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Leaning into the Problem, an Experimental Study of Mixing Groundwater with Geothermal Water, Towards Full Integration of Reykjavík's Two District Heating Systems

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ABSTRACT

Mixing of heated groundwater with geothermal water has proven problematic due to the different chemical properties of the two types of water. At their geological origins, the two water types are in equilibria with the reservoir they are extracted from and specific to the problem of mixing, the geothermal water contains a high monomeric silica concentration and a relatively high pH (>9.0). In contrast, the groundwater has a low silica concentration and lower pH but contains a small amount of magnesium. When mixed, silica and magnesium are introduced at alkaline conditions and thus amorphous magnesium silicate precipitates. The district heating system in the Reykjavik capital area is supplied with two sources of water, heated groundwater from two co-generative geothermal power plants and low temperature geothermal water from geothermal fields in Reykjavík. Because of this precipitation and resulting scaling issues, the district heating system is operated as two parallel systems with two types of water that cannot mix. Our proposed solution to this problem is to intentionally induce precipitation of magnesium silicate in the heated groundwater at the power plants in a controlled process to remove magnesium. We do this by mixing the high temperature geothermal water (post steam separation) with the heated groundwater to induce precipitation and remove it. In this process we produce pseudo low temperature geothermal water with a geochemical profile as close as possible to the water from the low temperature geothermal fields in Reykjavík. Experiments to develop and validate this solution have been performed on a laboratory scale and pilot scale tests are ongoing.

Our goal was to study the precipitation reaction through which magnesium silicate is formed. Firstly, high temperature geothermal water and heated groundwater were mixed in varying ratios to research whether scaling happened at any ratio of mixing and the effect of the mixing ratio on the rate of the reaction. We found that in mixtures with >20% geothermal water the reaction proceeds in a matter of days through homogenous nucleation, but only after a lag time that extended to about a week. We then mixed the resulting pseudo low temperature geothermal water from the previous experiments with real low temperature geothermal water from Reykjavík to confirm that no further precipitation occurs through mixing of the two types of water. This served to validate our proposed solution to being able to operate a single district heating system. No precipitation was found to happen, solidifying our belief that once a reliable process to perform this precipitation reaction at scale is developed, the two separated district heating systems in Reykjavík can be joined.

Secondly, we mixed the two types of water in the presence of magnesium silicate seed. With the addition of magnesium silicate seed the lag time is eliminated and the reaction proceeds through heterogenous nucleation in a few hours to provide a solution with a magnesium concentration below 0.5 mg/kg. The main factors that affect the rate of the reaction are pH, silica concentration, magnesium concentration, and the type, size, and amount of seed material.

Thirdly, we mixed the two types of water in a fluidized bed reactor that was packed with silica sand. Under these conditions the reaction proceeded through heterogenous nucleation in 5 minutes and resulted in an outlet stream of pseudo low temperature geothermal water with a magnesium concentration below 0.5 mg/kg.

1. INTRODUCTION

From the commencement of district heating in the Reykjavík capital area in Iceland and until 1990 the supply into the system was low temperature geothermal water from wells in the city. In 1990 the Nesjavellir geothermal co-generative power plant started production of hot water for the district heating system. Hot water production at Nesjavellir is based on heat exchange of cold groundwater with high temperature geothermal fluid. Initially, the hot water from the two different types of sources was mixed in the district heating system. A few months after the Nesjavellir power plant came online problems with pressure drop and system clogging became increasingly common. The cause of all these problems was analyzed and magnesium silicate scaling was found to be the culprit. About 5-6 months after the power plant commenced production of hot water the district heating system in the Reykjavík capital area was effectively split up into two systems to prevent further scaling in the system and after 10 months the split up was formalized. In the summer of 1991, a few of the main pipes in the system were "pigged" to clean out the magnesium silicate scaling. About 13 tonnes were cleaned out of the piping system but the estimated total amount of precipitation from solubility product calculations was 17 tonnes (Hauksson, 1995).

The precipitation of magnesium silicate in a geothermal environment is endothermic and produces an amorphous structure that can be described by the following chemical equation (Gunnarsson, 2002).

$$3Mg^{2+} + 2H_4SiO_4 + H_2O = Mg_3Si_2O_5(OH)_{4\,(s)} + 6H^+$$

From 1991 and onward the district heating system in the Reykjavík capital area has been operated as two different systems with water from different sources that never mix. As heating demand grew through the years another geothermal co-generative plant was constructed in Hellisheiði. Electricity production started in Hellisheiði in 2006 and hot water production in 2010. However, no additional capacity has been added to the part of the system that is supplied with low temperature geothermal water from wells in the city, as the low temperature geothermal fields supplying the system were at capacity in terms of peak load in the 1980s before the Nesjavellir power plant was constructed. This has resulted in Veitur Utilities, the operator of the system, having to make expensive changes to the district heating system to expand the distribution zone of heated groundwater from the geothermal power plants at Nesjavellir and Hellisheiði. The current operation of the system can be seen in Figure 1.

