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Integration of the Calcium Silicate Hydrate (CaSil) Technology into Geothermal Power Plants – Focus on Process Engineering Aspects

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ABSTRACT

A major challenge in geothermal energy utilization is the formation and precipitation of amorphous silica scale. Over time, pipes, valves and heat exchangers are blocked by the rock-like scale which decreases the efficiency of process equipment, and eventually become unfit for operation. Extensive regular cleaning efforts or replacements are the consequence, necessitating high servicing and operational costs. Current mitigation approaches aim to delay the precipitation by increasing the silica solubility through higher exit pressures and temperatures from the flashing process, or by dosing of acid and additives to retard the polymerization process. However, none of these existing technologies can solve the problem wholly whilst being financially attractive.

In a disruptive approach to address this issue, we have developed a new technology whereby we transform the dissolved silica species into a nanostructured calcium silicate hydrate (CaSil) material. The reaction takes place very rapidly and can transform – depending on the dosing regimen – enough dissolved silica to prevent the precipitation of silica scale. If desired, essentially all dissolved silica can be removed, to enable downstream membrane or adsorbent methodologies for extraction of dissolved minerals like lithium or zinc. Due to the surface chemistry of the CaSil material, no adherence of the particles to metal parts can occur. Consequently, CaSil-particles pass straight through the entire plant, and maintenance efforts are reduced greatly. Because dissolved silica is chemically transformed and removed from solution, additional energy can be extracted from geothermal brines without risking or promoting scale formation.

This paper will focus on the process engineering challenges of this new disruptive technology. Using the example of a pilot plant, which is currently deployed in the Taupo Volcanic Zone in New Zealand, the individual unit operations of the technology are explained. Our continuous pilot scale process is able to demonstrate the effectiveness and simplicity of the technology in a real-world operational environment. Silica scaling can be wholly prevented, while at the same time ensuring an enhanced energy recovery without oversaturating the geothermal brine in dissolved silica. Operational challenges during the development process will be highlighted and experiences and solutions discussed.

1. INTRODUCTION

The thermal energy of the earth can be utilized for electricity production in geothermal power plants. Hot water, steam, or a mixture of both is extracted from natural or artificially created geothermal reservoirs. The water in the reservoir contains a cocktail of different species in solution, such as chloride-based salts, precious metals and silica. The specific composition is dependent on the pressure, temperature and rock structure of the field and varies from site to site. Technical utilization of the sourced water requires pure steam, which is produced by reducing the pressure of the water in a flashing vessel. This causes a certain percentage of the water to boil off as steam, which then can be used to drive a turbine and generate electricity. Due to the mass reduction of the liquid phase, the dissolved chemical species are concentrated into a brine. Additionally, the water temperature decreases to the respective pressure-dependent boiling temperature. These two effects occur simultaneously, causing silica to exceed its solubility limit for the respective water temperature, which is a well-known effect (Iler, 1979; García et al., 2005). After an induction period the silica starts to polymerize. The length of the induction period and the rate at which the polymerization is taking place depends on the temperature, salt content, and pH value of the brine (Makrides et al., 1980). The polymerized silica forms a hard, rock-like structured scale, which blocks pipes, valves and heat exchangers over time. Silica can even be carried over in the steam, causing silica scaling on turbine blades (Richardson et al., 2014). In order to prevent scaling and subsequent damage to the blades the steam is scrubbed. Cold water is sprayed into the steam, which captures impurities, but leads to a loss in energy production. Energy remaining in the spent geothermal brine after flashing can also be used to generate further energy in a binary plant using heat exchangers or in heating projects. However, the formation of silica scale in the pipework, valves and heat exchangers significantly lowers the efficiency of the process equipment over time. Therefore, extensive cleaning efforts are required to remove the scale. The advanced removal of heat from the brine further promotes the problem of silica scaling, since lowering the temperature of the brine decreases the solubility of silica and boosts the polymerization process. A trade-off between energy production/direct heat usage and prevention of silica scaling must be achieved (Thorhallsson, 2011).

