LAMELLA SEPARATORS FOR RECOVERING NANO-STRUCTURED CALCIUM SILICATE HYDRATE FROM GEOTHERMAL BRINE

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ABSTRACT

One of the major challenges in geothermal energy utilization is the formation of silica scale from supersaturated geothermal brine. Over time silica scale blocks pipes, valves, heat exchangers and reinjection wells, which need to be regularly cleaned, serviced or replaced. High costs and downtimes for maintenance and replacement are the result. Many of the current technologies that address this challenge only attenuate the problem but can't solve it wholly.

The formation of silica scale in supersaturated geothermal brine can be fully prevented with the competitive transformation of dissolved silica into nano-structured calcium silicate hydrate (NCaSilH) particles. The NCaSilH-particles form within milliseconds and don't stick to metal surfaces. Dissolved silica can be reduced to safe levels at which no polymerization takes place, even at room temperature. This allows for an increased energy production of the geothermal power plant, reduces maintenance and replacement costs and can even create additional revenue for a useful NCaSilH-product. The particles agglomerate over time and are too big to be reinjected into the geothermal reservoir risking blockage of the porous rock structure. This means, that they need to be separated from the spent brine prior to reinjection of the brine.

In order to identify a suitable separation technology to separate NCaSilH-particles from geothermal brine settling experiments were conducted. Lamella separators were identified and investigated as a promising technology for the recovery of the silicate. We have constructed multiple laboratory models in a rapid prototyping approach to develop a suitable separator. An up-scaled version was built for pilot plant operation to demonstrate the technology to industry. We present data from the settling behaviour as well as the design process of the separator.

1. INTRODUCTION AND PRIOR RESEARCH

1.1 Geothermal Energy and Formation of Silica Scale

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 a natural or artificially created reservoir. The water contains a cocktail of different species like salt, precious metals and silica in solution. The specific composition is dependent on the pressure, temperature and rock structure of the field and varies from site to site. The pressure of the water is reduced in a flashing vessel, which causes a certain percentage of the water to boil off as steam. Then the steam drives a turbine, which produces electricity. Due to the mass reduction of the liquid phase, the chemical compounds are concentrated in the brine. This usually causes silica to exceed its solubility limit for the respective water temperature. After an induction period the silica starts to polymerize. The length of the induction period and the velocity 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, forming a scale on turbine blades. In order to prevent silica 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. During production the scale in the pipework and heat exchangers lowers the efficiency of the plant. Therefore, extensive cleaning efforts are needed to remove the scale. The usage of binary plants to use the excess heat of the brine only promotes the silica scaling again, since lowering the temperature of the brine decreases the solubility of silica and boosts the polymerization. A trade-off between energy production and prevention of silica scaling must be achieved (Thorhallsson, 2011). Parts of the spent brine are reinjected into the ground to increase the lifetime of the geothermal reservoir, prevent subsidence and dispose of the waste water, while the rest gets discharged into a nearby waterway (Diaz et al., 2016; Allis, 2000).

A common method to attenuate the silica scaling problem is hot reinjection, where the temperature of the brine is left comparatively high, which ensures a high silica solubility. The water is quickly reinjected so that the overall time, where silica is in a supersaturated state is equal or shorter than the induction period. However, with this method a lot of heat energy contained in the brine is unused. Other methods try to delay the polymerization of silica by extending the induction period via addition of chemicals (acids or dispersants) (Gunnarsson and Arnórsson, 2005).

1.2 Nano-structured Calcium Silicate Hydrate

As a competitive method for silica scale prevention, we developed the Nano-structured Calcium-Silicate Hydrate (NCaSilH) technology. Metal ions, which are injected into the geothermal water, react with silica and silicate ions to form an insoluble nano-structured calcium silicate hydrate product. The particles don't stick to metal due to a positive surface charge, leaving a clean surface in pipes and heat exchangers for optimal heat transfer. They possess a high surface area of 100 to 500 m²/g and can absorb 1 to 7 times their own weight in oil (McFarlane, 2007). The reaction forming the particles is very fast and completed within milliseconds, while the induction period for polymerized silica is usually several minutes. The silica concentrations within the brine can be regulated to safe levels, even for very low temperatures such as 60 °C. An economic power plant operation can be guaranteed for all operation points. The NCaSilH-product is useable for various applications for example as a concrete additive or paint filler, creating additional revenue. (Borrmann et al., 2005). The particles are very small as the particle size distribution in Figure 1 shows.