In 2018, a research project was started to solve the problem of mixing water produced at Hellisheiði and Nesjavellir with water from low temperature geothermal wells in the city. The mixing of heated groundwater with geothermal water has proven problematic due to the different chemical properties of the two types of water and the resulting magnesium silicate precipitation in any instance the waters mix. Our proposed solution to unify the district heating system in Reykjavík is to change the production of hot water at the Hellisheiði and Nesjavellir geothermal power plants by intentionally inducing precipitation of magnesium silicate in the heated groundwater in a controlled process to remove magnesium. We do this by mixing the high temperature geothermal water (post steam separation) with the heated groundwater to induce precipitation of magnesium silicate and remove it. In this process we produce pseudo low temperature geothermal water with a geochemical profile as close as possible to the water from the low temperature geothermal fields in Reykjavík. An example of the geochemical composition of the different types of hot water that feed the district heating system can be found in Table 1. During peak load, the Laugarnes field can provide 330 l/s of 120-130°C hot water from 10 wells, the Elliðaár field can provide 250 l/s of 75-92°C hot water from 8 wells and the Reykir and Reykjahlíð fields can provide about 2000 l/s of 65-100°C hot water from 34 wells (Gunnlaugsson, 2008).

A key challenge in the development of this process is to accelerate the rate of the precipitation reaction as much as possible while also operating the process at the scale, temperature, and pressure of the produced hot water. The peak production at Nesjavellir is currently 1500 l/s of 85°C hot water. Hellisheiði produces 990 l/s of 85°C hot water during peak load but the heat plant at Hellisheiði has not been fully constructed yet. The final size of the heat plant at Hellisheiði will have a maximum capacity of 1800 l/s of 85°C hot water. A full scale production unit that produces and removes magnesium silicate will therefore have to process 3000 l/s – 4000 l/s.

Experiments to develop and validate this solution have been performed on a laboratory scale and pilot scale tests are ongoing. This paper will present the results of the laboratory scale experiments along with the first results from an ongoing pilot scale study.

Table 1. The chemical composition of the hot water supplied to the inhabitants of the Reykjavík capital area through Veitur Utilities' district heating system. Laugarnes, Elliðaár, Reykir, and Reykjahlíð are low temperature geothermal fields that supply water directly into the district heating system. Nesjavellir and Hellisheiði are high temperature geothermal fields where hot water is produced through heat exchange between cold groundwater and high temperature geothermal water.

	Unit	Laugarnes RV-5	Elliðaár RV-39	Reykir MG-25	Reykjahlíð MG-39	Nesjavellir Heated groundwater	Nesjavellir Geothermal water	Hellisheiði Heated groundwater	Hellisheiði Geothermal water
Date		6.1.2021	1.2.2021	8.2.2021	19.2.2021	3.2.2021	3.2.2021	28.1.2021	28.1.2021
Temp	°C	128	83	86.9	92.3	85	190	85	120
pH		9.53	9.47	9.67	9.75	8.67	8.64	8.02	9.7
CO_2	mg/kg	16.1	26.4	22.9	24.8	44.0	19.3	23.3	19.5
H_2S	mg/kg	0.34	0.01	0.75	1.23	0.65	74.8	0.29	15.23
SiO_2	mg/kg	148.3	70.7	92.4	99.0	42.4	684.9	25.0	731.1
Na	mg/kg	70.9	41.0	42.7	47.3	16.5	165.95	5.2	215.3
K	mg/kg	3.15	0.96	0.89	1.18	2.36	29.2	0.66	37.94
Ca	mg/kg	3.58	3.56	2.46	1.95	10.67	0.382	5.17	0.61
Mg	mg/kg	0.0020	0.0070	0.0020	0.0010	5.074	0.013	2.959	0.015
Fe	mg/kg	0.009	0.016	0.005	0.002	0.005	0.026	0.002	0.015
Al	mg/kg	0.218	0.118	0.168	0.204	0.065	2.08	0.001	1.83
Cl	mg/kg	53.0	26.3	18.0	14.0	15.1	154.65	7.6	204.3
SO_4	mg/kg	25.5	13.3	17.1	17.6	14.6	11.61	3.8	17.3
F	mg/kg	0.879	0.250	0.690	0.801	0.174	1.32	0.097	1.64
B	mg/kg	0.049	0.010	0.035	0.041	0.089	1.79	-	1.1
O_2	µg/kg	0	0	0	0	0	0	0	0