A common method to attenuate the silica scaling problem is hot reinjection, where the temperature of the brine is left comparatively high after the flashing process, which in turn ensures a high silica solubility. The water is reinjected or discharged quickly so that the overall time where silica is in a supersaturated state is equal or shorter than the induction period of the polymerization. However, with this method a lot of the thermal energy of the brine is left unused and discarded. Other methods have tried to delay the polymerization of silica by extending the induction period via addition of chemicals (acids or dispersants) (Gunnarsson and Arnórsson, 2005). However, none have been wholly successful.

2 PILOT PLANT DESIGN

2.1 Lime Injection and Calcium Silicate Hydrate Formation

In a disruptive approach to address the issue of silica scaling we have developed a new technology whereby dissolved silica species are transformed into a nanostructured calcium silicate hydrate (CaSil) material (Borrmann 2009, 2018; Johnston et al., 2004, 2006, 2018). Calcium ions, which are injected into the geothermal water, react with silica and silicate ions to form a calcium silicate hydrate product. The particles don't stick to metal surfaces due to a positive surface charge, leaving clean surfaces in pipes and heat exchangers for optimal flow and heat transfer. The reaction takes place rapidly and is completed within seconds. Enough silica is transformed to lower the silica concentration well below the silica saturation level (at the final discharge temperature) and thus effectively prevents silica scale from forming. Therefore, extensive cleaning efforts or even replacements of pipes and process equipment are no longer required, significantly reducing the maintenance costs of power plants. Specific aspects of the chemistry of this reaction are detailed by Fraser et al. (2020). The chemical transformation also enables downstream membrane and adsorbent methodologies to be applied without silica fouling. This means dissolved minerals, like lithium or zinc, can be extracted from the geothermal water creating additional revenue streams to the power plant and diversifying the investment and business model.

To demonstrate the technology in a continuous process using hot, pressurized geothermal water, a pilot plant is being planned, tested and commissioned at the site of MB Century, Taupo, New Zealand, sourcing geothermal water from the nearby Wairakei Geothermal Power Plant. An initial small-scale system containing each of the key unit operations was built and commissioned in 2017 (Figure 1). This system had a nominal design flow rate of 10 L/min but was mostly operated between 10-15 L/min, which was made possible by the large safety factors built into the process equipment. The comparatively low flow rate allowed easy handling of all components and represented the first proof of concept of the technology in a real-world environment, demonstrating the robustness and simplicity of the technology (Borrmann et al., 2018). Two pipelines, one treated with the CaSil-technology and one untreated as a control, were included in this initial system. Both lines featured about 10 m of pipework to confirm that no CaSil particles would adhere to the steel pipe walls, in contrast to silica scale building up over time. Each line had its own flash vessel to reduce the brine to atmospheric pressure and safely discharge the geothermal water into a nearby waterway. Additionally, the treated line could be channeled to a third flash vessel which led into a lamella separator to separate and recover the CaSil-particles formed in the process.