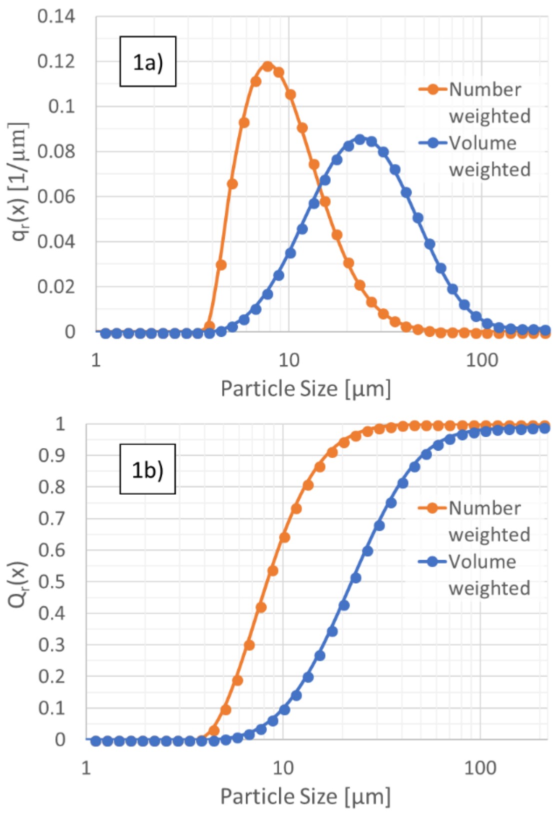

Figure 1: Particle size distribution of nano-strucutred calcium silicate hydrate product. Density curve (a) and cumulative distribution (b).

From the number weighted cumulative distribution, it becomes obvious that most particles are smaller than 30 µm. Some larger particles were measured, shifting the volume weighted distribution towards larger particle sizes. Examination under an electron microscope confirmed the small size of the individual particles. The larger particles consist of several smaller strongly bound particles which agglomerated. In the laboratory an enhanced ripening effect of the agglomerates has been observed. The average agglomerate size was estimated to be between 2 and 6 mm. Higher initial silica concentrations sped the ripening effect up. The particle size distribution was determined with a Malvern Mastersizer 2000 Hydro MU, which has a compulsory stirring unit with a dedicated pump rotating at 2000 rpm. The larger agglomerates broke apart due to the high shearing force induced by the stirrer, indicating a very weak flock. The measurement was repeated with a peristaltic pump at low flow rates, but the flock still broke apart confirming weak interparticle forces. The bigger agglomerate size could therefore only be estimated. If the NCaSilH particles should be reinjected into a reservoir they would likely block the porous rock structure. Therefore, the particles need to be removed from the brine.

2. LAMELLA SEPARATORS

2.1 Settling behaviour of NCaSilH

Due to the agglomeration, high surface area and porosity of NCaSilH-particles in suspension the settling didn't follow the individual stokes settling behaviour but zone settling or hindered settling behaviour. This meant, that the settling velocity was independent of the particle size and the bulk of material sets collectively as a unit. Depending on the mass concentration of the particles a clear boundary layer between suspension and clear supernatant formed. The higher the mass concentration of NCaSilH particles was the more defined the boundary layer was. However, settling rates for zone settling must be determined empirically with a settling test, since there are too many variables influencing the settling velocity. For the experiment a large vessel with a volume of 3 L was filled with suspension and the settling boundary layer subsequently recorded. The vessel was 190 mm high and slightly conical with a diameter between 155 (top) and 130 mm (bottom). To make up for the conical shape the equivalent diameter of the passed through volume was taken to calculate the settling rate. The average of two measurement points was taken to smoothen the curve. A differently shaped vessel will yield slightly different results due to wall effects. The compression point is dependent on the vessel height.