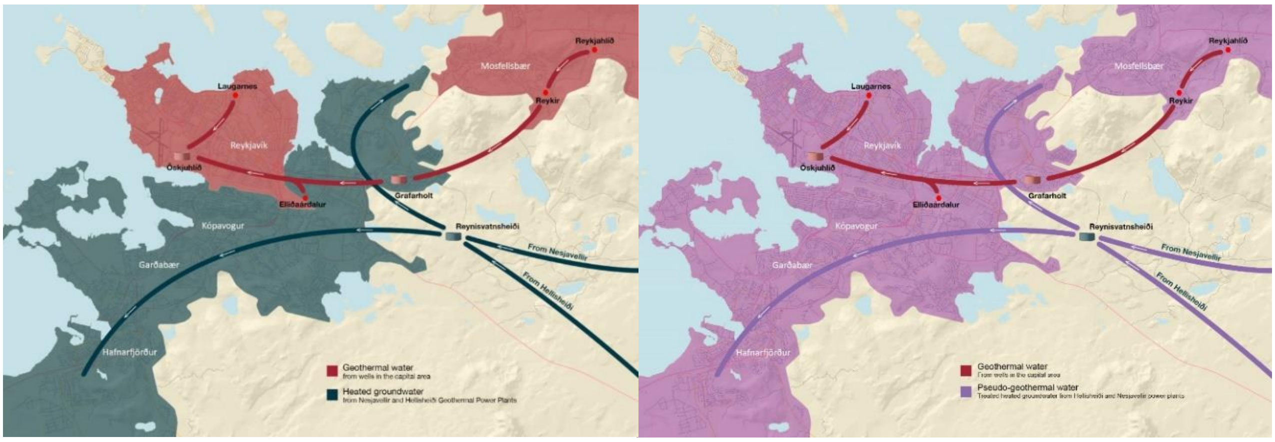

Figure 1. A depiction of the district heating system in the Reykjavík capital area. The current operation of the system can be seen on the left, with a split between the direct use of low temperature geothermal water (red) and heated groundwater (blue). The future operation of the system can be seen on the right, with a mixture of low temperature geothermal water and pseudo low temperature geothermal water (purple) supplying all parts of the capital area.

2. METHOD

2.1 Analytical Methods

Liquid samples taken during each of the three different phases of experiments were analyzed in a number of different ways. Acidity was measured with a Metrohm 913 pH meter with a Unitrode Pt1000 electrode. Elemental concentrations were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES) after filtration through a 0,22 µm filter and acidification to 2% nitric acid concentration with trace metal grade HNO_3 (99.999% on a trace metal basis). Solid samples were analyzed with X-ray diffraction (XRD) and scanning electron microscope (SEM).

2.2 Homogeneous Precipitation Experiments and Confirmation of Hypothesis

The primary experiments had the goal of developing a better understanding of the mixing of geothermal water and heated groundwater and the conditions necessary for precipitation of magnesium silicate. The experiments were performed in 2 L plastic bottles in a heat bath at 84°C. Heated groundwater was mixed with high temperature geothermal water from the Hellisheiði and Nesjavellir power plants in mixtures where the percentage of geothermal water mixed with the heated groundwater was 0-30%. The high temperature geothermal water collected at Hellisheiði was the water phase of the geothermal fluid after two flashing stages, down to 120°C at 1 barg. The high temperature geothermal water collected at Nesjavellir was the water phase of the geothermal fluid after a single flashing stage, down to 192°C at 12 barg. Heated groundwater at both power plants was collected at 84°C. Each experiment was allowed to proceed for 1-4 weeks with samples daily at first and then weekly. Each experiment was performed in triplicate.

2.3 Kinetic Experiments with Magnesium Silicate Seed

Benchtop kinetic experiments were performed to study the rate of reaction for the precipitation of magnesium silicate in the presence and absence of seeding material in 1 L borosilicate glass round bottom flasks at a constant temperature on a stirring hot plate in an oil bath. The same types of water were used as in the previous experiments and the mixing ratios were also the same; 0-30% of geothermal water mixed with heated groundwater. A typical experiment started with the mixing of geothermal water with the heated groundwater at either power plant in a plastic bottle. The bottle was insulated and then transported to the laboratory (20-50 min away). At the laboratory the mixture was poured into a 1 L borosilicate glass round bottom flask and placed in an oil bath on a stirring hot plate and brought to the desired temperature for the experiment (30-90°C). Once the desired temperature had been reached a background sample of the mixture was taken. Seed material was then added (0,2-10 g) which marked the start time of the experiment. Liquid samples were typically taken from the mixture after 10, 30 and 60 minutes, and subsequently every hour until the end of the workday. The last samples were taken the same evening and/or the following morning. If the magnesium concentration in the following morning sample was trending downwards but not yet below the desired 0,5 mg/kg mark, additional samples were taken.

2.4 Flowthrough Experiments in Fluidized Bed Reactor

Flowthrough experiments were performed in an experimental set up at the Hellisheiði geothermal power plant. The flowthrough system was connected directly to process streams at the power plant for high temperature geothermal water and heated groundwater. The main component of the system was a 3,4 m tall borosilicate glass column (DN 50), that was 1/3 filled with silica sand to function as a fluidized bed reactor (FBR). Heated groundwater and geothermal water were mixed through needle valves a short distance from where the flow entered the bottom of the FBR. The ratio between the heated groundwater and geothermal water was set by adjusting the position of the needle valves in accordance with the measured conductivity of the mixture. The ratios ranged from 0-50% high temperature geothermal water mixed with the heated groundwater. As the rate of magnesium silicate precipitation onto silica sand is relatively slow, the reaction was kick-started with the injection of a potassium hydroxide (KOH) solution and a magnesium chloride ($MgCl_2$) solution into the bottom of the column with a dosing pump. This injection results in a strong supersaturated solution and rapid precipitation of magnesium silicate occurs on and around the silica sand. When a sufficient amount of magnesium silicate had precipitated on and around the sand, the dosing of KOH and magnesium chloride was ceased and the precipitation reaction from a mixture of high temperature geothermal water and heated groundwater was allowed to proceed.

During each experimental run samples were taken from the inlet and outlet of the FBR without disrupting the continuous operation of the FBR. Each sample was analyzed for temperature, conductivity, turbidity, and acidity, and the main mineral components were analyzed with ICP-OES. After each adjustment of the ratio of geothermal water to heated groundwater, the FBR was allowed to reach equilibrium for 30 minutes prior to sampling. Figure 2 shows a schematic and a photograph of the FBR system as well as the on-site testing facilities.

