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Direct Mixing of Geothermal Water into Heated Groundwater to Improve Water Quality in the District Heating System of the Reykjavík Capital Area

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ABSTRACT

The Hellisheiði geothermal power plant has produced hot water for the Reykjavík capital area since 2010. The power plant is co-generative, producing electricity using steam turbines and hot water for district heating through heat exchange between the geothermal water and cold groundwater. The cold groundwater is saturated with oxygen when it is pumped out of the ground and becomes supersaturated after going through the heat exchangers. Deaeration of the water is necessary after passing through the heat exchangers as the presence of dissolved oxygen in the hot water causes corrosion in the carbon steel pipes of the district heating system. The deaeration process is a combined physical and chemical process and takes place in a set of deaerators. Physical deaeration removes most of the oxygen via low-pressure boiling and the remaining oxygen is chemically removed by injection of a small amount of steam. Geothermal steam contains hydrogen sulfide (H_2S) which reacts with oxygen and provides a surplus of H_2S in the water in the district heating system to react with any oxygen that may be introduced into the system, e.g. in storage tanks. However, H_2S is acidic and thus steam injection lowers the pH of the heated groundwater. From the commencement of hot water production at the Hellisheiði geothermal power plant, keeping a simultaneously acceptable pH and H_2S level has proven problematic. To keep from corroding the pipes in the district heating system in Reykjavík the pH must be above 8,0. The average pH from the start of production is 7,9 and the pH has in certain instances been measured as low as 7,0.

A project to adjust this chemical balance in the heated groundwater started as a research project in 2018 and came into operation on a full scale in February 2022. In this project a small amount of geothermal water is mixed with the heated groundwater after deaeration along with condensate from the steam turbines to adjust the temperature of the water. The geothermal water contains 20-30 mg/kg of H_2S and has a pH of ~9.2. It is fairly buffered compared to the heated groundwater and becomes dominating in the mixture even though the mixing ratio never exceeds 2%. Through this mixing the pH and H_2S can be adjusted simultaneously to an appropriate level. In addition to adjusting the chemical balance this mixing increases the production of hot water at the Hellisheiði geothermal power plant by 20-40 l/s at peak capacity, reduces the need for geothermal water re-injection, and the steam injection can be lowered significantly, resulting in more available steam for electricity production.

1. INTRODUCTION

From the beginning of district heating in the Reykjavík capital area in Iceland and until 1990 the supply of water into the system was geothermal water from low temperature fields within the city. Issues with corrosion arose quickly due to oxygen uptake as the water was led from the wells to the piping system in open channels. After these issues, closed piping from wells to the consumers was introduced with tanks to mitigate the fluctuating water demand. Some oxygen finds its way into the water in the tanks but the presence of hydrogen sulfide (H_2S) in the low temperature geothermal water acts as a natural corrosion protector and reacts with the oxygen that enters the district heating system in the tanks to form SO_4^{2-} (Gunnlaugsson, 2003). This naturally occurring H_2S has protected the district heating system in Reykjavik from corrosion for about 90 years. In 1990 the Nesjavellir power plant commenced operation, introducing a new type of water into the district heating system; heated groundwater. The groundwater is saturated with oxygen when it enters the thermal plant at Nesjavellir and this oxygen can be highly corrosive to the carbon steel pipes in the district heating system. The traditional way to deal with a problem of this kind would have been to set up a physical deaeration system and mix sodium sulfite into the water to remove the last remaining oxygen after the physical deaeration. This however was not the chosen way to deal with the problem. An innovative way was developed to minimize the chemical use at the Nesjavellir power plant by making use of what was available on site. Instead of sodium sulfite, a small amount of geothermal steam is injected into the deaerator system. The geothermal steam contains H_2S which acts in same way as it does when it occurs naturally in the low temperature geothermal fields in Reykjavik; it reacts with any remaining oxygen in the water after physical deaeration and thus protects the district heating system in Reykjavik from corrosion (Gunnlaugsson and Einarsson, 1989).