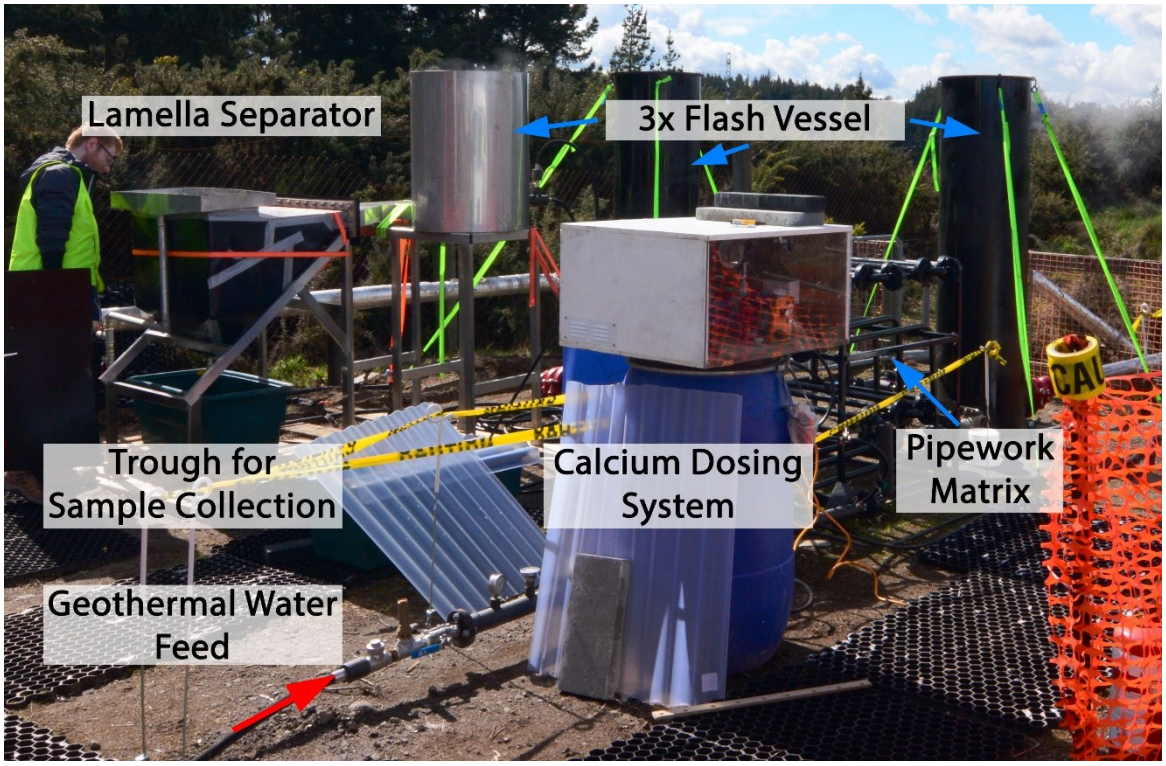


Figure 1: Picture of our proof-of-concept continuous pilot system to demonstrate key unit operations for the calcium silicate hydrate technology located in Taupo, New Zealand.

The initial calcium dosing system comprised a stirred barrel containing the calcium agent, a peristaltic pump and an injection port. Several injection port designs were tested. Initially, a T-junction port formed from a 1-inch pipe diameter with a 90 mm long branch was used. However, this delivered comparatively low flow velocities due to the large volume in the branch and resulted in non-uniform mixing into the pulsating brine stream. The T-branch acted as a reservoir for the calcium agent, which was periodically washed out by the pulsating brine, resulting in calcium to silica ratios which were first too high and then too low once the reservoir refilled. Further problems arose if the dosing pump came to a sudden stop, as the backpressure of the brine forced a small amount of brine up the branch, which reacted with the calcium, forming a scale which adhered on the sides of the injection port. In order to overcome these issues an improved injection lance was designed to introduce the calcium agent directly into the brine flow and with an increased injection velocity. This design reliably delivered consistent dosing flow. However, caking of the lance following a sudden pump stop was still observed to occur, and could even block the injection lance due to its small diameter. However, this problem was purely operational and was solved by introducing the possibility to switch the pump feed to wash water in order to flush calcium agent from the delivery pipe and injection lance before stopping the dosing pump. A static mixer with six mixing elements

was also included downstream of the injection lance to aid the mixing process and compensate for the low flow velocities. With the mixer in place the calcium silicate formation progressed well. Light deposits of calcium carbonate were found on the mixer blades, which did not have any effect on the process itself. The deposits were likely formed due to incorrect dosing events when the brine flow rate dropped significantly and the optimal dosing window was overshot.

