Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Pilot Scale Geothermal Gas Separation, Hellisheiði Power Plant, Iceland

Ingvi GUNNARSSON[1], Bjarni Már JÚLÍUSSON[1], Edda Sif ARADÓTTIR[1], Bergur SIGFÚSSON[2] and Magnús Þór ARNARSON[3]

[1] Reykjavík Energy, Bæjarháls 1, 110 Reykjavík, Iceland

2 Reykjavík Energy, Bæjarháls 1, 110 Reykjavík, Iceland. Current affiliation: European Commission, Joint Research Centre, Institute for Energy and Transport, Westerduinweg 3, 1755 LE Petten, Netherlands

[3] Mannvit, Grensásvegi 1, 108 Reykjavík, Iceland

Keywords: Geothermal gas emission, separation, re-injection, gas abatement

ABSTRACT

Reykjavik Energy has since the commissioning of Hellisheiði Power plant in 2006 put more effort into developing methods to lower geothermal gas emission from its geothermal power plants. The aim is to make the geothermal power production more environmentally friendly by lowering H_2S emissions and therefore to decrease local atmospheric pollution caused by its foul smell and toxic and corrosive properties as well as lowering emission of CO_2. The gas abatement method Reykjavík Energy is aiming towards is to dissolve the geothermal gases in effluent water from the power plant and re-inject them back into a geothermal reservoir. An essential part of developing a gas reinjection method is to separate the geothermal gases based on their solubility in water. Getting rid of the poorly soluble geothermal gases prior to reinjection greatly reduces the water needed to dissolve gases before injection.

A pilot scale gas separation station was built next to Hellisheiði Power Plant, SW Iceland as a part of geothermal gas re-injection projects. The goal of the pilot operation is to develop commercially feasible methods to separate geothermal gases prior to re-injection into the ground. Capacity of the pilot gas separation station was around 2% of the total gas exhaust from the Hellisheiði Power Plant. Three kinds of technologies are under scrutiny in the station, a membrane system for H_2 removal, a system comprised of adsorption and desorption towers which separates the soluble gases CO_2 and H_2S from the rest of the geothermal gases and a distillation column to separate CO_2 and H_2S. The flexible design and construction of the gas separation station provided opportunities to combine the systems or run them on their own. This pilot scale gas separation station provided gas for two gas re-injection projects Sulfix (re-injection and mineral sequestration of H2S into the high temperature reservoir) and CarbFix (re-injection and mineral sequestration of CO2 into a low-temperature reservoir).

Based on the successes of some parts of the pilot scale gas separation station and gas reinjection a gas separation station is being built next to Hellisheiði power plant capable to dissolving around 15% of H_2S from the power plant along with some CO_2. This gas separation station will start operation in the spring of 2014 and subsequently large scale re-injection of geothermal gases starts.

1. INTRODUCTION

Emission of geothermal gases is an inevitable part of high temperature geothermal utilization and is in some cases one of the main environmental problems associated with geothermal power production. Lowering gas emission from geothermal power plants is therefore an important task for decreasing their environmental impact and makes the geothermal industry more environmentally friendly than present.

During exploitation of the high temperature geothermal reservoir the geothermal fluid loaded with geothermal gases undergoes boiling, phase separation and cooling before the water phases, brine and condensate, are disposed. Re-injection back into the ground in the vicinity of the geothermal reservoir has become the common practice in the geothermal industry as that disposal method carries the least environmental impact. The gases are concentrated in the condensers of the turbines and only small portion of the gases condense with the steam, leaving the rest as non-condensable gas (NCG). The NCG´s are removed from the condenser by vacuum pumps and are vented into the atmosphere.

Following the commissioning of Hellisheiði Power Plant, SW Iceland in 2006, an increase in H_2S concentration in air was observed in communities near the power plant. (Thorsteinsson et. al, 2013, Gunnarsson et. al, 2013 and Ólafsdóttir and Gardarson, 2014). A new regulation on atmospheric H_2S concentration was implemented by the Government of Iceland in 2010 and will become stricter in 2014. The new regulation puts high demands on Icelandic geothermal industry to lower gas emission from geothermal power plants. To address this problem a cooperation between Icelandic power companies (Reykjavík Energy, HS-Orka and Landsvirkjun) was started in 2012 with the task of exploring what was the best solution to the problem (Juliusson et al. 2014).

The gas abatement method Reykjavík Energy has been aiming at since 2007 is to dissolve the geothermal gases in effluent water from the power plant and re-inject them back into a geothermal reservoir. Dissolving the gases prior to or during the re-injection promotes necessary water rock reactions to sequester the gas in the basaltic formation receiving the gas loaded waters. Storage security is greatly increased and formation of stable minerals sequestering the gases is facilitated (Gíslason et al., 2013, Matter et al., 2013 and Gíslason and Oelkers, 2014,). Two experimental reinjection projects, SulFix and CarbFix (e.g. Aradottir et. al, 2011, Gunnarsson et. al, 2011) have been operated and the experience from these projects used as a foundation for geothermal gas injection at a larger scale.

