

Geothermal Gas Emission From Hellisheiði and Nesjavellir Power Plants, Iceland

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ABSTRACT

Emission of geothermal gases is an inevitable part of high temperature geothermal utilization. Annually Hellisheiði and Nesjavellir Power Plants Iceland emit 61800 tons CO₂ and 28200 H₂S. New regulation set by the government of Iceland in 2010 on H₂S concentration in air puts high demands on the geothermal industry in Iceland to lower H₂S emission from their power plants. Reykjavík Energy has been working on solution to lower gas emission from its power plants since commissioning of hot water production in Nesjavellir power plant in 1990. Since commissioning of Hellisheiði Power Plant in 2006 that was followed by an increase in H₂S concentration in nearby town and communities more focus was put on H₂S abatement. Three experimental pilot scale projects have been in planning and operation since 2006. Gas separation station involves separating geothermal gas into soluble (CO₂ and H₂S) and non-soluble gases (H₂, N₂, Ar) and two experimental gas re-injection projects SulFix and CarbFix have been or are being carried out. The geothermal gases are dissolved in water and injected into the bedrock. In SulFix the target zone is the >200°C high temperature geothermal system below 800 m and in Carbfix the target zone is 30-80 °C between 400-800 m. Industrial scale injection of geothermal gases is planned in 2014 where around 15% of H₂S from Hellisheiði Power Plant will be injected into >200°C formations along with CO₂ after dissolution in condensate water from the power plant. Further increase in gas injection from Hellisheiði Power Plant will then be planned based on the experience of that injection. Injection of H₂S back into the geothermal system where it came from has to be considered an environmentally benign method of H₂S abatement.

Introduction

Atmospheric disposal of geothermal gases is an unavoidable part of high temperature geothermal utilization and in some

cases the main environmental concern with exploiting the geothermal resource. The emitted gases have both local and global environmental effects, making lowering the gas emissions from geothermal power plants one of the important challenges of the geothermal industry.

Geothermal fluids contain dissolved CO₂, H₂S, H₂, N₂, CH₄ and Ar. Concentration of individual gases can range from ppb levels to several thousand ppm depending on geological settings, temperature and composition of the geothermal reservoir. The origin of the gases is either magmatic, meteoric or they are formed in the geothermal reservoir in water rock reactions. They can be both considered reactive and conservative constituents and have long been used by reservoir scientists to characterize the physical nature of and manage production from hydrothermal systems (e.g. Ármannsson et al., 1982; Gudmundsson and Arnórsson, 2002). In liquid dominated geothermal fields majority of the gases are dissolved in the fluid in the geothermal system. During utilization and depressuration of the geothermal fluid the gases are concentrated in the steam phase and are finally vented out of the condensers of the turbines to atmosphere. The gas emission therefore inevitably affects the air quality around the power plants as the concentration of the geothermal gases increases. Under certain weather conditions and if good distribution of the gases at the disposal site is not secured the gases can affect air quality tens of kilometers from the power plant site.

Since the commission of Hellisheiði Power Plant in 2006 the characterizing foul smell of H₂S is much more frequent in Reykjavík (Figure 1). As a result new regulation on atmospheric concentration of H₂S was set by the government of Iceland in 2010 and becomes valid in 2014. The new regulation puts high pressure on the geothermal industry in Iceland to lower gas emission from geothermal power plants. After July 2014 the average annual concentration can't go higher than 5,0 µg/m³ air and 24 hour average can't be above 50 µg/m³ air.

This paper provides an overview of the amount and composition of geothermal gas emitted from Reykjavík Energy (RE) power plants. Experimental projects that RE have undertaken to develop methods to treat the geothermal gases, dissolve them in effluent waters from the power plants and re-inject them into the

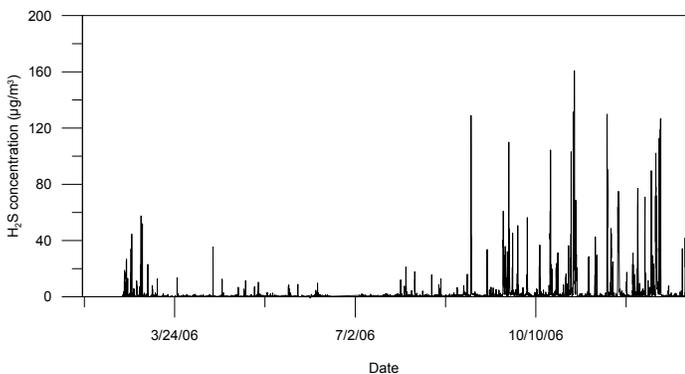


Figure 1. One hour average atmospheric concentration of H_2S in Reykjavík. The dashed line represents the commissioning of Hellisheiði Power Plant.

ground are described. The aim of the projects is lower gas emission from high temperature geothermal power plants and therefore to make them more environmentally friendly.

