PROCEEDINGS, 51st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 9-11, 2026
SGP-TR-230

Silica Scaling Control in Geothermal Wellhead Silencers with Emphasis on Sulphuric Acid Application

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Keywords: Silica scaling; geothermal energy; wellhead silencers; sulphuric acid injection; pH control; silica polymerization; corrosion management; Olkaria geothermal field

ABSTRACT

Silica scaling is one of the most persistent and costly operational challenges in high-enthalpy geothermal systems, particularly within geothermal wellhead generator silencers. Rapid depressurization, intense flashing, turbulence, and cooling of geothermal fluids at the wellhead cause dissolved silica to become supersaturated, resulting in precipitation of amorphous silica on internal silencer surfaces. Accumulated silica scale restricts flow paths, increases backpressure, degrades acoustic attenuation performance, and significantly raises maintenance frequency and operational costs.

This paper presents a comprehensive analysis of silica scaling control in geothermal wellhead silencers, with emphasis on the application of sulphuric acid as a chemical pH-modification strategy. Mechanical, operational, and chemical mitigation methods are reviewed, while sulphuric acid injection is discussed in detail based on laboratory studies and field observations from the Olkaria geothermal field, Kenya. Chemical mechanisms, operational considerations, corrosion risks, and environmental implications are examined. The study demonstrates that optimized sulphuric acid dosing significantly suppresses silica polymerization, reduces scale deposition, and improves silencer reliability, offering a practical and scalable solution for geothermal operations.

1. INTRODUCTION

Geothermal energy is a renewable and sustainable source of base-load electricity derived from heat stored within the Earth's crust. Unlike intermittent renewable sources such as solar and wind, geothermal power plants provide continuous and reliable energy with low greenhouse gas emissions. Kenya, located along the East African Rift System, has emerged as a global leader in geothermal development, with the Olkaria geothermal field forming the backbone of national geothermal power generation. Figure 1 shows the geothermal prospect in the Kenan rift valley that includes the Geater Olkaria Geothermal field.

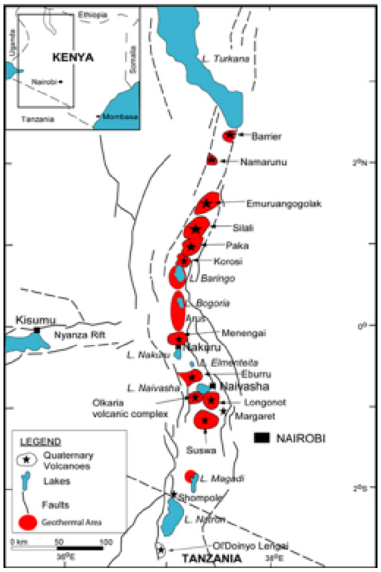


Figure 1: **Map showing the Greater Olkaria Geothermal prospect within the Kenyan Rift Valley (Ofuona, 2002)**

Despite these advantages, geothermal energy production is constrained by several technical challenges, among which mineral scaling remains one of the most severe. Silica (SiO_2) scaling is particularly problematic due to the high concentrations of dissolved silica in geothermal fluids and the strong sensitivity of silica solubility to temperature, pressure, and pH. Silica scaling differs from carbonate scaling in that it is more chemically stable, harder to dissolve, and often requires aggressive or carefully controlled chemical treatment.

Wellhead generator silencers are surface installations designed to reduce noise and control pressure during steam discharge, well testing, and commissioning. Conditions inside silencers—characterized by rapid flashing, droplet formation, intense turbulence, and abrupt cooling—are highly favorable for silica polymerization and deposition. As a result, silencers often experience faster and more severe silica scaling than downstream equipment such as separators and pipelines. This paper provides a detailed discussion of silica scaling control strategies in geothermal wellhead silencers, with particular emphasis on sulphuric acid application as a proactive mitigation method.

2. PROBLEM STATEMENT

Silica scaling in geothermal wellhead silencers presents a persistent operational problem that directly affects plant reliability and economics. During geothermal fluid discharge, rapid pressure drop and cooling cause dissolved silica to exceed its solubility limit, resulting in precipitation of amorphous silica on silencer internals. Continuous scale accumulation reduces effective flow area, increases backpressure, degrades acoustic performance, and accelerates mechanical wear.