Figure 2: *Left:* A schematic of the FBR used in the flowthrough experiments showing the inlet streams of geothermal water and heated groundwater, dosing connections and the resulting pseudo-geothermal water after passing through the FBR. *Middle:* The glass FBR column during operation. *Right:* Experimental facilities located at the Hellisheiði power plant.

3. RESULTS

3.1 Homogeneous Precipitation Experiments and Confirmation of Hypothesis

The purpose of the initial experiments was to establish the mixing ratio of high temperature geothermal water and heated groundwater needed to cause homogeneous precipitation of magnesium silicate in an environment without any additional surfaces apart from the bottle surface and without agitation. The development of the concentration of magnesium in these experiments can be seen in Figure 3a-b. In mixtures containing up to 15% of high temperature geothermal water no reduction in magnesium concentration is observed over the timescale of the experiments (about 200 hours). When high temperature geothermal water makes up 20% of the mixture magnesium concentration starts to decline gradually to a value below 0.5 mg/kg after an approximately 50-hour lag period.

After the precipitation of magnesium silicate has occurred in the mixture containing 20% high temperature geothermal water in the experiment described above and the precipitated magnesium silicate has been filtered out, the mixture has a geochemical profile that is similar to water from the low temperature geothermal fields in the Reykjavík capital area. We choose to call this mixture pseudo low temperature geothermal water. To ensure that the potential for further precipitation is eliminated during mixing of the pseudo low temperature geothermal water with low temperature geothermal water from the Reykjavík capital area, experiments mixing these two types of water were performed. The results of those experiments can be seen in Figure 3c. No change in magnesium concentration was seen in any of these experiments, verifying that once the magnesium is removed to below 0,5 mg/kg no further precipitation of magnesium silicate can occur upon mixing with low temperature geothermal water.