2.2 Enhanced energy extraction

The chemical transformation of dissolved silica into colloidal calcium silicate decreases the silica saturation index (SSI) of the geothermal water. Enough dissolved silica is transformed in the reaction to lower the silica concentration well below the saturation level after flashing. This means that more heat energy can be extracted from the brine without risking silica precipitation and scaling. An example to illustrate and quantify this advantage is the binary stage of the Wairakei Power Plant in New Zealand. The brine flow through the binary plant is about 2800 t/h with an initial temperature of 127 °C and discharge temperature of 87 °C, generating 14 MW electric power. The average silica concentration in the geothermal water is about 525 ppm. This means the SSI of the brine is about 1 on entering the heat exchanger (HEX) and 1.6 on exit from the heat exchanger. The HEX has to be cleaned approximately every six months due to silica deposition and drop in performance (Thain and Carey, 2009; Zarrouk et al., 2014).

With the CaSil-technology, about 350 ppm of silica is left unreacted in the brine after treatment at a pH value of 10 to 10.5. The reduction in silica concentration alone would result in an SSI of just under 0.7 once the brine enters the Wairakei binary HEX. However, the increased pH also increases the solubility of silica in the brine. Formulas to estimate the pH-adjusted silica solubility were taken from Brown (2011). The values presented are based on a pH of 10. Due to the shift in pH the SSI of the incoming brine at 127 °C decreases from 0.7 to 0.04. If the same HEX exit temperature of 87 °C is chosen, an SSI of 0.1 at the exit would be the consequence. No silica would deposit in the HEX and semi-annual cleaning would become obsolete, saving maintenance cost and reducing downtime. Even at temperatures as low as 60 °C an SSI of only 0.3 would occur, while the binary plant could generate 9.5 MW more electrical power, assuming the same efficiency factor. This equals a 68 % increase in energy production from the binary plant without the need to change working fluids or the binary plant technology employed. In fact, a fluid temperature of 30 °C would have to be established in order to increase the SSI past 1 and thus initiate silica polymerization. This makes the geothermal fluid very simple to handle and silica scaling virtually impossible – even at low temperatures. Even if silica precipitation were to occur, the calcium silicate would act as a condensation seed providing significantly more active precipitation sites on its surface due to its nano-structured nature (Iler, 1979). Therefore, silica would form preferably on the surface of a CaSil-particle instead of the pipe wall, adding another layer of safety.

Because the CaSil-material does not adhere to metal surfaces, a clean surface for optimal heat transfer is provided. Preliminary experiments have been conducted to investigate the effect of CaSil-particles on metal walls. A CaSil-suspension was cycled over long periods of time through a laboratory scale plate-and-frame heat exchanger to see if any deposition would occur. After up to six weeks of running the heat exchanger showed no signs of scale, hard deposition or performance loss. Soft deposits due to low flow velocities could easily be removed with a brush (Borrmann et al., 2009).