As the district heating demand of Reykjavík and the neighboring communities grew, a second geothermal power plant was constructed and started production of hot water for the city in 2010, at Hellisheiði. The same system for oxygen removal was constructed and has been operated ever since. However, the operation of the system has not been as successful in Hellisheiði as in Nesjavellir. The groundwater in Hellisheiði has a lower mineral content than the groundwater in Nesjavellir and is thus less resistant to pH changes during deaeration, i.e. is less buffered. The H_2S that is introduced into the heated groundwater through steam injection is acidic. In Hellisheiði the heated groundwater ends up with a pH below 8,0 in this process and thus can corrode the district heating system through acidic corrosion after having been treated to prevent oxygen corrosion. As a result, corrosion has been observed in the district heating system, mainly in the pipeline leading from Hellisheiði to Reykjavík and a storage tank at

Reynisvatnsheiði, used to store and mitigate hot water use from Hellisheiði (Figure 1). As the hot water from Hellisheiði enters Reykjavík, it mixes with the hot water from Nesjavellir and the potential for acidic corrosion is countered as the water from Nesjavellir generally has a higher pH. To ensure that hot water supplied to the city from the Nesjavellir and Hellisheiði power plants does not cause significant scaling and/or corrosion of carbon steel in the district heating system, a quality standard exists to define a range of acceptable pH, H_2S and O_2 levels in the hot water.

Table 1. Water quality standards to prevent scaling and or corrosion of carbon steel for heated groundwater that enters the district heating system in the Reykjavík capital area from Hellisheiði and Nesjavellir geothermal power plants.

	Unit	Range
pH	-	8.0 – 8.7
H2S	mg/kg	0.2 – 0.7
O_2	µg/kg	0
Temp.	°C	84 - 85

In 2018, an opportunity to deal with the corrosion problem of the Hellisheiði pipeline emerged from a research project on the mixing of geothermal water and heated groundwater. It was found in laboratory experiments that mixing a small amount of geothermal water from Hellisheiði with the heated groundwater resulted in water for the district heating system that has a slightly higher mineral content than the heated groundwater and is therefore more buffered and less susceptible to the acidifying effect of the injection of geothermal steam. If the mixing ratio is kept low enough, e.g. at 2% geothermal water with 98% heated groundwater, oxygen corrosion is prevented due to the presence of H_2S in the geothermal water, acidic corrosion is prevented due to a slightly higher pH level and the potential for magnesium silicate scaling, which can occur in the mixing of these two types of water, is avoided.

More details on the experiments performed to verify that no magnesium scaling was to be expected can be found in the paper Leaning into the Problem, an Experimental Study of Mixing Groundwater with Geothermal Water, Towards Full Integration of Reykjavík's Two District Heating Systems, published at this conference (Brynjarsson et al., 2023).

Following successful laboratory experiments, implementation of this solution to adjust the chemical balance of hot water for district heating started in 2021 with the design of a self-regulating automatic mixing system. Condensate from the steam turbines is mixed with the geothermal water to match the temperature of the district heating system prior to mixing with the heated groundwater and to enable an easier operation of the mixing system as well as increasing the total amount of water produced at the Hellisheiði Power Plant by another 1-2%. These changes have now been made to the production of hot water at Hellisheiði and the system came online in February 2022.

Figure 1: Two pieces of cement lining from storage tanks in the district heating system of the Reykjavík capital area. The piece of cement lining on the left is from a storage tank which is fed with hot water from the Nesjavellir power plant. The piece of cement lining on the right is from a storage tank fed with hot water from the Hellisheiði power plant. An XRD analysis confirms that both cement lining pieces have a layer of amorphous magnesium silicate scaling precipitated on top of them. However, in the piece of lining from the Hellisheiði storage tank the magnesium silicate contains a significant amount of iron, 24% of the weight of the sample, as is also evident from the strong red color of the sample.

2. METHOD

The changes made to the production of hot water at Hellisheiði to achieve an improved chemical balance were relatively straight forward. Two process connections were made, one to a pipeline containing geothermal water after the second geothermal fluid flash stage and one to a pipeline containing condensate from steam turbines 1-4. These connections come together in a DN200 pipe that links to the Hellisheiði pipeline that transports hot water from the Hellisheiði Power Plant to Reykjavík. The ratio between the geothermal water (120°C) and condensate (43°C) that is injected into the hot water is set using a control valve on the condensate that is adjusted via a temperature measurement downstream. The mixture is set to 81°C to ensure a roughly equal ratio of the two. The total flow of the geothermal water and condensate mixture is controlled with a second control valve that ensures proportional flow of geothermal water and condensate using both the flow of the mixture and the total flow of hot water in the Hellisheiði pipeline. The ratio of the mixture to total hot water flow is set to 2-4%.

Before the system came online, samples were taken to analyze the evolution of the chemical composition of the hot water throughout the district heating system. The sampling consisted of water samples that were analyzed with ICP (Inductively Coupled Plasma – Optical Emission Spectrometry) and stainless steel (SS304) coupons that were inserted into operational pipelines and left for a few months to either corrode or collect precipitation. After the system came online in February 2022, the same series of measurements was repeated to see if there was a noticeable difference from earlier samples. Additionally, H_2S concentration, O_2 concentration and pH was continuously monitored using inline meters at the power plant before and after the changes were made to the hot water production.