Current mitigation practices rely heavily on mechanical cleaning and frequent shutdowns, which are costly and disruptive. Furthermore, generalized scale control strategies often fail to address the unique thermodynamic and hydrodynamic conditions within silencers. There is therefore a critical need for targeted, proactive, and chemically informed silica scaling control strategies tailored specifically to geothermal wellhead silencers.

3. OBJECTIVES

The objectives of this study are to examine the fundamental chemical and physical mechanisms of silica scaling in geothermal wellhead silencers, to review mechanical, operational, and chemical methods available for silica scaling reduction, to evaluate sulphuric acid injection as a primary chemical control method, to analyze laboratory and field data from high-enthalpy geothermal systems, and to develop recommendations for sustainable and safe silica scale management.

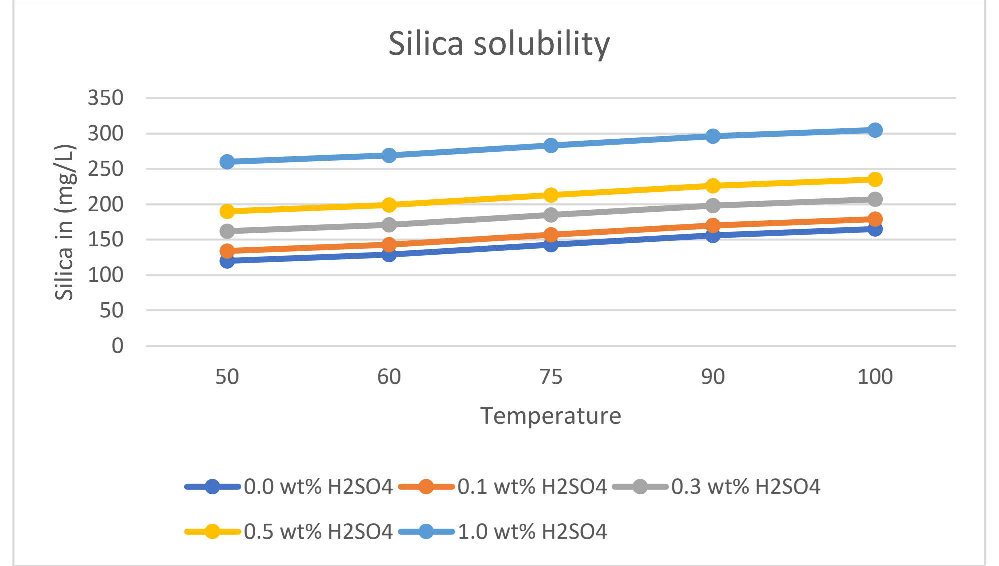
4. METHODOLOGY

4.1 Literature Review and Field Data Analysis

Published literature, operational reports, and field data from high-enthalpy geothermal systems—particularly the Olkaria geothermal field—were reviewed. Emphasis was placed on silica chemistry, scaling mechanisms, and mitigation practices applied at the wellhead and in silencers.

4.2 Laboratory Evaluation

Synthetic geothermal brines with high silica concentrations were prepared and subjected to controlled temperature conditions between 50 °C and 100 °C and varying pH levels. Sulphuric acid concentrations ranging from 0.1 to 1.0 wt% were tested to determine their effect on silica solubility, polymerization rate, and dissolution efficiency. Corrosion behavior of common silencer construction materials was also assessed using carbon steel and stainless-steel coupons. Figure 2 shows that there is a clear and systematic increase in dissolved silica with increase in both **temperature** and **sulphuric acid concentration**, producing a family of upward-sloping curves



Temperature (°C)	**0.0 wt% H2SO4**	**0.1 wt% H2SO4**	**0.3 wt% H2SO4**	**0.5 wt% H2SO4**	**1.0 wt% H2SO4**
50	120mg	134 mg	162 mg	190 mg	260 mg
60	129mg	143mg	171mg	199 mg	269 mg
75	143mg	157mg	185mg	213mg	283mg
90	156mg	170mg	198mg	226mg	296 mg
100	165mg	179mg	207mg	235mg	305mg

Figure 2: Effect of change in Temperature and sulphuric acid concentration on the dissolution of silica

4.2.1 Effect of temperature

For all acid concentrations, silica solubility increases steadily from 50 °C to 100 °C. This reflects the endothermic nature of silica dissolution, where higher temperatures favor the formation of dissolved silicic acid, thereby increasing silica carrying capacity of the fluid.