Hellisheiði and Nesjavellir Power Plants

Nesjavellir and Hellisheiði Power Plants are combined heat and power plants located to the north and south of the Hengill central volcano which is located in the western volcanic zone SW-Iceland, approximately 20-25 km southeast of Reykjavík (Figure 2). The Hengill volcanic system produces primarily basaltic rocks and is cut by an active NE-SW fissure swarm (Franzson et al., 2010). The Hellisheiði and Nesjavellir geothermal areas are

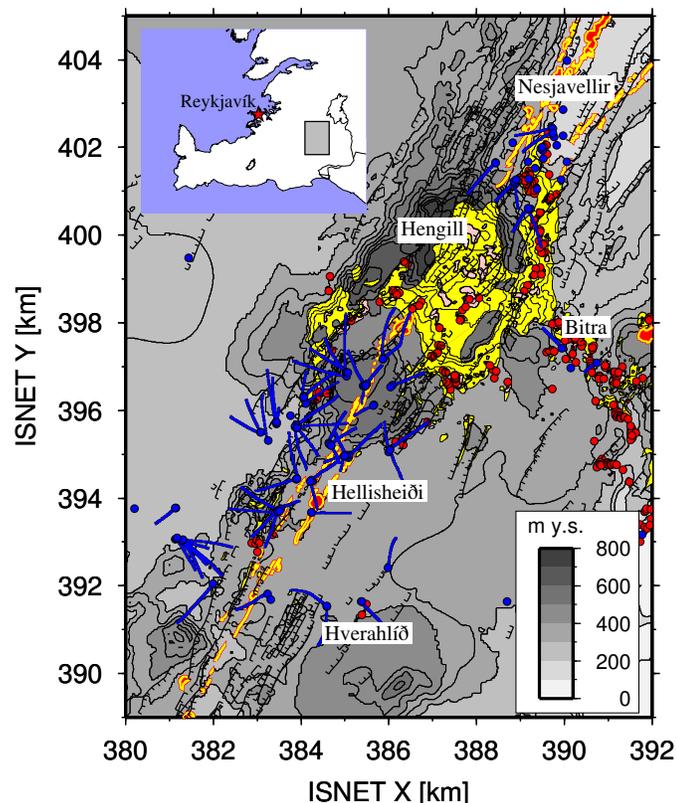


Figure 2. Map of Hengill area. Blue lines and dots are well paths. Red dots are fumaroles and yellow is surface alteration.

liquid dominated fields characterized by low salinity and high H_2S and H_2 . The temperature in the fields varies considerably but in the main production zones it is between 260°- 320°C (Giroud, 2008, Scott, et al., 2011, Stefansson et al., 2011, Gíslason et al., 2005).

Power generation started in Nesjavellir power station in 1990 with the production of 100 MW_{th} for district heating in Reykjavík. Hot water production has since been increased in several steps and was in 2005 290 MW_{th} . Electricity production started in 1998 with two 30 MW_e turbines. The third 30 MW_e turbine was installed in 2001 and the fourth in 2005. Currently Nesjavellir Power station is producing 290 MW_{th} and 120 MW_e .

Hellisheiði Power Plant was commissioned in 2006 with the installment of two 45 MW_e turbines. In 2007 a 33 MW_e low pressure turbine that uses steam from a second stage flashing of the separated geothermal water was started and two additional 45 MW_e turbines were started in 2008 and another two in 2011. Heat exchanges were commissioned in 2010 producing 133 MW_{th} for space heating in Reykjavík. Total installed capacity in Hellisheiði power plant is 303 MW_e and 133 MW_{th} . Further expansion of hot water production is planned before 2020.