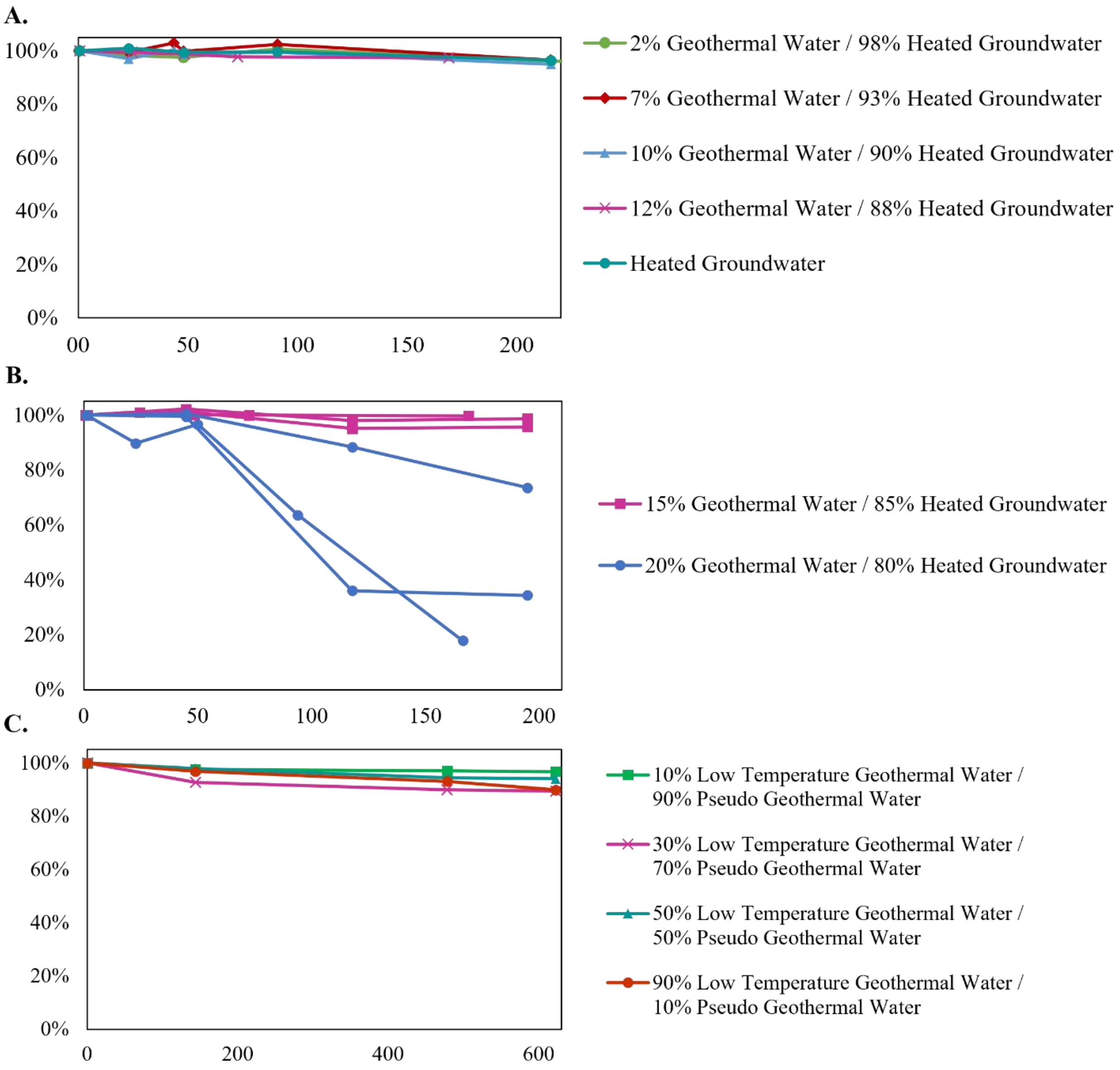

Figure 3: The development of magnesium concentration in mixtures of heated groundwater, high temperature geothermal water and low temperature geothermal water. A. Mixtures of 0-12% high temperature geothermal water and 88-100% heated groundwater. B. Mixtures of 15% and 20% high temperature geothermal water and 80% and 85% heated groundwater, respectively. C. Mixtures of 10-90% low temperature geothermal water and 10-90% pseudo low temperature geothermal water.

3.2 Kinetic Experiments with Magnesium Silicate Seed

In the kinetic experiments several factors were varied to study their individual effects on the rate of precipitation of magnesium silicate. These factors were:

1. Type of seeding material
2. Amount of magnesium silicate seeding material
3. Ratio between the high temperature geothermal water and heated groundwater
4. Temperature of the reaction

Prior experience of magnesium silicate scaling in the district heating system has indicated that the precipitation reaction is influenced by the type of surface that is available. Rust, prior scaling and turbulent flow are known instigators of further magnesium silicate scaling. As the current focus is on increasing the rate of the reaction as much as possible, several different seeding materials were tested to study their capacity to induce precipitation of magnesium silicate. Silica concentration and pH have a strong effect on the reaction but to provide a clear and concise analysis of the results only magnesium concentrations are reported. Additional data is available upon request. Unless stated otherwise, all kinetic experiments were conducted at 90°C with rapid stirring using a ratio of 15% geothermal water to 85% heated groundwater and 0.40g of magnesium silicate collected from a geothermal setting. A horizontal black line is used to indicate the desired upper limit of magnesium concentration, 0.5 mg/kg.

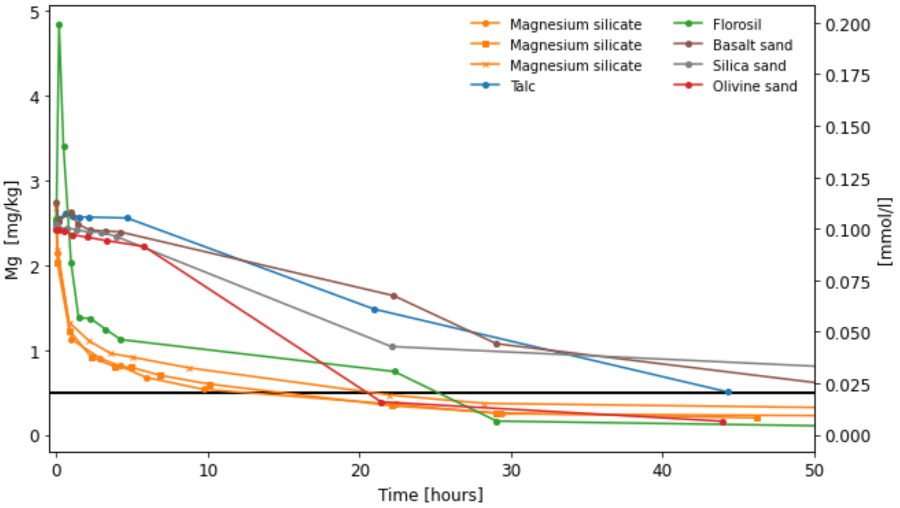

Figure 4: The development of magnesium concentration in mixtures of geothermal water and heated groundwater in kinetic experiments with different types of seeding material.

Figure 4 shows the development of the magnesium concentration with respect to time with different types of materials used to seed the precipitation reaction. The three types of sand (basalt, silica, and olivine) exhibit similar behavior regarding their effect on magnesium concentration. The decrease of magnesium is linear and slow relative to a geothermal magnesium silicate seed, only reaching the desired magnesium concentration in 20-50 hours.

Florosil and Talc are types of magnesium silicate with a different physical structure to the magnesium silicate that forms in a geothermal setting. The presence of talc results in the same slow linear decrease as seen with the three types of sand, indicating the same surface incompatibility, but Florosil shows different results. During the first half hour of the experiment, magnesium concentration spikes followed by a rapid decrease. Simultaneously, the concentration of dissolved silica is doubled (not shown here) indicating the dissolution of the seed material. The increased concentrations of magnesium and silica greatly influence the rate of precipitation but when most of the magnesium has been removed, the concentration of silica is still rising and has reached levels that are unsuitable for use in district heating.

The magnesium silicate seeding material shown in orange was collected from within the district heating system and shows the highest capacity for magnesium removal. The magnesium concentration is halved in the first hour and subsequently reaches the desired magnesium level in 10-15 hours. The results shown above indicate that the best seeding material available is magnesium silicate formed in geothermal conditions and therefore the following experiments where the amount, temperature, and mixing ratios are varied all make use of that material.