4.2.2 Effect of sulphuric acid concentration

At any given temperature, silica solubility increases with increasing H_2SO_4 concentration. For example, at 100 °C, silica solubility rises from about 165 mg (0.0 wt%) to 305 mg (1.0 wt%). Acid addition lowers the pH, kinetically inhibiting silicic acid polymerization and stabilizing silica in its monomeric form, thus suppressing scale formation.

4.2.3 Combined temperature–acid interaction

The curves are nearly parallel, indicating that temperature and acid concentration act synergistically but independently: temperature controls thermodynamic solubility, while acid controls polymerization kinetics. Higher acid concentrations consistently shift the solubility curve upward across the entire temperature range.

4.2.4 Implications for geothermal silencers

The results demonstrate that moderate sulphuric acid dosing significantly increases silica solubility even at relatively low temperatures (50–100 °C), which are typical of wellhead silencers. This confirms the effectiveness of acid dosing as a silica scaling control strategy by maintaining silica in solution and delaying precipitation.

Overall, the curves illustrate that increasing temperature and decreasing pH both favor higher silica solubility, thereby reducing the likelihood of amorphous silica scale formation in geothermal surface equipment.

The data in Table 1 shows a clear increase in corrosion with increasing sulphuric acid concentration for both carbon steel and stainless steel, confirming the aggressive nature of acidic environments. This is graphically represented in figure 3.

Table 1. 3 Months Coupon Corrosion Data

3 Months Coupon Corrosion Data		
H_2SO_4 (wt%)	Carbon steel(mm)	Stainless steel(mm)
0	0.03	0.0075
0.1	0.051	0.0105
0.3	0.094	0.0165
0.5	0.136	0.0225
1	0.243	0.0375