Emission of Geothermal Gases

The concentration and ratio of gases in the fluids in the Nesjavellir and Hellisheiði geothermal fields have been extensively studied (e.g. Giroud, 2008, Arnorsson et al., 2010., Scott, et al., 2011, Stefansson et al., 2011). They are characterized by relatively low concentration of CO_2 compared to other geothermal fields in Iceland as well as low initial steam fraction. The concentration of gases in the steam is close to 0,4%. The concentration of CO_2 appears to be source controlled whereas the concentration of H_2S and H_2 are close to equilibrium with mineral buffers comprised of epidote, pyrite, pyrrhotite and prehnite.

Direct measurement of the gas emission is not installed in either of the power plants. The amount and concentration of the gases is therefore estimated from the composition of the steam entering the turbines. A small portion of the gases is lost in the vacuum pumps of the condensers as the water that is used to seal the vacuum pumps saturates with geothermal gas, primarily the more soluble gases H_2S and CO_2 . The amount of gas emitted as calculated from steam composition is therefore slightly overestimated. Direct measurement, using gas chromatograph, of the gases coming from the condensers supports that some of the H_2S and CO_2 is lost in the vacuum pumps. Air mixes with the geothermal gas in the condensers of the turbines as the vacuum in the condensers is used to draw air along the turbine axis to prevent geothermal steam escaping into the turbine hall. Percentage of air in the geothermal gases pumped out of the condensers can be as high as 30%.

Composition of gases as calculated from steam composition is shown in Table 1. Both gases are characterized by low CO_2 and high H_2S and H_2 concentration. Higher concentration of H_2 and H_2S from Nesjavellir power plant compared to the gas from Hellisheiði Power Plant is because of higher initial steam fraction in the geothermal reservoir (Arnorsson et al., 2010).

Annual gas emission from Nesjavellir and Hellisheiði power plants are shown in figure 3. The gas emission has been increasing almost constantly since the commissions of the power plants. In

2012 the annual emission of H₂S was around 28200 tons (16900 tons from Hellisheiði and 11300 tons from Nesjavellir Power plants). Annual emission of CO₂ in 2012 was around 61800 tons (43200 tons from Hellisheiði and 18600 tons from Nesjavellir Power plants). No data for gas emission from Hellisheiði Power plant is available for 2006.

Table 1. Composition of geothermal gas emitted from Hellisheiði and Nesjavellir power plants, S-W Iceland.

	CO ₂	H ₂ S	H ₂	CH ₄
Nesjavellir	43.0%	33.9%	23.0%	0.2%
Hellisheiði	58.1%	29.4%	12.3%	0.2%

Emitted gas composition is calculated from gas concentration in steam

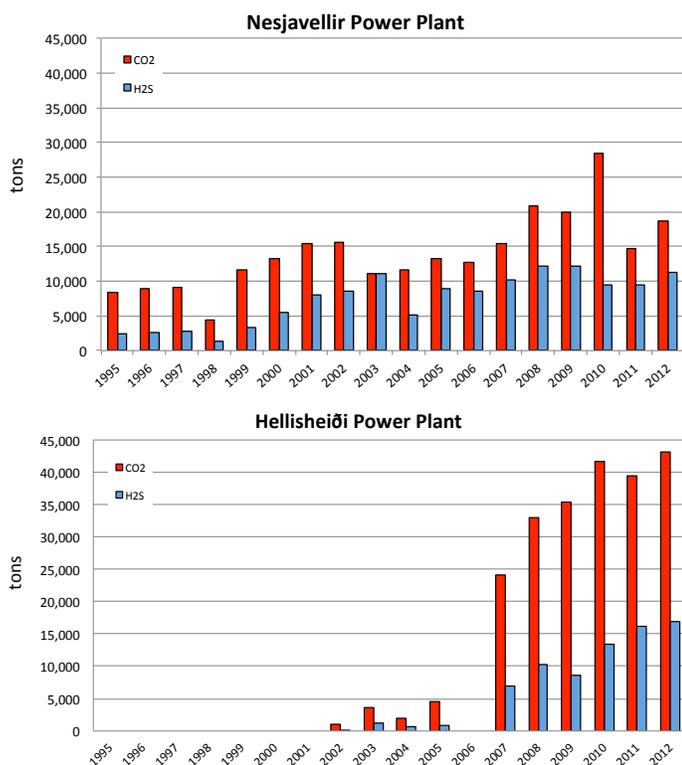


Figure 3. Gas emission from Nesjavellir and Hellisheiði Power plants.

