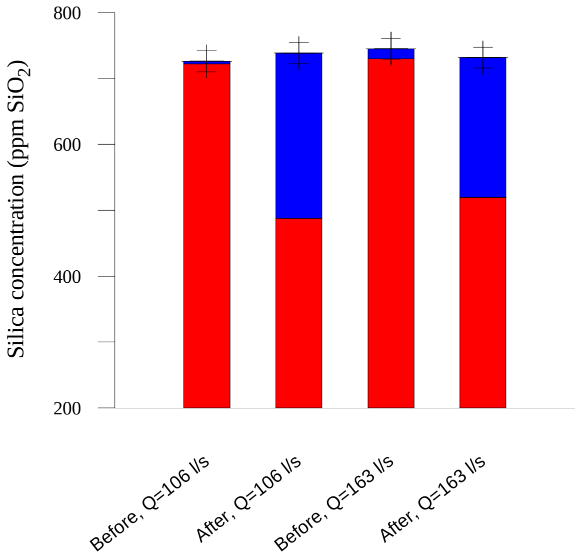

Figure 2: Concentration of silica before and after the retention tank in Nesjavellir Power Plant. Height of the red column is the concentration of monomeric silica and blue column is polymeric silica. The error bars are 3% uncertainty of the total silica analysis.

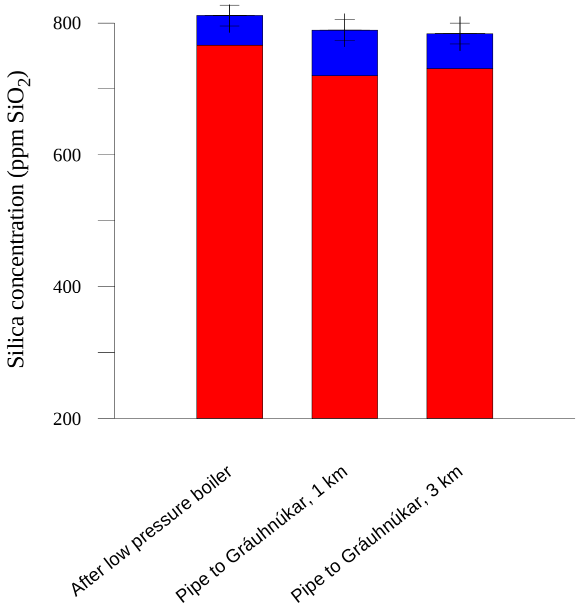

Figure 3: Concentration of silica in Hellisheiði Power Plant after the low pressure boiler and in the pipe going to Gráuhnúkar. Height of the red column is the concentration of monomeric silica and blue column is polymeric silica. The error bars are 3% uncertainty of the total silica analysis

4.2.1 Nesjavellir Power Plant

The saturation state of amorphous silica is shown in Fig. 4. The x-axis is not linear because the timescale for each process in the power plant is very different. Silica concentration in the production wells in Nesjavellir is between 650-850 ppm SiO_2. Steam and water are separated at 12 bara and the separated water is passed through heat exchangers to heat fresh ground waters for space heating in Reykjavík. The silica concentration in the separated water depends on which boreholes are in production but usually lies between 700-800 ppm SiO_2. Monomeric silica concentration for the calculations presented here is shown in Table 1. Before the heat exchangers the separated water is 188°C and after the heat exchangers it is 80°C. The saturation state of amorphous silica changes from being undersaturated by 184 ppm SiO_2 to being 411 ppm SiO_2 supersaturated (Fig. 4). It is therefore evident that the separated waters are highly supersaturated with respect to amorphous silica making its disposal at this stage problematic. In the retention tank monomeric silica concentration decreases from 720 to 487 ppm SiO_2 when the flow in 106 l/s and it decreases from 730-519 ppm SiO_2 when the flow is 163 l/s. The pH of the separated water rises from 8,43 to 8,66 measured at ambient temperature because monomeric silica forms a weak acid in solution which is being removed during silica polymerization (Gunnarsson and Arnórsson, 2005). The supersaturation with respect to amorphous silica after the retention tank is 168 and 199 ppm SiO2 for 106 and 163 l/s flow, respectively. The condensed steam in Nesjavellir Power Plant is 55°C and mixing the separated water with condensed steam dilutes all dissolved elements. Temperature of the mixture is around 73°C which lowers the solubility of amorphous silica by 27 ppm SiO_2. Mixing lowers the pH form 8,66 to 8,50 measured at ambient temperature. The supersaturation after mixing with the condensed steam is 63 and 94 ppm SiO_2 for 106 and 163 l/s flow through the retention tank. Treatment of the separated water from Nesjavellir Power Plant therefore reduces the supersaturation of amorphous silica from 411 to 94-63 ppm SiO_2, depending on the flow through the retention tank (Fig 4).