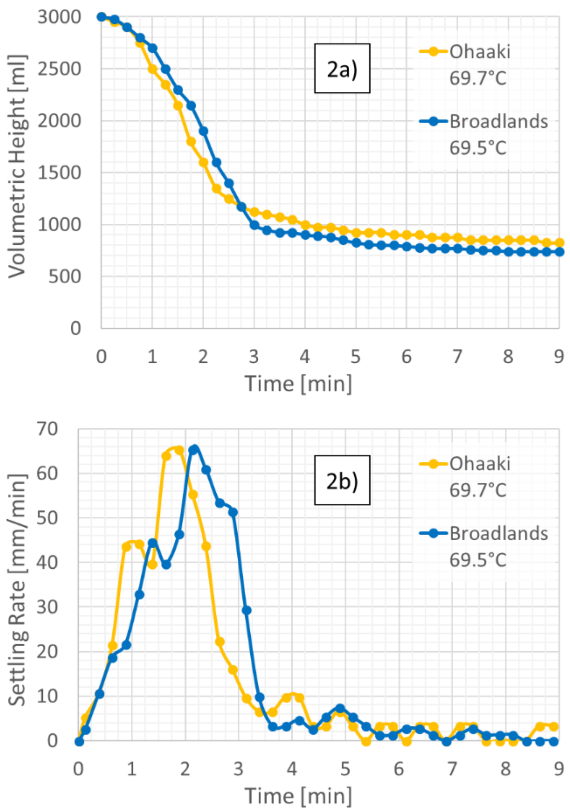

Figure 2: Settling height vs. time (a) and settling rate (b) for two samples of NCaSilH produced from geothermal brine collected from the Ohaaki kiln (Ohaaki) and a wellhead of the Ohaaki power station (Broadlands).

The samples shown in Figure 2 were collected from the Ohaaki Kiln, Broadlands, New Zealand (named Ohaaki) and from a wellhead of the Ohaaki power station prior to flashing (Broadlands). Most of the settling happened within the first 3 – 4 minutes. After that the settling velocity stagnated and the suspension reached its compression point. After the compression point the particles slowly approach a finite end value. This indicates that a separation beyond the compression point is not economical and should be terminated, since a substantial increase in compression requires a large time frame. The maximum settling velocity for a roughly 70 °C hot suspension was determined to be about 65 mm/min. At lower temperatures the settling velocity decreases accordingly due to an increased viscosity of the water. However, due to turbulences and thermal currents these values should only be considered as rough estimates.

Due to the sample preparation the samples are compromised. In order to stop the precipitation of the silica the pH-value has to be lowered, which causes sulphur to precipitate, changing the overall chemistry of the sample. However, they are still useful as a guideline, since conducting experiments with fresh geothermal water is not always possible. Based on this settling velocity the theoretical minimal size of a circular settling tank could be calculated. Figure 3 gives the necessary tank diameter in respect to the settling velocity.

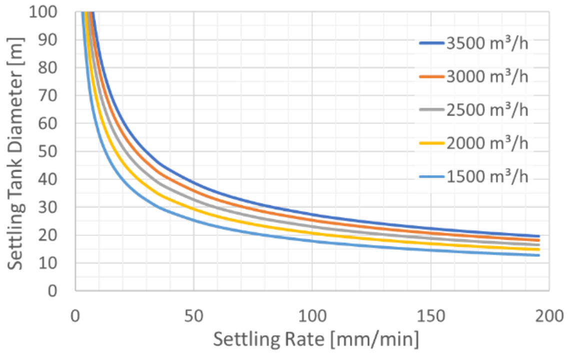

Figure 3: Minimal theoretical settling tank diameter vs. settling rate for selected flow rates.

For the two samples and an assumed brine flow of 2000 m³/h after flashing a tank diameter of about 25 m would be required. However, a safety factor must be included due to induced turbulences and fluctuations in the settling process. For a 50 % increase in surface area of the settling tank the diameter would increase by 22 %, resulting in a settling tank diameter of about 31 m, which is comparatively large. In order to guarantee a safe separation of the particles, high maintainability and redundancy the flow should be split into smaller fractions, which increases the overall footprint of the separation facility. Experiments showed, that the settling velocity can be altered by flocculants. Preliminary flocculant experiments were conducted; further research on the use of flocculants will be presented in future publications.

2.2 Design of a functioning Lamella Separator

For our approach we considered several solid-liquid separation technologies to separate the NCaSilH-product from geothermal brine. While band filters, rotary drum filters or continuous centrifuges would be suitable for separating the NCaSilH particles, they have moving parts, need to be serviced regularly and are relatively expensive to operate. The high volume flows require large machines and were therefore considered uneconomical for separating the NCaSilH-product from the brine in the first instance. Hydrocyclones are already used in geothermal power plants for flashing and are a common method in industry. The comparatively low footprint and easy maintainability speak for their principle. Due to the weak nature of the flocks (see above) they were not considered in this study.

Filter cartridges proved to be applicable for separating the particles in the laboratory but suffered from fouling. In a real-world application, the lifetime of such a cartridge would most likely be comparatively short due to the high temperatures and pressure. The service life would also be short due to the large volume flows that need to be handled.