3. RESULTS

The direct mixing system described above has had an overall positive effect on the production of hot water at Hellisheiði and on the district heating system. Before its implementation, the hot water met quality standards in the district heating system 36% of the time, but since then the quality standards have been fulfilled 90% of the time (Figure 2). The remaining 10% when the quality standard was not met was due to operational challenges with the adoption of a new automated system. The chemical composition of the hot water prior to this change in production, the hot water after the direct mixing began, the geothermal water and the condensate can be found in Table 1.

Table 2: An example of the chemical composition of the hot water for district heating at Hellisheiði before and after system changes and the chemical composition of geothermal water and condensate at Hellisheiði.

Hellisheiði **Type of water**	**Unit**	**Hot water for district heating - Prior to changes**	**Hot water for district heating - After changes**	**Geothermal water**	**Condensate**
Date	-	28.1.2021	4.5.2022	29.9.2021	14.12.2021
Temp.	°C	85	85	120	43
pH	-	8.02	8.43	9.28	6.6
CO_2	mg/kg	23.3		21.1	2.1
H_2S	mg/kg	0.29	0.20	26.45	0.79
SiO_2	mg/kg	25.0	28.1	715	0.043
Na	mg/kg	5.2	7.2	211.6	0.093
K	mg/kg	0.66	0.93	40.49	0.015
Ca	mg/kg	5.17	5.30	0.47	0.06
Mg	mg/kg	2.959	3.00	0.013	0.004
Fe	mg/kg	0.002	0.05	0.025	0.095
Al	mg/kg	0.001	0.04	1.76	0.003
Cl	mg/kg	7.6		202.8	0.08
SO_4	mg/kg	3.8		15.7	0.43
F	mg/kg	0.097		1.42	0.047
B	mg/kg			1.2	
Diss. O_2	µg/kg	0	0	0	0

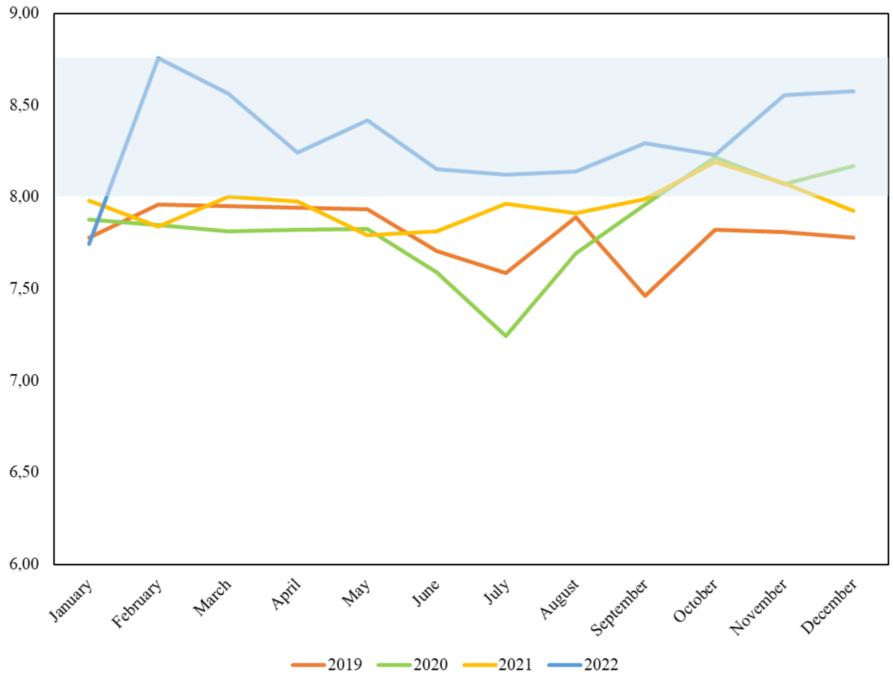

Figure 2: The pH of hot water from Hellisheiði from 2019 to 2022. The blue area represents the range of pH defined in the quality standard for hot water from Hellisheiði. Only in 2022 is that quality standard upheld for most of the year. The system described in this paper was implemented in February 2022.