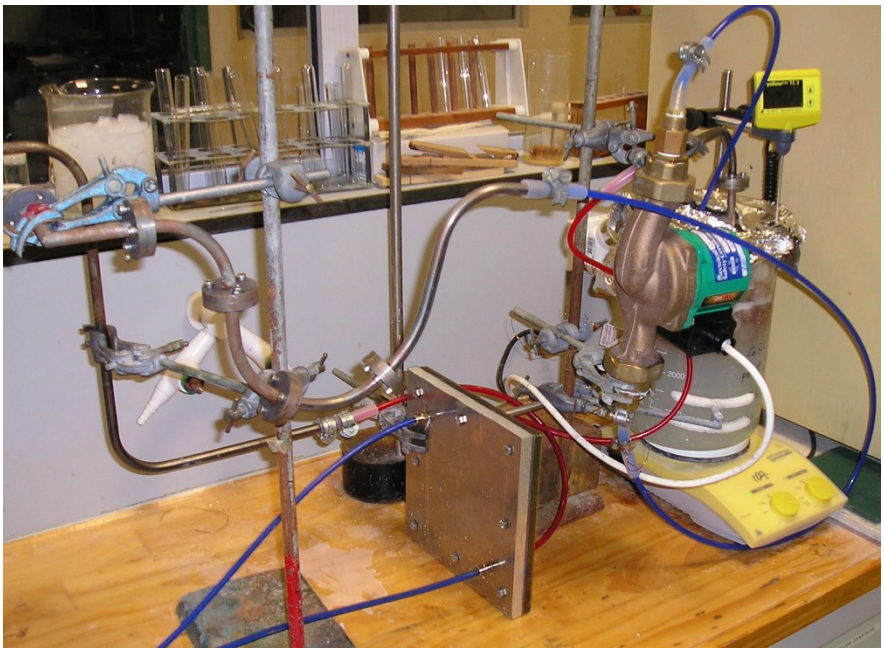


Figure 2: Laboratory scale plate-and-frame heat exchanger to test deposition of CaSil-material.

In contrast to the laboratory trials, the geothermal industry usually employs shell and tube heat exchanger designs. In order to incorporate a heat exchanger into the geothermal CaSil system at Taupo we acquired a shell and tube heat exchanger and three additional double pipe heat exchangers to cool the brine even further, if desired. A thorough redesign process has enabled the maximum throughput of the system to be extended from 10 L/min to 30 L/min, as well as automating key unit operations and components in order to now realize a fully operational small-scale pilot plant. A pipework matrix with two 32 m-long pipelines, one for the treated brine and one as an untreated control line, has been added. The plant is using a programmable logic controller (PLC)

for data collection and control of automated valves, pumps and motors. Figure 3 shows a digital rendering of the newly designed pilot plant under construction at the Wairakei, Taupo site.

At the time of writing some components remain in fabrication and are yet to be installed on-site. Commissioning will commence during the fourth quarter of 2019. The performance of the heat exchanger will be monitored in situ, via measurements of the pressure loss, transferred heat energy and rate of flow. Potential depositions in pipes, the plenum or on the tube sheets will be monitored and quantified periodically during downtimes.