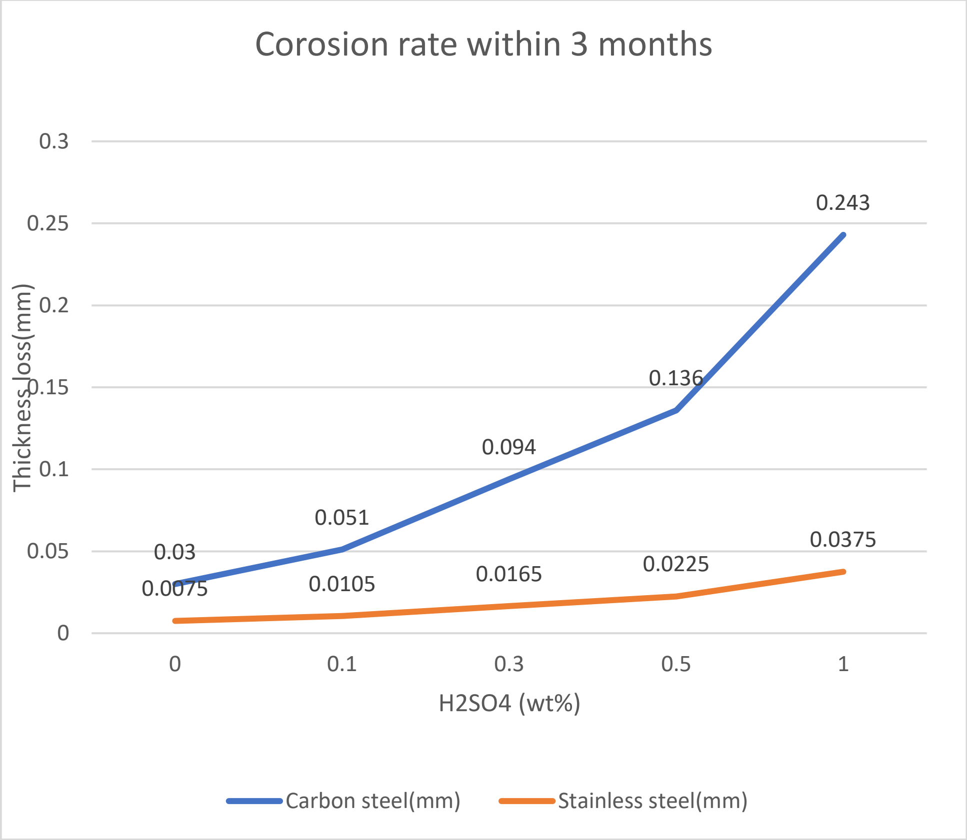


Figure 3. The corrosion rate for 3 months

Carbon steel corrosion increases sharply with acid concentration due to:

$$Fe + H_2SO_4 \rightarrow FeSO_4 + H_2 \uparrow$$

a) **Effect of H_2SO_4 concentration**
Corrosion depth increases progressively as acid concentration rises from 0 to 1.0 wt%. For carbon steel, corrosion increases from **0.03 mm (0 wt%)** to **0.243 mm (1.0 wt%)**, while stainless steel increases from **0.0075 mm** to **0.0375 mm** over the same period. This indicates that acid dosing, while effective for silica control, enhances metal dissolution.

b) **Material comparison**
Carbon steel exhibits significantly higher corrosion than stainless steel at all acid concentrations—approximately **6–7 times greater**. This reflects the lack of a stable passive oxide film on carbon steel, whereas stainless steel benefits from a chromium-rich passive layer that provides enhanced acid resistance.

c) **Rate sensitivity to acid addition**
The corrosion increase is non-linear, particularly for carbon steel, with a sharp rise above **0.5 wt% H_2SO_4**. This suggests a threshold beyond which protective surface films are rapidly broken down, accelerating uniform corrosion.

d) **Operational implications**
Although sulphuric acid effectively suppresses silica scaling, higher dosages substantially increase corrosion risk, especially for carbon steel components. This highlights the need for **optimized acid dosing**, use of **corrosion-resistant alloys**, or incorporation of **corrosion inhibitors** in geothermal wellhead silencer systems.

Overall, the results demonstrate a trade-off between **silica scaling control and material durability**, emphasizing careful balancing of acid concentration in long-term geothermal operations.

4.3 Practical Application

A controlled temporary sulphuric acid dosing system was installed upstream of selected wellhead silencer on the hot brine line. Operational parameters monitored included pH, silica concentration, pressure drop across silencers, visual scale accumulation, and corrosion indicators. Field observations from the Olkaria geothermal field were analyzed to assess the effectiveness of sulphuric acid injection under real operating conditions. Figure 4 shows the schematic diagram of a proposed full acid dosing system.