The timescale for flow of separated water through the power station has been estimated by Gíslason, 1995 when the flow of separated water was 100 l/s. The flow through each heat exchanger is 50 l/s and the time is 40 seconds. The separated water reaches the retention tank in around 200 seconds. When the flow is 163 l/s the separated water reaches the retention tank in around 140 seconds. This short time is not enough to initiate silica scaling in the pipes leading to the retention tank.

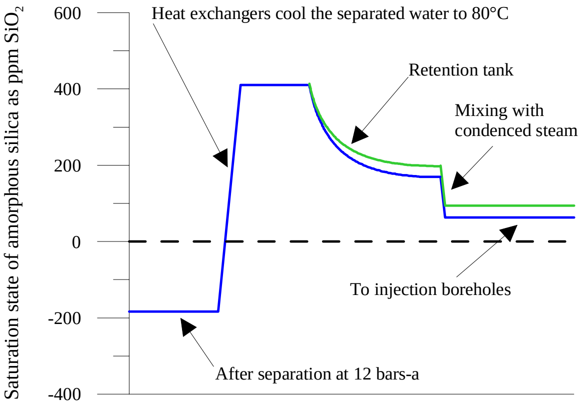

Figure 4: Saturation state of amorphous silica in separated water from Nesjavellir Power Plant.

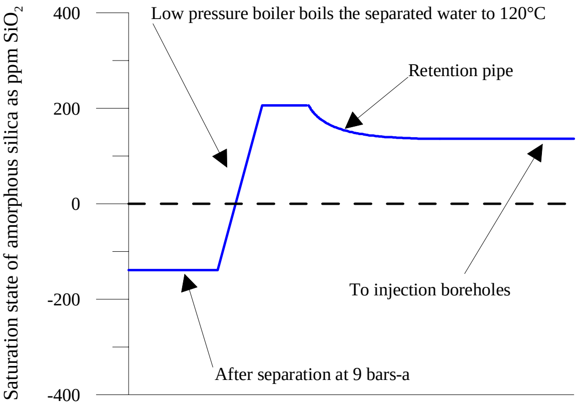

Figure 5: Saturation state of amorphous silica in separated water from Hellisheiði Power Plant.

4.2.2 Hellisheiði Power Plant

The silica concentration in the separated water from Hellisheiði Power station is between 700-800 ppm SiO_2. The saturation state of amorphous silica in the separated water as it goes through the power plant is shown in Fig. 5. The high temperature geothermal fluid is separated at 9 bar-a. Majority of the separated water goes through a low pressure boiler where it boils from 9 to 2 bara to produce steam for a low pressure turbine. Separated water that does not go into the low pressure boiler flows into shallow boreholes after boiling to 1 bar-a. After the low pressure boiler most of the separated water flows along 3.3 km pipe to Gráuhnúkar area where it is re-injected into the ground. Before the low pressure boiler the separated water is amorphous silica undersaturated by 139 ppm SiO_2. After the low pressure boiler the supersaturation is 206 ppm SiO_2. Silica polymerization in the pipe going to the injection site in Gráuhnúkar lowers the supersaturation to 136 ppm SiO_2. In the retention pipe polymerization of silica is finished after approximately 1 km (Table 1.) When sampling was performed the flow was 180 l/s and the retention time in the pipe is 4 hours. After 1 km the retention time is around 70 minutes.

5. CONCLUSIONS AND DISCUSSION

Deposition of silica is the main scaling problem from the separated waters from Nesjavellir and Hellisheiði Power Plants. Ageing the waters allowing the monomeric silica in excess of amorphous silica solubility to polymerize, hence lowering the silica scaling potential of the waters is the silica scaling potential reducing method that is currently in operation in Nesjavellir and Hellisheiði Power Plants, Iceland.

The retention tank in Nesjavellir Power Plant reduces the concentration of monomeric silica from around 730 ppm to 487 and 519 ppm SiO_2 when the flow of separated water is 106 and 163 l/s. This reduces the supersaturation with respect to amorphous silica form 411 ppm to 169 and 199 ppm SiO_2 for the two flow rates. Mixing the separated water after the retention tank with condensed steam further lowers the supersaturation to 63 and 94 ppm SiO_2. The retention tank in Nesjavellir was opened and examined in September 2004 after eight months operation and again in September 2008 after more than four years in operation. The inside the tank was coated by <1 to 3 mm layer of amorphous silica. At the bottom of the tank was a thin layer of fine amorphous silica powder. It is therefore evident that minor deposition of silica occurs inside the retention tank, but generally the tank can be considered as a successful method to reduce the silica scaling potential of the separated water from Nesjavellir Power Plant.