Coupons (SS304) were inserted in pipelines throughout the district heating system to monitor corrosion and precipitation. The coupons were weighed before and after being in pipelines in the district heating system. Coupons were inserted both before and after the system came online to understand if there was a difference in the interplay between the water and the piping in the district heating system after the system came online. The coupons inserted into the pipeline from Hellisheiði right by the power plant before the system came online had decreased in weight after having been in the pipeline for 280 days. A detailed analysis of the coupons was performed by Gerosion with X-ray spectroscopy. The analysis confirmed that the coupons had indeed corroded and that the corrosion rate was 0.025 mm/year. For all other coupons inserted in pipelines during this project no change in weight has been observed and no visible scaling or corrosion could be seen on the coupons. Since the direct mixing system came online, no discernable change in magnesium concentration can be seen through the district heating system (Table 3), indicating that there is no magnesium silicate scaling.

Table 3. Development of magnesium concentration, pH and hydrogen sulfide concentration through the district heating system in the Reykjavík capital area after the implementation of direct mixing of geothermal water and condensate with the heated groundwater.

Location	Distance from Power Plant (km)	Mg (mg/kg)	pH	H_2S (mg/kg)
Hellisheiði Power Plant	0	2.89±0.08	8.63±0.06	0.57±0.06
Storage Tanks	20	2.82±0.11	8.21±0.09	0.56±0.06
Entering distribution system*	20	4.57±0.08	8.46±0.15	0.48±0.04
Seljahverfi	25	4.55±0.10	8.46±0.15	0.41±0.04
Ásland	35	4.55±0.11	8.23±0.29	0.40±0.04

*Hot water from Hellisheiði mixes with hot water from Nesjavellir before entering the district heating system. Hellisheiði makes up 30-40% of the heated groundwater entering the district heating system.

An immediately visible positive impact on the district heating system includes the termination of acidic corrosion in the Hellisheiði pipeline, which has been observed from the absence of a rusty color of water when water samples are taken from the pipeline and the absence of corrosion of coupons inserted in the Hellisheiði pipeline after the implementation of the system. The major operational issue facing the production of hot water at Hellisheiði before implementation was the simultaneous adjustment of pH and H_2S concentration. Through the implementation of a direct mixing system this problem has been effectively eliminated. An added bonus is the automated regulation of the mixing process which replaced the steam injection system that had to be manually adjusted each time a major production change occurred. This has resulted in a much more stable level of pH and H_2S concentration than before.

Through the implementation of this system, the maximum production capacity of hot water at Hellisheiði has been increased by 40 l/s. Since this increase is achieved through direct mixing of geothermal water and condensate with the heated groundwater, the same 40 l/s of the geothermal water and condensate no longer need to be reinjected into the geothermal field at Hellisheiði during maximum hot water production. This alleviates some of the pressure of the reinjection system. Additionally, since the geothermal water that is mixed in contains H_2S, the steam injection in the deaeration system can be reduced. Unfortunately, there is no data available on the amount of steam injected into the deaerators prior to the implementation of the direct mixing of geothermal water and condensate so it is complicated to evaluate the amount of steam that is no longer needed for this purpose. Anecdotally, operators estimate that only a third of the amount of steam needed before is currently being used. The steam that is no longer needed to adjust the H_2S level of the hot water can now be used for electricity production.

4. DISCUSSION

The benefits of this project are:

1) Termination of acidic corrosion in the Hellisheiði pipeline
2) Fulfillment of quality standards for hot water in the district heating system in the Reykjavík capital area
3) Increased maximum production of hot water at Hellisheiði, by 40 l/s
4) Reduced amount of geothermal water and condensate reinjected into the geothermal reservoir at Hellisheiði
5) Increased automation of the quality of hot water at Hellisheiði
6) Decreased steam injection into heated groundwater, resulting in slightly increased electricity production without increasing the amount of geothermal fluid extracted from the reservoir.

The benefits detailed above will be retained through the lifetime of energy production from the geothermal field in Hellisheiði. The final production capacity of hot water at Hellisheiði with this change will be 1870 l/s instead of 1800 l/s; a 4% increased production capacity from the same utilized field without any increase in the rate of fluid production from the reservoir.

The success of this project has already inspired a new research project on how this could be implemented at ON Power’s other geothermal power plant at Nesjavellir. Although the two power plants are very close to each other geographically, the chemistry of both the geothermal fluid and the groundwater in the area differs quite a bit. The Nesjavellir power plant is also designed in a different way to the Hellisheiði power plant. A major hurdle to the implementation of a similar system in Nesjavellir is the fact that the pipeline that connects Nesjavellir with the district heating system in the Reykjavík capital area is at maximum capacity.

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