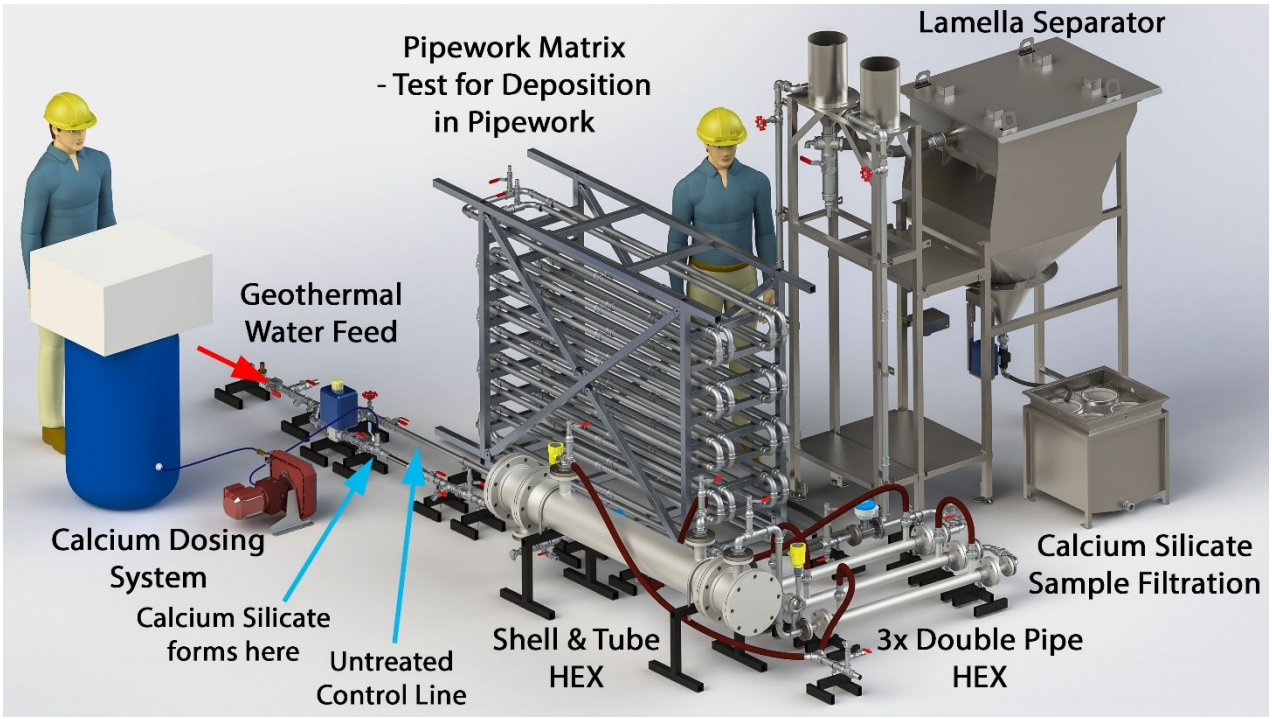


Figure 3: Rendered picture of new pilot plant setup including shell and tube and three double pipe heat exchangers.

2.3 Separation of CaSil-Particles

If the calcium silicate hydrate particles are reinjected into the ground along with the spent geothermal brine, they could block the porous structure of the reinjection wells. Therefore, it is preferable to separate the particles from the liquid flow prior to discharge. To identify a suitable separation technology several important factors were considered:

I. In a large scale application, the separator has to be able to process large volume flows, hence requires a small specific footprint to keep the overall footprint low;
II. Energy consumption has to be kept to a minimum; and,
III. Low capital and operating expenditures are required.

For our pilot plant operation, low capital cost and easy maintenance were of highest importance. Therefore, we decided to utilize a lamella separator, which is an improved version of a conventional settling tank and relies on the natural settling behavior of particles. The working principle is depicted in Figure 4.

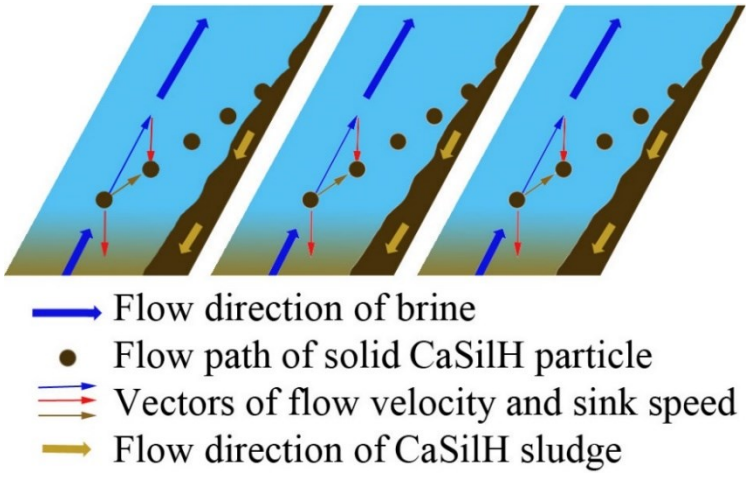


Figure 4: Working principle of a lamella separator in counter-current design.

The lamella separator is comprised of angled plates, or lamella, which are stacked horizontally. In the depicted counter-current design, geothermal brine loaded with CaSil-particles flows through the lamella package in an upward direction. The CaSil-particles follow a slightly shallower angle due to their higher density and consequent sedimentation velocity. Eventually, the particles hit the lamella plate, accumulate to a sludge and slide down, in the opposite direction to the brine flow. The cleared supernatant is channeled off the top of the lamella while the sludge falls into a compression area and sludge cone underneath the lamella, where it compacts further and can be extracted from an outlet at the bottom of the separator. The separation process requires calm and laminar flow conditions, as turbulence can resuspend the already settled particles, resulting in particle breakthrough into the supernatant brine flow. Due to the stacking of the plates, the separator can equal up to 20 % of the footprint of a comparable conventional settling tank while offering the same settling surface area.