Experimental Gas Abatement Projects

Reykjavík Energy has been working on projects to lower gas emission from its power plants since hot water production started in Nesjavellir Power plant in 1990. It was not until 2006 with the commissioning of Hellisheiði Power plant and increased H₂S concentration in air in Reykjavík that gas abatement came into more focus. Conventional abatement method usually involves oxidizing the H₂S to form either elemental sulfur or sulfuric acid. Both are important widely used in various industrial processes. There is however no market for it in Iceland and transport to nearest market expensive. Conventional proven industrial solutions for H₂S abatement also considerably increase the operational cost of the power plants.

The method RE is focusing on and experimenting with involves dissolving the H₂S and CO₂ in effluent waters from the

power plant and re-inject it back into the bedrock. To test that process three experimental projects are currently being carried out adjacent to Hellisheiði Power plants. The projects involve treating the geothermal gas in gas separation station dissolve them in water and re-inject them into the ground in the SulFix and CarbFix projects.

Gas Separation Station

Geothermal gases can be divided into two categories depending on their solubility in water. The sour gases CO₂ and H₂S are soluble in water but other geothermal gases H₂, N₂, CH₄ and Ar are much less soluble in water and need to be separated from the soluble gases prior to dissolution in water. Injection of insoluble gases, even in small quantities will lead to a build-up of gas pressure in the aquifer receiving the water and inhibit the solubility of the sour gases in the aqueous phase or call upon unpractical amounts of water needed for complete dissolution of the geothermal gas.

Gas separation station was built next to Hellisheiði Power Plant to treat the geothermal gas prior to dissolution in water. Three kinds of technologies were initially under scrutiny in the station, a membrane system for H₂ and N₂ removal, a system comprised of absorption and desorption towers which separates the soluble gases CO₂ and H₂S from the rest of the geothermal gases and a distillation column to separate CO₂ from H₂S. The flexible design and construction of the gas separation station provides opportunities to combine the systems or run them on their own. Figure 4 shows a simplified schematic diagram of the gas separation process.

The operation of the adsorption and desorption unit has been a success and it effectively separated the soluble and non-soluble gases. Membrane system has not been tested to date but it is design to also separate the non-soluble gases from the soluble gases. In distillation column the difference in volatility of CO₂ and H₂S are used to separate the two gases. Liquid H₂S and water mixture that concentrated on the bottom of the distillation column is highly corrosive and operation had to be stopped because of severe corrosion in the cooling element at the bottom of the column.

Experimental Injections of Geothermal Gases

The Sulfix and Carbfix projects involve re-injecting geothermal gases into basaltic formations with the aim of sequestering the dissolved gases in mineral in the bedrock. Description of the SulFix project is provided in Gunnarsson et al., (2011) and of the CarbFix project in e.g. Aradóttir et al., (2011) and Gíslason et al., (2010).

The SulFix project aims at assessing the feasibility of *in situ* H₂S mineral sequestration in basaltic rocks. Around 100 tons geothermal gas has been injected in the SulFix project. The gas separation station described above provided gas for the injection. Composition of injected gas in volume percentages was 64% CO₂, 35% H₂S and 1% H₂. The gases were dissolved at 7-8 bars in both separated geothermal water and condensate water on the surface prior to injection and subsequently injected to a depth of around 1000-1400 m into the 270°C geothermal system. Temperature of the injected water was 95-100°C for the separated geothermal water and 40°C for the condensate water.

CarbFix is a combined industrial/academic research project between Reykjavik Energy, the Institute of Earth Science at the University of Iceland, Earth Institute-Lamont-Doherty Earth Observatory at Columbia University in New York and the Centre National de la Recherche Scientifique/Universite Paul Sabatier in Toulouse, that was developed in order to assess the feasibility of *in situ* CO₂ mineral sequestration in basaltic rocks. To date two types of gases have been injected in the CarbFix project. Around 176 tons pure CO₂ and 65 tons gas mixture from the gas separation station. Composition of the gas from the gas separation station in volume percentages was 75% CO₂, 24% H₂S and 1% H₂. 1000 tons gas mixture injection is planned for 2013. The CarbFix storage formation lies between 400-800 m depth, is 30-80°C warm and consists of relatively fresh basalts (Aradóttir et al. 2011, Alfredsson et al., 2008). Rather than injecting CO₂ directly into geological formations, CarbFix has developed a technology to dissolve CO₂ into formation fluids and well water during injection. Once dissolved, CO₂ is no longer buoyant compared to pore fluids, improving considerably security due to decreased leakage risks. This approach of solubility trapping also promotes carbonation of the host rock and thus facilitates the safe long-term sequestration of CO₂ in the subsurface.