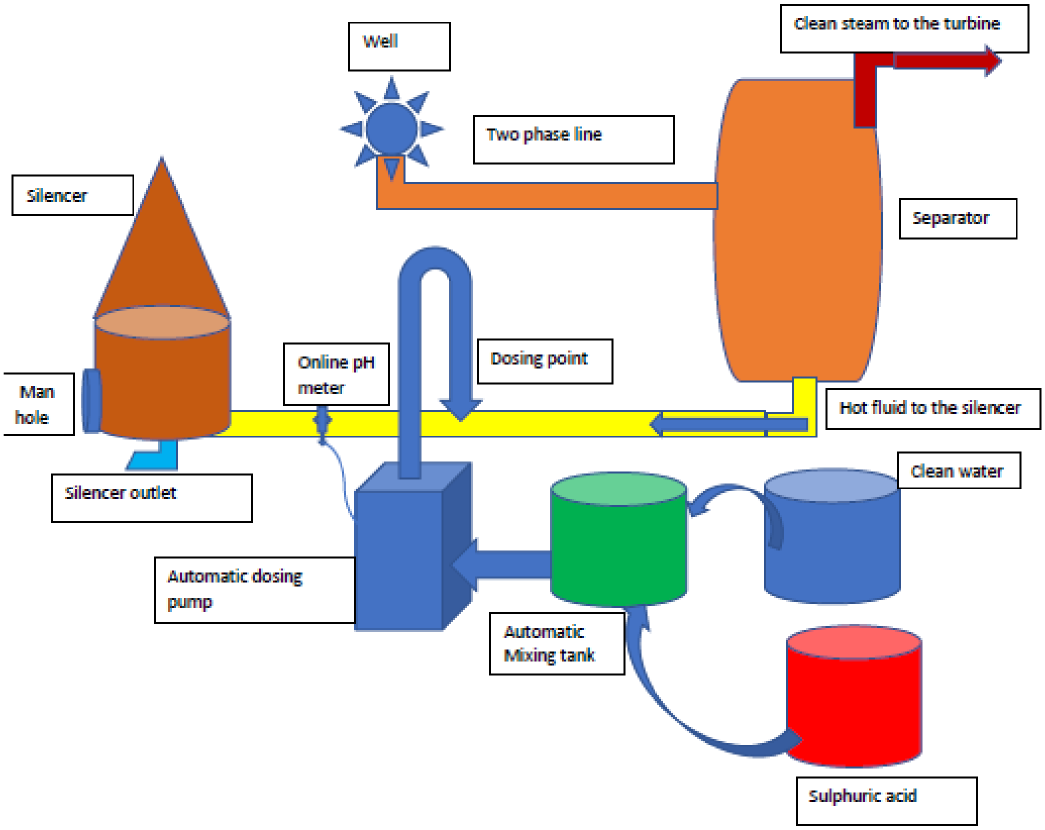


Figure 4. The Schematic diagram of a proposed full system to facilitate acid dosing.

5. SILICA SCALING MECHANISM

Silica scaling occurs when dissolved silica becomes supersaturated in water, polymerizes, and deposits as amorphous silica. In geothermal systems, it is influenced by temperature, pH, concentration, and fluid chemistry.

Silica is present in geothermal fluids primarily as monomeric silicic acid (H_4SiO_4) at reservoir conditions. As fluids ascend and cool, silica solubility decreases, leading to supersaturation and polymerization through condensation reactions expressed as
$nH_4SiO_4 \rightarrow (SiO_2)_n + 2nH_2O$.

Loss of acidic gases such as CO_2 and H_2S during flashing increases pH, accelerating condensation and deposition of amorphous silica. The solubility of silica in water is prograde with temperature, with geothermal fluids often equilibrated with quartz at reservoir temperatures and crossing into the amorphous silica scaling region as cooling proceeds.

5.1 Silica Dissolution

At high temperatures and pressures, silica minerals (quartz or amorphous silica) dissolve, forming monomeric silicic acid:

$$\mathrm{SiO_2(s) + 2H_2O \rightleftharpoons Si(OH)_4(aq)}$$

This enhances silica transport in geothermal fluids.

5.2 Supersaturation

During ascent, cooling, pressure drop, and CO_2 degassing increase pH, reducing silica solubility and creating supersaturation—a driving force for scaling.

5.3 Silicic Acid Polymerization

Supersaturated silicic acid condenses to form siloxane bonds:

$$\mathrm{Si(OH)_4 + Si(OH)_4 \rightarrow (HO)_3Si\text{–}O\text{–}Si(OH)_3 + H_2O}$$

This leads to oligomers, colloidal silica, and amorphous gels. Polymerization is fastest at neutral to mildly alkaline pH (≈6.5–8).

5.4 Nucleation and Growth

Polymer chains reaching critical size nucleate either homogeneously in solution or heterogeneously on surfaces. Rough surfaces, corrosion, or existing scale accelerate deposition.