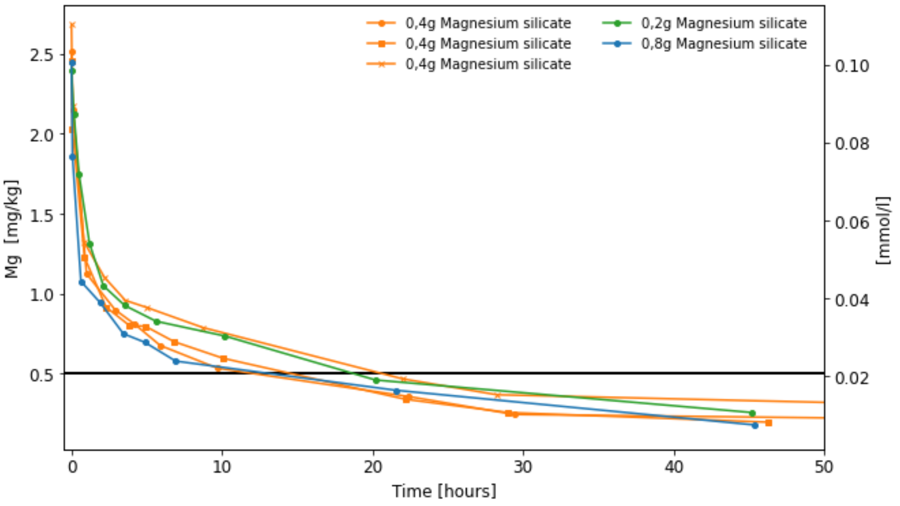

Figure 5: The development of magnesium concentration in mixtures of geothermal water and heated groundwater in kinetic experiments with varying amounts of geothermal magnesium silicate seeding material.

Figure 5 shows the development of magnesium concentration using different amounts of the chosen magnesium silicate seeding material. Although the difference in the lowering of the magnesium concentration between experiments with a different amount of seeding material is not striking, the increased surface availability does have an accelerating effect on the precipitation of magnesium silicate. Using half the seeding material makes the initial magnesium concentration drop slightly more gradually and increases the time needed to reach the 0,5 mg/kg goal concentration. Conversely, twice the amount of seeding material steepens the initial concentration drop and shortens the reaction time.

It should be noted that one of the experiments using a standard amount of seeding material (marked with orange crosses) had a higher initial magnesium concentration and therefore needed a longer time to reach the goal concentration. These fluctuations in magnesium concentration (±0,3 mg/kg) can be expected from the groundwater source depending on which groundwater boreholes are in use at the time and how much hot water is being produced. These experiments were not all conducted in triplicate due to a shortage of seeding material so their results can only be interpreted as indicative for the effect of the amount of seeding material but it stands to reason that the amount of seeding material and thus the amount of surface available can only increase the rate of reaction as long as other factors such as temperature and mixing ratios of heated groundwater and geothermal water do not limit the reaction. This indicates that there could be considerable room for improvement by using more of the seeding material in a continuous process.

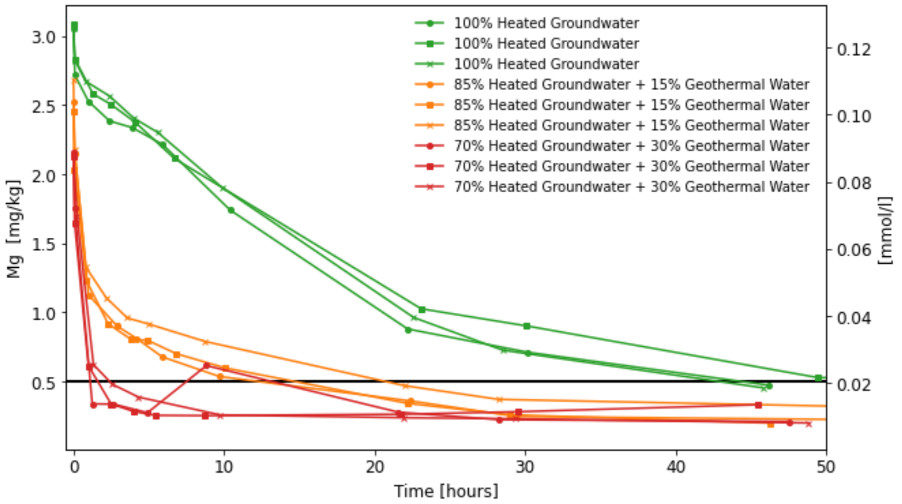

Figure 6: The development of magnesium concentration in mixtures of geothermal water and heated groundwater in kinetic experiments with different ratios of mixing.

Figure 6 shows the development of the magnesium concentration with respect to time with different ratios of high temperature geothermal water mixed with the heated groundwater. A higher ratio of geothermal water results in a faster drop in the magnesium concentration of the mixture. The addition of geothermal water into heated groundwater increases the silica concentration and the pH of the mixture and accelerates the precipitation of magnesium silicate. This effect is simultaneously the problem with mixing water from the current two district heating systems and the proposed solution of treating the water during production at the Hellisheiði and Nesjavellir power plants, hence the title *'Leaning into the problem'*. The difference lies in performing the precipitation reaction in a controlled process, removing magnesium from the mixture and producing water that can readily be mixed with the geothermal water from the low temperature geothermal fields in Reykjavík.