It was necessary to develop a custom-designed prototype lamella plate separator for the CaSil pilot plant, as even the smallest commercially available lamella separators were too oversized for the volume flow of the first demonstration plant, and typically contain plastic parts which will not survive the hot geothermal brine. There is rather little information available on how to build a lamella separator for this type of application, so the design of the first separator was reverse engineered in a rapid prototyping approach. The design process and results from operation are presented by Schweig et al. (2018) and Borrmann et al. (2018). This lamella separator was successful in proving the concept of separating CaSil-particles from hot geothermal brine. However, during long term operation several shortcomings in the initial separator design became apparent. The compression area and sludge cone of the separator were very hard to clean after operation, due to the lamella plates being welded to the frame and restricting access. Feed connections to and from the separator also included some large flat surface areas in the flash vessel, the connector piece from flash vessel to separator and at the bottom of the sludge cone. These flat surfaces were included to simplify the overall system build, but during operation CaSil-particles were observed to settle on these surfaces, forming sludge deposits. The overall performance was not affected by this, but regular and thorough cleaning of the hard-to-reach areas became essential.

In light of the above issues, and with the intention of increasing the pilot plant maximum throughput from 10 L/min to 30 L/min, a new design iteration of the lamella separator was developed. This also allowed further design improvement and optimization of the separation efficiency. The design process was informed by CFD-simulations which enabled a shotgun approach to test numerous design options more quickly than with rapid prototyping. The simulations proved to be a useful tool to identify promising separator geometries and design features. The key design target was a calm, slow brine flow without induced turbulences which could resuspend particles. Attention was also placed on an even loading of all flow paths and the lamella package. Once a suitable geometry was found a small laboratory scale model was built out of Perspex for a nominal flow of 525 mL/min with a hydraulic loading rate of 1.5 m/h. Experiments were conducted with dye tracer streams, as well as synthetic CaSil-suspensions. No turbulence was observed that could resuspend CaSil-particles at volume flows up to 2 L/min (equivalent to 5.7 m/h loading rate), which was 4 times the design value. With the addition of a flocculant the separator was successfully operated with no visible particles in the overflowing supernatant, at a volume flow of 3 L/min (8.5 m/h, 6 times the design rating). The flow conditions were still very calm at this loading rate, but this represented the highest flow rate possible. Due to the separators comparatively small volume (L 220 × W 180 × H 330 mm, 5.7 L total liquid volume) the compression area and sludge cone (1.4 L volume) could not drain fast enough and filled up completely with particle sludge. Additionally, particle bridging effects were observed above the sludge drain, which impeded extraction of the settled particles from the sludge cone. However, the drain outlet was only 8 mm wide, so a larger drain diameter is a straightforward solution to eliminate this problem. In short, the laboratory-scale model was deemed to be very successful, so the decision was made to scale this design up to attain 30 L/min of throughput at 1.7 m/h. A CFD-simulation was used to confirm comparable laminar flow conditions in the scaled-up separator, as observed in the small model. The large-scale separator was manufactured in July and August 2019. More detailed results of the design process, operation and experiences of the small scale as well as the large-scale model will be published in the future.

In addition to the dye and CaSil tests, a pressurized test was conducted. For this a lid was placed on top of the separator and fixed via a flange connection. The sludge and supernatant outlet were fitted with needle valves to control the outflow and therefore internal pressure of the separator. A pressure gauge and manual relief valve for air bleeding were included in the lid. On average the separator was operated around 0.25 bar_g. A maximum pressure of 0.5 bar_g was reached but quickly decreased again due to excessive bulging of the Perspex and serious risk of destruction of the Perspex model. As expected, no change in settling behavior of the CaSil-particles was observed. This indicates that the CaSil-technology can be fully pressurized, although further research is required to fully characterize separation performance at higher pressure levels. Results of the pressurized experiments will be published later, along with the design process and results.