Investigation of lamella separators was started on the advice from Professor Edgar Schicker. Lamella separators are based on the principle of gravity settling, but in a more compact way than a conventional settling tank. The required footprint of a lamella separator can be up to one fifth of a comparative settling tank. The name of the separator stems from inclined plates, or lamella, which represent its settling surface.

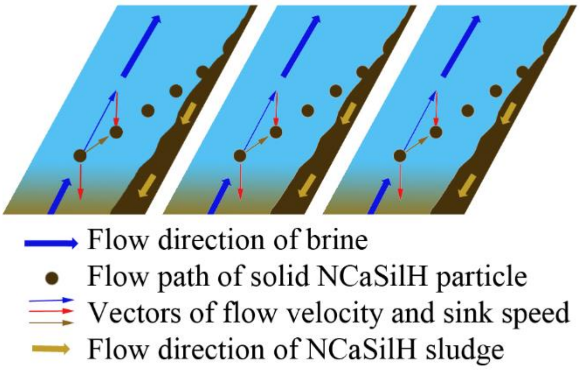

Figure 4: Schematic of a lamella separator showing the flow of brine and particles

There are three main principles for operating a lamella separator, the co-current, cross-current and counter-current method. A schematic for the function of a lamella separator is shown in Figure 4. Particles suspended in brine rise up in the channels between the lamellae. Due to the higher density of the particles they follow a shallower velocity vector angle. Eventually, the particles hit the lamellae, aggregate to a sludge and slide off. Because the brine and sludge are flowing in opposing directions this approach is called the counter-current method. The particles fall into a collection chamber at the bottom, where they can compress further and are drained afterwards. The cleared brine can be taken off at the top. For a good separation process low velocities and therefore low Reynolds numbers are desired. Turbulences only disturb the settling process and should be prevented in the lamellae area. In the context of separating NCaSilH-particles from hot geothermal brine thermal currents might occur. Suitable steps need to be taken to prevent the formation of a thermal gradient within the separator, for example by insulating the surfaces of a separator.

For the design of a lamella separator an empirical rapid prototyping approach was chosen. Over three iterations a functioning separator on laboratory scale with a separation efficiency above 99 percent was developed. The models were crafted out of clear Perspex, so flows could be visually observed. All the separator tests were carried out using an artificial silica source, sodium silicate. The suspension was continuously prepared with a silica concentration of about 1000 ppm, giving the suspension a mass concentration of NCaSilH-product of 0.1 %wt.

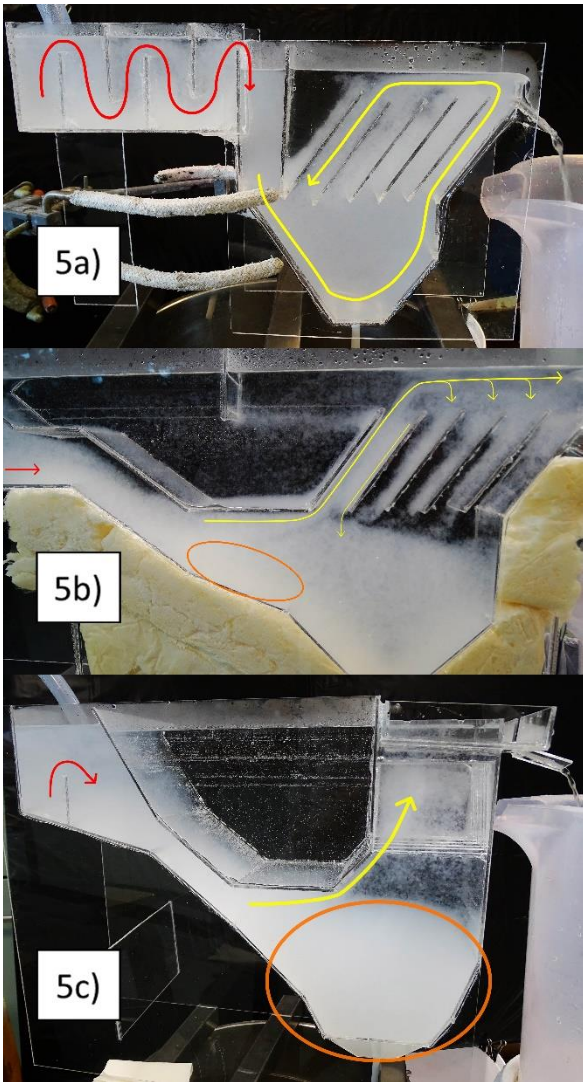

Figure 5: Different laboratory separators; model 1 (a), model 2 (b) and model 3 (c).