5.5 Deposition and Hardening

Colloidal silica attaches to surfaces and dehydrates, forming hard, glass-like amorphous silica:

$$\mathrm{Si(OH)_4 \rightarrow SiO_2(amorphous) + 2H_2O}$$

5.6 pH Influence

- Low pH (<4–5): Polymerization slow
- Neutral pH (6–8): Maximum scaling
- High pH (>9): Silica remains soluble as silicate
- Acid dosing (e.g., H_2SO_4) helps control scaling.

5.7 Metal Ions and Impurities

Cations (Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}) bridge silica particles, accelerating coagulation and forming mixed metal–silica scales.

5.8 Aging and Irreversibility

Fresh scale is soft, but dehydration and further polymerization over time create dense, insoluble silica that is hard to remove.

Figure 5 shows the effect of pH on silica polymerization rate.

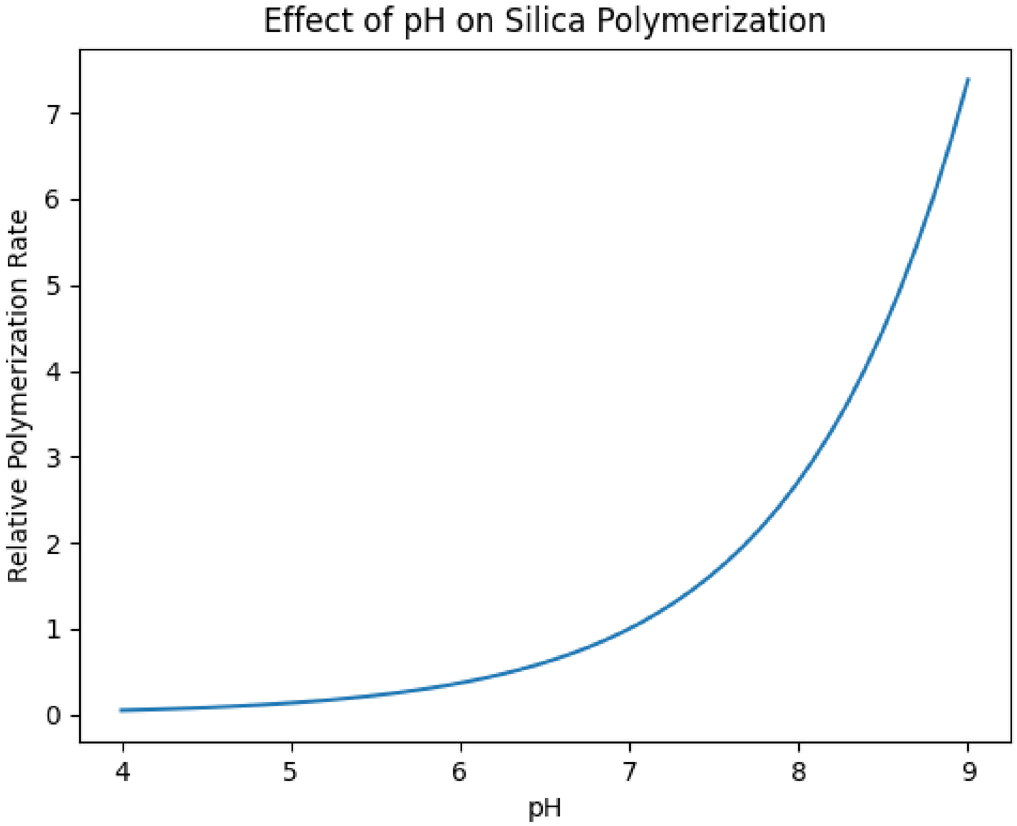


Figure 5. The Effect of pH on Silica Polymerization Rate, (Bélteky, 1979)

At pH 2–3.9 The polymerization rate reaches its absolute minimum at approximately **pH 2**, the isoelectric point.

At pH 4.5–5.5 Sulphuric acid injection typically targets a pH of **4.5 to 5.0**. In this range, the scaling rate is significantly lowered compared to neutral brine.

At pH 7–9 The polymerization rate increases rapidly as pH moves toward neutral or slightly alkaline levels. At **pH 7**, silica deposition is most aggressive.

At pH > 9: Even though solubility increases at very high pH due to the formation of silicate ions, polymerization rates remain high until silica becomes fully soluble.