The 3.4 km long pipe going from Hellisheiði Power Plant to the injection site in Gráuhnúkar reduces the concentration of monomeric silica from 811 to 730 ppm SiO_2. Amorphous silica supersaturation in the separated water reduces from 206 to 136 ppm SiO_2. The less polymerization of monomeric silica observed in the separated waters from Hellisheiði results from higher temperature and pH-value of the water. The water in the pipe is usually 122°C but can be as high as 174°C. Silica polymerization has not been analyzed at higher temperatures than 122°C, but supersaturation with respect to amorphous silica is reached at 145°C. At higher temperature no silica polymers should be present in the separated water. Production of hot water for space heating is planned in 2011. The separated waters will pass though heat exchangers where is cools to 80-90°C. This will make the separated water highly supersaturated with respect to amorphous silica and ageing the water from Hellisheiði Power Plant will become even more important than it is today. Mixing the separated water with condensed steam will then also be an important step in treatment of the separated water to reduce the risk of silica scaling before re-injection.

REFERENCES

Arnórsson, S., Sigurdsson, S. and Svavarsson, H. (1982). The chemistry of geothermal waters in Iceland. I. Calculation of aqueous speciation from 0° to 370°C. Geochim. Cosmochim. Acta 46, 1513-1532.

Bjarnason, J. Ö. (1994). The speciation program WATCH, version 2.1. National Energy Authority. Reykjavík. 7 pp.

Candelaria, M. N. R., Garcia, S. E., Baltazar, A. D. J., Solis, R. P., Cabel, A.C. Jr., Nogara, J. B., Reyes, R. L., Jordan, O. T. (1996). Methods of coping with silica deposition - the PNOC experience. Geothermal Resources Council Transactions, 20, 661-672.

Chan, S. H. (1989). A review on solubility and polymerization of silica. Geothermics 18, 49-56.

Crerar, D. A., Axtmann, E. V. and Axtmann, R. C. (1981) Growth and ripening of silica polymers in aqueous solutions. Geochim. Cosmochim. Acta 45, 1259-1266.

Gallup D. L. (1998). Investigations of organic inhibitors for silica scale control in geothermal brines. Geothermics 27, 485-501.

Gallup, D. L. and Featherstone, J. L. (1985). Acidification of steam condensate for incompatibility control during mixing with geothermal brine. US Patent 4,522,728.

Gill, J. S. (1993). Inhibition of silica-silicate deposition in industrial wasters. Colloids and Surfaces A 74, 101-106.

Gíslason G. (1995) Injection tests in NN-2, Nesjavellir Reykjavík Energy report, 8 pp. [In Icelandic].

Gudmundsson, S. R. and Einarsson, E. (1989). Controlled silica precipitation in geothermal brine at the Reykjanes geo-chemical plant. Geothermics 18, 105-112.

Gunnarsson, I., Arnórsson, S. and Hauksson, T. (2002) Nesjavellir Power Plant. Experiments to prevent silica deposition form waste water. Science Institute Report RH-02-02, University of Iceland, 104 p. [in Icelandic]

Gunnarsson, I. and Arnórsson, S. (2003) Silica scaling: The main obstacle in efficient use of high-temperature geothermal fluid. IGC 2003, 30-36.

Gunnarsson, I and Arnórsson, S. (2005). Impact of silica scaling on the efficiency of heat extraction from high-temperature geothermal fluids. Geothermics, 34, 320-329.

Gunnarsson, I and Arnórsson, S. (2008). Polymerization of silica in high temperature geothermal fluids. Science Institute Report RH-02-08, University of Iceland, 99 p. [in Icelandic].

Rothbaum, H. P. and Rhode, A. G. (1979). Kinetics of silica polymerization and deposition from dilute solutions between 5 and 180°C. J. Colloid Interface Sci. 71, 533-559.

Sugita, H., Bando, Y. and Nakamura, M. (1998). Removal of silica from geothermal brine by seeding method using silica gel. J. Chem. Eng. Japan 31, 150-152.

Sugita, H., Kato, K., Ueda, A., Matsunaga, I., Sakurai, Y., Yasuda, K., Bando, Y. and Nakamura, M. (1999). Field tests on silica removal from geothermal brines in Sumikawa and Onuma geothermal areas. J. Chem. Eng. Japan 32. 696-700.

Ueda, A., Kato, K., Abe, K., Mogi, K., Furukawa, T., and Ishimi, K. (2000). Recovery of silica from the Sumikawa geothermal fluids by addition of cationic reagents. J. Geoth. Res. Soc. Jnp. 22, 249-258.

Ueda, A., Kato, K., Mogi, K., Mroczek, E. and Thain, I. A. (2003). Silica removal from Mokai, New Zealand, geothermal brine by treatment with lime and a cationic precipitant. Geothermics 32, 47-61.

Weres, O., Yee, A. and Tsao, L. (1981). Kinetics of silica polymerization. J. Colloid Interface Sci. 84, 379-402.

Yanagase, T., Suginohara, Y. and Yanagase, K. (1970) The properties of scales and methods to prevent them. Geothermics (special issue 2), 1619-1623.