In the first model the suspension intake was realized vertically. This caused a large unwanted current within the separator (yellow line). A small labyrinth chamber to calm the incoming flow down was attached afterwards (red line), which mitigated the effect, but the current was still too strong. A slight separation of 7.5 % was achieved, which was based on the residual mass concentration of particles in the supernatant. The removed suspension from the sludge outlet on the bottom showed no measurable compression of particles. The model showed that the intake into the separator had to be horizontal and relatively slow. The second model featured a large intake area in the front to calm down any currents. Dye experiments showed that all the water rose in the first lamella in a very concentrated and narrow stream. The lamellae after that served no purpose. Because the water flow only concentrated in a small area the velocity was high. At first, the flow was considered to be a result of thermal currents, but insulation of the walls and using water at room temperature showed no improvement. The supernatant outlet of the separator, a weir towards the right side, probably caused or at least promoted the observed chimney effect, which resulted in an unbalanced loading of the lamella. While loading the separator with suspension some particles settled onto the lamella, proving the principle works for separating NCaSilH-product. Parts of the carried over product settled on its way towards the outlet, giving the separator a separation efficiency of 57.2 %. A slight compression of the settled particles was observed, increasing the mass concentration to 0.18 %wt. To make use of all lamellae and increase the separation efficiency further the third model was designed and constructed. Here, the lamellae were turned by 90 °, so the suspension flow was perpendicular towards the lamellae. The suspension distributed evenly over the whole width of the flow channel, so the lamellae were loaded evenly. This was achieved by directing the flow onto a baffle plate (red line). Most of the particles settled directly into the compression area (orange circle), while the rest was taken by the suspension flow towards the lamellae (yellow line). Over the lamellae the residual particles settled steadily. The supernatant overflow was revised and weirs were placed on three sides of the separator, distributing and slowing down the outflow. A chimney effect could be prevented. With the changes put in place a separation efficiency of 99.8 % was achieved. The compression of the particles was also increased to 0.24 %wt. The particles in the clarified suspension were very small and not visible. Due to their small size they are impossible to separate by gravity in an economical fashion without using flocculants, granting the separator design an excellent separation efficiency.

Based on the third laboratory model a larger separator was designed for a nominal flow rate of 8 L/min, to be used in a pilot plant to demonstrate the technology. A CFD simulation of the separator was recorded by Haiam Abbas of the Heavy Engineering Research Association (HERA) using ANSYS R17.0. The streamlines of the flow and velocities are shown in Figure 6.

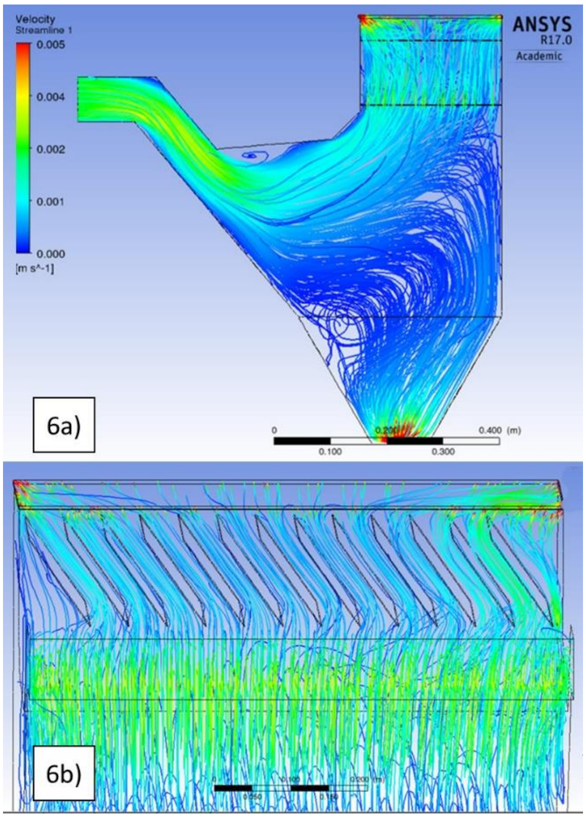

Figure 6: CFD model of the scaled-up model showing the streamlines and velocities of the water. Side view (a) and detailed view of the lamellae (b).