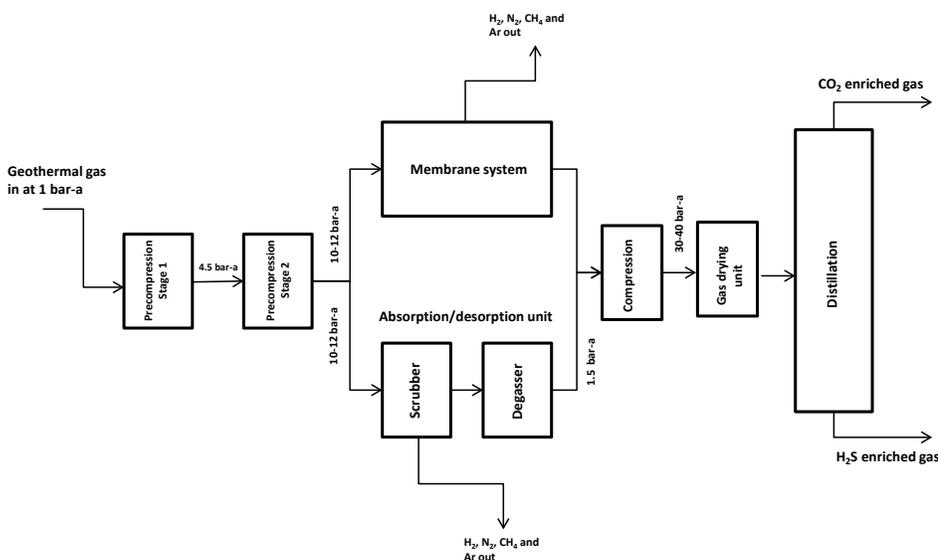


Figure 4. Simplified schematic overview of the gas separation station operated with Hellisheiði Power Plant, Iceland.

From Pilot to Industrial Scale

RE plans to take the first step in substantially lowering gas emission from Hellisheiði Power Plant in 2014. Around 400 g/s of geothermal gas will be dissolved in water and re-injected back into the >200°C geothermal reservoir at depth below 800m. The composition of the injected gases will be approximately 65% CO₂, 35% H₂S and traces of H₂. The successes and failures in the pilot scale gas treatment and injection projects described above greatly contribute to the design and setup of the industrial scale gas injection.

Schematic of the gas injection scheduled to start in 2014 is shown in Figure 5. The geothermal gas is pressurized to 5 bar and the soluble gases separated from the rest in a water absorption

tower. The absorption tower is operated with condensate water that has been cooled from 40°C to 10 °C. The solubility of the geothermal gases is higher at lower temperature. The gas loaded condensate water is then injected back into the geothermal reservoir as shown in Figure 5. The gas loaded water has a pH value between 4-5 and is corrosive to carbon steel in the injection well casing. To protect the casing from corrosion the gas loaded water is injected in a pipe that extends below the casing and separated geothermal water with pH between 9-9,5 is injected between the casing and the gas injection pipe. This setup prevents the gas loaded low pH water to be in contact with the well casing.

Based on the experience of this first step of industrial scale gas injection in Hellisheiði further actions will be taken to make sure that H₂S concentration in atmosphere does not exceed the regulated levels in inhabited areas in Iceland.

Summary and Discussion

The main environmental problem of high temperature geothermal utilization in Iceland is the atmospheric disposal of H₂S. Instead of focusing on conventional industrial method of H₂S removal from gas stream Reykjavik Energy is developing innovative methods aiming at capturing the H₂S and CO₂ from the emission, dissolve it in effluent waters from the power plant and re-inject it back into the geothermal reservoir. Predictive reactive transport simulations indicate *in situ* H₂S and CO₂ and mineral sequestration basalts to be a viable option in reducing sour gas emissions from geothermal power plants as they predict fast mineralization of injected gases (Aradóttir et al., (2013). Injection of H₂S will increase significantly the reservoir H₂S equilibrium concentrations. This will result in mineralization of pyrite and possibly other sulfides as well. Based on reaction modeling, the main factor affecting the H₂S mineralization capacity is related to the mobility and oxidation of iron (Stefánsson et al., (2011). General experience in dealing with H₂S rich fluids is that if dissolved iron is also present the H₂S is highly reactive and deposits very fast as iron sulfide mineral. One of the main concerns with the industrial scale gas re-injection described above is that depo-