Flocculation proved to be a valuable technique to improve the separation rate of CaSil-particles. Not only did the particles form very stable and large flocs, the sedimentation velocity was boosted significantly. A series of sedimentation experiments under laboratory conditions were conducted with a jar tester to identify optimal dosing procedures. Sodium silicate served as an artificial silica source to eliminate potential side effects from impurities in geothermal water affecting the experiment. Even small amounts of flocculant added to the CaSil-suspension (1 g of dry flocculant per m³ of suspension) increased the settling performance drastically. Depending on the dosing regimen and initial silica concentration, the sedimentation velocity was increased by up to 2000 % at a dosage of 3 g of dry flocculant per m³ of suspension. All experiments were conducted at room temperature, as well as 60 °C water temperature. In order to simulate a high temperature dosing application, several samples of various flocculant solutions were first heated to 140 °C for 30 minutes in an autoclave. Sedimentation experiments were then repeated with the heated flocculants. Even after being exposed to high temperatures the flocculants showed an effectiveness of 80 to 90 % compared to the non-heated solutions.

These findings are important as it implies that flocculant dosing and separation of CaSil-particles could feasibly be implemented upstream of a binary heat exchanger, in a fully pressurized system at high temperature. Pressurizing the solid-liquid separator has the obvious advantage that the whole brine pipeline of the power plant can then be kept under pressure. This would enable the CaSil-technology to be easily integrated into existing fully pressurized power plant designs, with the pressure of the water being used to propel the brine flow to remote reinjection wells and save operating costs for pumps. An additional advantage of the CaSil-separation stage is that small particles which are carried along with the sourced water flow are also removed from the brine flow. If not properly

separated, these particles can also gradually fill up reinjection wells over time, decreasing the injectability and necessitating costly re-drilling operations.

During initial on-site tests, the separated sludge was collected in troughs, which were gradually filled up with sample. In order to reduce the contact time and orient the process to a more industrial applicable post-processing methodology, a gravity filtration system has been designed to dewater the sludge extracted from the separator. Experiments in the laboratory showed that solids concentration in the sludge of up to 3 wt% were achieved after about 10 minutes of gravity filtration using a Ø 120 mm 50 µm filter bag. Once pressure by hand was applied, further water could be removed, leading to a solids concentration of 8.5 wt%. For large scale applications an automated band filter and filter press system can be used to mechanically dewater the CaSil-material and prepare the cake for ensuing transport and use. CaSil material has multiple applications, like copper or nitrate uptake from wastewater streams or as an additive for concrete and paper, creating additional revenue. Cairns et al. (2020) detail the use of this unique material more closely.

3. CONCLUSION

Silica scaling represents arguably the single largest hindrance in the full utilization of geothermal heat sources. The CaSil-technology transforms silica into a calcium silicate material and effectively prevents the formation of silica scale. Our first proof-of-concept system was able to demonstrate the simplicity and robustness of the technology. However, a design approach closer to industry standards was necessary.

Our demonstration plant went through a thorough redesign process, now featuring a PLC system, sensors to measure process parameters and actuators to automate routine pump and valve tasks. This redesign enables us to adjust the calcium agent dosing much finer in relation to the present brine flow, which will ultimately result in a more uniform product. Additionally, a heat exchanger will be used to cool the geothermal brine and demonstrate that no silica fouling occurs in pipes and the heat exchanger. The lowered brine temperature is expected to aid the separation efficiency due to a reduction in convection currents which have been observed at high temperatures. The effect of brine temperature on separation efficiency will be investigated in detail. Furthermore, the addition of flocculant will be studied. Preliminary laboratory experiments showed a significant increase in sedimentation velocity and floc stability. A new design iteration of a lamella separator was developed to further improve and optimize the geometry. A laboratory scale model made from Perspex was operated successfully with and without flocculants. The design was upscaled to fit our newly developed CaSil-pilot plant. Operational results of the revised plant will be published and discussed in the future.

If the CaSil-technology is applied in large-scale geothermal power plants, an increased energy yield from the extracted brine stream can be achieved without risking silica polymerization. This decreases maintenance costs and downtime significantly, while providing more electric energy and opening up additional revenue streams like mineral extraction or marketing of CaSil-based products.

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