The streamlines within the separator match the observed flow of the laboratory model, showing good accordance with the laboratory scale. The detailed view of the lamellae shows an increased velocity towards the right side within the lamella area, indicating an uneven loading of the lamellae. This could be an artefact from the simulation. If an unbalanced loading and therefore increased velocities occur in a separator, the separation will still take place to a certain point. For a 50 % increase in velocity the lamella needs to be twice as long, so a generous safety factor should be allowed. The separation process stops to be reliable once higher Reynolds numbers are met and turbulences occur. Turbulences prevent the particles from depositing safely onto the lamella and can result in breakthrough. The separator was built by AE Tilley Ltd., Wellington, New Zealand. Figure 7 shows a picture of the commissioned pilot plant, that is currently based in Taupo, New Zealand on the premises of MB Century, sourcing water from the Wairakei power station.

Figure 7: Commissioned pilot plant in Taupo, New Zealand.

In the pilot plant the incoming geothermal water is treated with calcium ions to form NCaSilH-particles. After about 10 m of pipework the water enters a flashing vessel (silver cylinder) to reduce the pressure of the water to atmospheric pressure. The suspension flows through a connector piece into the separator. The separator itself is covered in neoprene to reduce heat losses, prevent thermal currents and create a safe work environment. Because the composition of the used geothermal water is ever-changing the separation efficiency is changing. The average silica concentration in the water is about 400 ppm, for which an average separation efficiency of 98.5 % could be achieved. The decrease in separation efficiency originates from the low silica concentration. With lower initial silica concentrations, the agglomeration time for the particles to form sufficiently big particles increases drastically, but because that time is not available the separation worsens. However, only small particles usually smaller than 5 µm were discharged over the outlet. With an increase in silica concentration the separation efficiency rises due to increased agglomeration. Is the silica concentration lowered the efficiency worsens further. During operation some design flaws became obvious like poor serviceability and settling of particles in unwanted spots. In order to improve the handling and performance of the separator further we are currently developing a new model featuring a slightly more compact design. Different geometries are simulated with CFD software in order to investigate the flows and check for turbulences. Results for the simulation as well as laboratory tests will be presented in the future.

3. CONCLUSION

The NCaSilH-technology enables us to prevent the formation of silica scale in geothermal power plants. Instead, the silica is transformed into a nano-structured calcium silicate hydrate, which can be used in the concrete industry, creating additional revenue for the power plant. Because the treatment can take out enough silica to be stable even at room temperature more energy can be harvested from the geothermal water.

Particle size analyzation showed that most particles are smaller than 30 µm. However, the particles loosely flock, form relatively large agglomerates and need to be removed from the brine. Otherwise reinjection wells and the porous structure of the reservoir would likely block up. Settling experiments confirmed a zone settling behaviour rather than individual stokes settling. Therefore, the settling velocity had to be determined empirically. Two samples from geothermal water were used to form NCaSilH-particles, showing a maximum particle settling velocity of about 65 mm/min at roughly 70 °C. At lower temperatures the settling velocities decrease accordingly due to an increased viscosity of the water. However, due to turbulences and thermal currents these should only be considered rough estimates.

Lamella separators proved to be a suitable method for separating NCaSilH-particles from high-volume brine flow in the first instance. The footprint of a lamella separator equals about a fifth of a comparative conventional settling tank, decreasing the required space for a separation facility substantially. A separation efficiency of 99.8 % was achieved in the laboratory. With a fast prototyping method, observing the present flows and subsequently refining the geometry a functioning lamella separator was designed and constructed. Three iterations were necessary to find a suitable geometry. For our pilot plant an upscaled version of the third laboratory model was designed and validated in a computational fluid dynamics simulation. The simulated streamlines matched the observations made in the laboratory well. The up-scaled version reached a separation efficiency of about 98.5 %. The loss in separation efficiency originates from the low silica concentration in the sourced geothermal water. Because of that the agglomeration time for the particles to form sufficiently big particles was greatly increased, but because only a certain amount of time was available very small agglomerates entered the separator. The smaller particles yielded a decreased settling velocity reducing the separation efficiency. Usually only particles smaller than 5 µm were found in the overflow of the separator. Due to small servicing problems and to improve the separation efficiency further a new model is currently being developed. For this computational fluid dynamics simulations are used to find the best suitable geometry. Results of the simulations as well as laboratory experiments will be presented in the future.

ACKNOWLEDGEMENTS

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