In the experiments using only heated groundwater, magnesium is still removed by the presence of the magnesium silicate seeding material, but not as rapidly. This indicates that the experimental conditions here are more aggressive toward magnesium removal than conditions in the district heating system itself, as this effect is not observed in our current operation of the district heating system. Without any addition of geothermal water, the reaction proceeds gradually and reaches the goal concentration in ~50 hours. Adding 15% geothermal water to the mixture shortens the reaction time to 10-15 hours and a further increase to 30% shortens the reaction time to 1 hour. This is caused by lowering the initial concentration of magnesium and increasing the initial silica concentration and pH. Adjusting the ratio of geothermal water gives control over the rate of magnesium removal but there are limits to how much can be used in the process. Currently, the aim is to produce water whose mineral content is similar to that of the water that is used directly from the low temperature geothermal fields in Reykjavík. To achieve that, the mixing ratio of geothermal water in the magnesium removal process should be close to 15%.

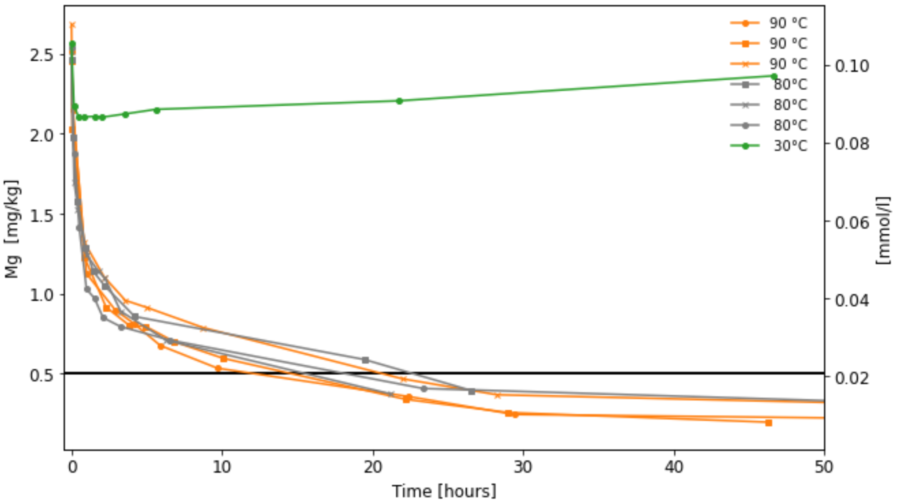

Figure 7: The development of magnesium concentration in mixtures of geothermal water and heated groundwater in kinetic experiments with different experimental temperature conditions.

Figure 7 shows the development of the magnesium concentration in a mixture of heated groundwater and geothermal water at different temperatures. No discernible difference can be seen between the concentration development at 80°C and 90°C. At 30°C there is a small initial drop in the magnesium concentration but then it stabilizes and even rises towards the end of the experiment. The precipitation reaction is endothermic and temperature dependent (Hauksson, 1995), but a more detailed temperature analysis would be helpful in determining the optimal temperature for rapid magnesium removal in a continuous system.

3.2 Flowthrough Experiment in Fluidized Bed Reactor

Passing a mixture of high temperature geothermal water and heated groundwater through the FBR packed with silica sand had very little effect on the outlet magnesium concentration. Given the short residence time and lack of appropriate surface, the rate of precipitation was slow, and the magnesium concentration drop in the FBR was only ~0.1-0.2 mg/kg. However, with prior priming of the sand by injection of a potassium hydroxide (KOH) solution and a magnesium chloride ($MgCl_2$) solution to precipitate a large amount of magnesium silicate, the magnesium concentration dropped dramatically over the FBR. Once pH and magnesium dosing was ceased and normal operation of the FBR was resumed, the magnesium concentration drop over the FBR was 1.5-2.0 mg/kg, which is sufficient to lower the concentration of magnesium below the target concentration of 0.5 mg/kg. The results of experiments performed in the FBR post injections of KOH and $MgCl_2$ can be seen in Figure 9.

The residence time in the FBR was 5-7 minutes and the flowrate was 600-900 ml/min. The reaction therefore took place much faster in the FBR than it did in the kinetic experiments. This can probably be contributed to the increased available and compatible surface for the precipitation reaction to proceed on. We think an even faster reaction rate can be achieved through optimization of the FBR. A key optimization factor is the seeding material. The FBR was packed with silica sand which is not very effective as a seeding material for the precipitation of magnesium silicate as can be seen from the kinetic experiments (Figure 4). After the FBR was decommissioned, the sand in the reactor was used in kinetic experiments to see if the injections of KOH and $MgCl_2$ had affected its efficacy as a seeding material. White flakes that formed in the sand during the FBR experiments were also picked out of the sand and used in a kinetic experiment. SEM and XRD confirmed that the white flakes are magnesium silicate. The results of these experiments can be seen in Figure 8. The magnesium silicate from the FBR performed better in the kinetic experiments than the standard magnesium silicate that came from the district heating system in Reykjavík.