sition of sulfide mineral or even elemental sulfur occurs in or in the vicinity of the injection well resulting in decreased transmissivity of the injection well. At pH-4-5 the injected gas rich fluid dissolves the basaltic rock in the geothermal system readily releasing iron into the H₂S loaded fluid. Lack of reliable thermodynamic data and rate constants for precipitation of sulfide minerals makes 100 tons gas injection in the SulFix project did however not affect the transmissivity of the injection well. If successful, this method of H₂S abatement will both have lower startup and operational cost compared to conventional H₂S removal methods. Injection of H₂S back into the geothermal system where it came from is an environmentally friendly solution of decreasing air quality in the vicinity of geothermal power plants.

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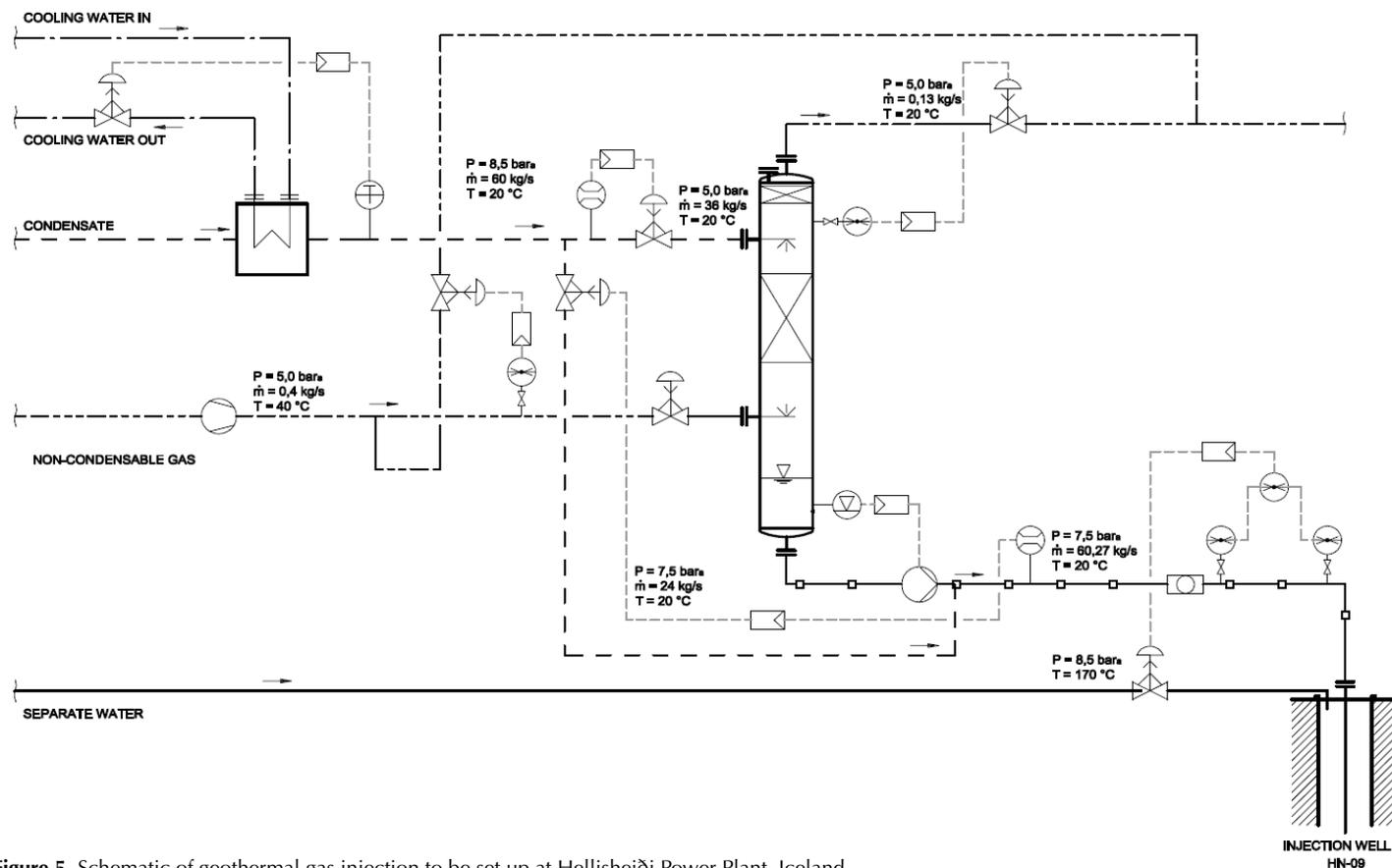


Figure 5. Schematic of geothermal gas injection to be set up at Hellisheiði Power Plant, Iceland.