6. GENERAL METHODS FOR SILICA SCALING CONTROL

6.1 Physical and Operational Methods

Physical and operational strategies include pressure and temperature management to reduce excessive flashing, controlled flashing locations away from sensitive equipment, mechanical removal methods such as hydro blasting and pigging, and dilution using condensate or brine to lower silica concentration.

While these methods provide partial relief, they are generally reactive and do not prevent scale formation.

6.2 Chemical Methods

Chemical approaches offer proactive control by modifying silica chemistry. These include pH modification using acids or bases, application of silica inhibitors and antiscalants, and pre-removal of silica using adsorption or membrane technologies. Among these options, sulphuric acid injection has proven particularly effective in wellhead silencer applications.

7. APPLICATION OF SULPHURIC ACID FOR SILICA SCALING CONTROL

Sulphuric acid (H_2SO_4) is widely used in geothermal operations to control silica scaling through pH reduction. Injection of dilute sulphuric acid upstream of the silencer lowers the fluid pH to a moderately acidic range, typically between 5 and 5.5, significantly inhibiting silica polymerization and delaying precipitation.

Sulphuric acid dissociates according to
$H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}$.

The increased proton concentration suppresses condensation reactions and promotes the formation of soluble silicic acid, thereby reducing the rate of amorphous silica deposition.

$SiO_2(s) + 2H^+ \rightarrow H_4SiO_4(aq)$

Laboratory and field applications in the Olkaria geothermal field have demonstrated reductions in silica deposition rates exceeding 70% when sulphuric acid dosing is properly optimized.

8. CASE STUDY: OLKARIA GEOTHERMAL FIELD

The Olkaria geothermal field in Kenya is a high-enthalpy volcanic system with reservoir temperatures exceeding 250 °C in some zones. Produced fluids are characterized by high dissolved silica concentrations, often exceeding 1,000 ppm, making silica scaling a dominant operational challenge.

Field observations indicate that silica scaling is particularly severe in wells with high steam fractions and limited brine availability. Wells such as OW-914 have experienced rapid scale buildup within wellhead silencers, leading to increased pressure drop and frequent maintenance shutdowns. Trials of controlled sulphuric acid injection upstream of silencers resulted in significant reductions in scale accumulation, stabilized pressure drop, and possible extended maintenance intervals.

9. CORROSION AND ENVIRONMENTAL CONSIDERATIONS

While sulphuric acid application is effective for silica scaling control, it introduces potential risks related to corrosion and environmental impact. Acidic conditions can accelerate corrosion of carbon steel components, necessitating the use of corrosion inhibitors, stainless-steel alloys, or protective coatings.

Environmental considerations include safe handling, storage, and neutralization of acid. Automated dosing systems with secondary containment and real-time pH monitoring are essential to minimize environmental and safety risks.

10. RESULTS AND DISCUSSION

Laboratory experiments identified an optimal sulphuric acid concentration range of 0.3–0.5 wt% for effective silica scaling control. Within this range, silica polymerization was significantly suppressed without excessive corrosion of metallic components.

Field results from Olkaria demonstrated reduced pressure drop across silencers, improved flow stability, and possibility of extended maintenance intervals. These results confirm that sulphuric acid application addresses the root chemical causes of silica scaling rather than merely removing deposited scale.

11. CONCLUSIONS

Silica scaling in geothermal wellhead silencers is driven by rapid thermodynamic changes, high dissolved silica concentrations, and unfavorable pH conditions. Among available mitigation strategies, sulphuric acid injection provides an effective, practical, and scalable chemical control method. When properly implemented with adequate monitoring and corrosion management, sulphuric acid application significantly improves silencer performance and operational reliability.

12. RECOMMENDATIONS

Automated sulphuric acid dosing systems with real-time pH control should be implemented. Corrosion-resistant materials and inhibitors should be used in acid-treated systems. Chemical control should be combined with optimized flashing and periodic mechanical cleaning. Long-term monitoring and environmental impact assessments should be conducted to ensure sustainable operation.

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