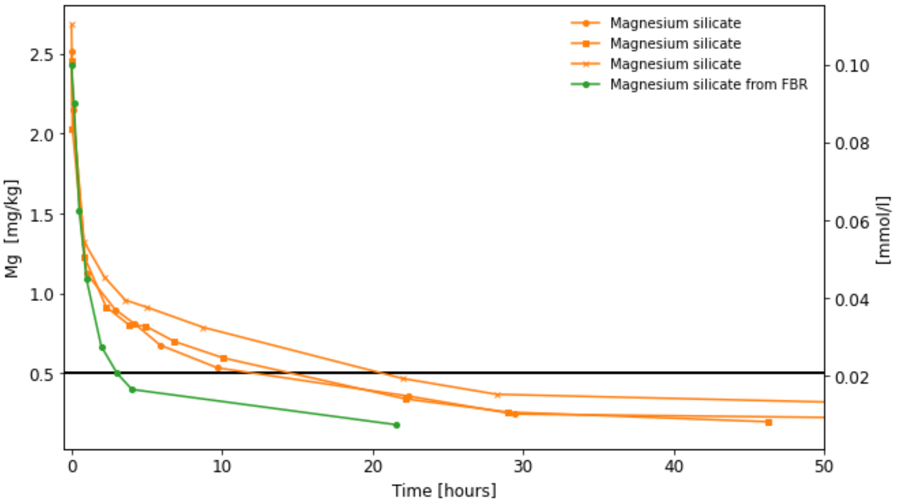

Figure 8: The development of magnesium concentration in mixtures of geothermal water and heated groundwater in kinetic experiments comparing the standard magnesium silicate with magnesium silicate collected from the FBR.

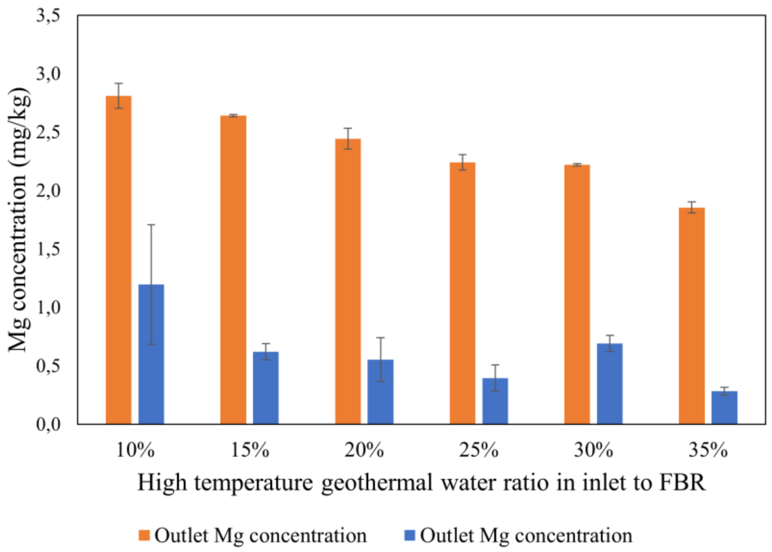

Figure 9: A comparison of the concentration of magnesium in the inlet and outlet of the FBR as a function of the ratio of high temperature geothermal water in the inlet to the FBR. A significant drop in magnesium concentration takes place in the FBR at all the tested ratios. A general trend of lowering magnesium concentration in the outlet at higher mixing ratio of high temperature geothermal water can be seen apart from the 30% mixing ratio.

4. DISCUSSION

The difference in the rate of magnesium silicate precipitation between the types of experiments indicates that heterogeneous nucleation is the preferred method for this reaction to proceed as quickly as possible and that the more seeding material that is readily available the faster the reaction proceeds. The type of seeding material is very important, as can be seen from both the kinetic experiments and the FBR experiments. A higher temperature results in a faster precipitation reaction. This is supported by previous research (Hauksson, 1995). The ratio between the high temperature geothermal water and heated groundwater affects the rate of the reaction. In the kinetic experiments which were batch experiments this difference was easier to discern than in the FBR experiments which were continuous experiments.

KOH and $MgCl_2$ injection was necessary to kick start the magnesium silicate precipitation reaction in the FBR. As can be seen from the kinetic experiments, the silica sand that the column was packed with is not very effective to seed this reaction. There is a chance that this injection will be necessary to start the process of precipitation in the full scale plant. However, we hope to be able to find or produce enough seed material so that the startup procedure does not rely on chemical use.

The results from the experiments detailed in this paper indicate that it is possible to unify the district heating system in the Reykjavík capital area with the proposed method of changing the production of hot water at the Hellisheiði and Nesjavellir power plants to produce water with a geochemical profile similar to water from the low temperature geothermal fields in the capital area. Remaining efforts include more flowthrough experiments in a pilot scale FBR system to gather information prior to demonstration scale testing which is expected to be performed in the next two years. A key challenge during the design, construction, and operation of the demonstration scale plant will be proving out the economics of the project, finding the right seed material and monitoring the system for deterioration in the effectivity of the seeding material over longer periods of time.

The overall benefit of unifying the district heating system in the Reykjavík capital area will be immense. The current operation of the system does not allow for the most sustainable use of the available resources. The low temperature fields could provide a much higher peak load if the recharge time was longer than it is now. In addition, the high temperature fields are not utilized in the most sustainable manner since electricity production is kept constant throughout the year to meet demand for electricity, but hot water production varies depending on demand. Ideally, the two sides of the district heating system could be unified. The power plants could provide a base load to the system while the low temperature fields provide peak load.

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