References

- Alfredsson H, Oelkers E, Hardarson B, Franzson H, Gíslason S (2013) The geology and water chemistry of the Hellisheiði, SW-Iceland carbon storage site. *Int J Greenhouse Gas Control* 12: 399-418.
- Aradóttir, E. S. P., I. Gunnarsson, B. Sigfússon, G. Gunnarsson, B. M. Juliusson, E. Gunnlaugsson, H. Sigurdardóttir, M. T. Arnarson, and E. Sonnenthal, 2013. Towards cleaner geothermal energy utilization. Capturing and sequestering CO₂ and H₂S emissions from geothermal power plants. *Transport in Porous Media* (submitted).
- Aradóttir, E. S. P., H. Sigurdardóttir, B. Sigfússon and E. Gunnlaugsson, 2010. CarbFix: a CCS pilot project imitating and accelerating natural CO₂ sequestration, *Greenhouse Gas Sci Technol.* 1: 105-118, 2011.
- Armannsson H., G. Gíslason and T. Hauksson 1982. Magmatic Gases in Well Fluids Aid the Mapping of the Flow Pattern in a Geothermal System, *Geochimica Cosmochimica Acta*, 46, 167-177.
- Arnórsson, S., E. Angcoy, J. O. Bjarnason, N. Giroud, I. Gunnarsson, H. Kaasalainen, C. W. Karingithi, and A. Stefánsson, 2010. Gas chemistry of volcanic geothermal systems. *Proc. World Geothermal Congress, Bali, Indonesia*.
- Franzson H., E. Gunnlaugsson, K. Árnason, K. Sæmundsson, B. Steingrímsson and B. S. Hardarson, 2010. The Hengill Geothermal System, Conceptual Model and Thermal Evolution. *Proc. World Geothermal Congress, Bali, Indonesia*.
- Giroud, N. 2008. A Chemical Study of Arsenic, Boron and Gases in High-Temperature Geothermal Fluids in Iceland. PhD Thesis, University of Iceland.
- Gíslason, G., G. Ívarsson, E. Gunnlaugsson, A. Hjartarson, G. Björnsson, and B. Steingrímsson, 2005. Production monitoring as a tool for field development. A Case history from Nesjavellir field, Iceland. *Proc. World Geothermal Congress Antalya, Turkey*.
- Gíslason, S. R., D. Wolff-Boenisch, A. Stefánsson, E. Oelkers, E. Gunnlaugsson, H. Sigurdardóttir, B. Sigfússon, W. S. Broecker, J. Matter, M. Stute, G. Axelsson, and T. Fridriksson, 2010. Mineral sequestration of carbon dioxide in basalt: A pre-injection overview of the CarbFix project, *Int J Greenhouse Gas Cont* 4: 537-545, 2010.
- Guðmundsson B. T. and S. Arnórsson 2002. Geochemical monitoring of the Krafla and Namafjall geothermal areas, N-Iceland. *Geothermics*, 31, 195-243.
- Gunnarsson, I., B. Sigfússon, A. Stefánsson, S. Arnórsson, S.W. Scott and E. Gunnlaugsson, Injection of H₂S from Hellisheiði Power Plant, Iceland, *Proceedings, 36th Workshop on Geothermal Reservoir Engineering*, 2011.
- Scott S., I. Gunnarsson, A. Stefánsson, S. Arnórsson, E. Gunnlaugsson 2011. Gas Chemistry of the Hellisheiði Geothermal Field, SW-Iceland. In: *Proceedings, 36th Workshop on Geothermal Reservoir Engineering*, Stanford.
- Stefánsson A., S. Arnórsson, I. Gunnarsson, H. Kasalainen, and E. Gunnlaugsson 2011. The geochemistry and sequestration of H₂S into the hydrothermal system at Hellisheiði, Iceland. *Journal of Volcanology and Geothermal Research*, 202, 179-188.