An essential part of developing a gas reinjection method is to separate the geothermal gases based on their solubility in water. Getting rid of the poorly soluble geothermal gases prior to re-injection greatly reduces the water needed to dissolve gases before injection. A pilot scale gas separation station was built and operated as an addition to Hellisheiði Power Plant, SW Iceland. The goal of the pilot operation is to develop commercially feasible methods to separate geothermal gases into streams of CO_2 and H_2S rich gas and a stream of less soluble geothermal gases (H_2, N_2, CH_4 and Ar) prior to re-injection into the ground. The capacity of the pilot gas separation station was 2% of the total gas exhaust from the Hellisheiði Power Plant. Three kinds of technologies were initially under scrutiny, a membrane system for H_2 removal, a system comprised of adsorption and desorption towers which separates the soluble gases CO_2 and H_2S from the rest of the geothermal gases and a distillation column to separate CO_2 from H_2S. The flexible design and construction of the gas separation station provided opportunities to combine the systems or run them on their own.

In this paper the pilot gas separation station is described. Major components of the station are detailed, operational difficulties reported and the composition of the gas after each step of the gas separation process reported. An industrial scale gas separation station currently being built next to Hellisheiði power plant is also described. In this station around 15% of the H_2S from the power plant will be dissolved and subsequently re-injected into the ground.

2. HELLISHEIÐI POWER PLANT

Hellisheiði Power Plant is a combined heat and power plants located to the south of the Hengill central volcano which is located in the western volcanic zone SW-Iceland, approximately 20-25 km southeast of Reykjavík (Fig. 1). It was commissioned in 2006 with the installment of two 45 MWe turbines. In 2007 a 33 MWe low pressure turbine that uses steam from a second stage flashing of the separated geothermal water was started and two additional 45MWe turbines were started in 2008 and another two in 2011. Heat exchanges were commissioned in 2010 producing 133 MWth for space heating in Reykjavík. Total installed capacity in Hellisheiði power plant is 303 MWe and 133MWth. Further expansion of hot water production is planned before 2020.

Each step in increased production is followed by an increased gas emission from the power plant. The average composition of the gases calculated from the composition of the steam going in the turbines is 69% CO_2, 29% H_2S, 0.75% H_2, 1.3% N_2 and 0.12% CH_4. The gases are currently being released on top of one of the cooling towers to minimize the risk of high concentration of gases close to the power plant. In 2012 the annual emission of H_2S and CO_2 was around 16900 and 43000 tons, respectively (Gunnarsson et al., 2013).

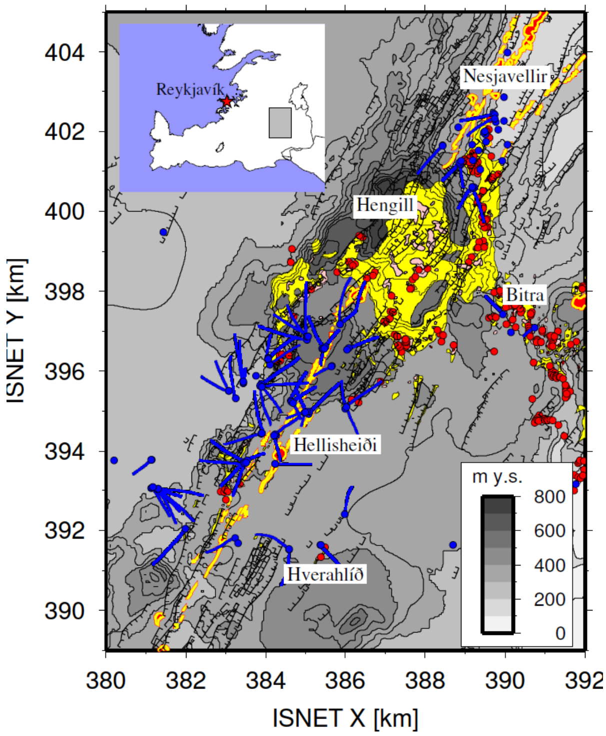

Figure 1. Map of Hengill area. Blue lines and dots are well paths. Red dots are fumaroles and yellow is surface alteration.

3. PILOT GAS SEPARATION STATION

The main components of geothermal gas are CO_2, H_2S, H_2, CH_4, N_2 and Ar (e.g. Arnórsson, et. al., 2010 and Giggenbach, 1980). Concentration of individual gases can range from ppb levels to several thousand ppm depending on geological settings, temperature and composition of the geothermal reservoir and the processes the geothermal water has gone through in the reservoir. The sources of the geothermal gases are either volcanic, meteoric or they are produced by water rock reactions in the reservoir (e.g. Arnórsson, et. al., 2010). The geothermal gases can be divided into two categories depending on their solubility in water. The sour gases CO_2 and H_2S are much more soluble in water than the other geothermal gases H_2, N_2, CH_4 and Ar. If the aim is to dissolve the gases before injection, getting rid of the insoluble gases is a priority. The injection of insoluble gases, even in small quantities will lead to a build-up of pressure in the injected aquifer and inhibit the dissolution of H_2S and CO_2 in the aqueous phase or call upon unpractical amounts of water needed for complete dissolution of the geothermal gas making running cost of this method of gas disposal more expensive and much less feasible in areas where water resources are limited.

In order to optimize gas composition for injection of CO_2 and H_2S from Hellisheiði power plant Reykjavík Energy built a gas separation station to separate the geothermal gases into streams of enriched CO_2, H_2S and less soluble gases (H_2, N_2, CH_4, Ar) (Fig. 2). Simplified schematic overview of the gas separation station is shown in Fig. 3, where the main components of the station are shown. The station was designed for separating 200 Nm^3/hour of geothermal gas which corresponds to approximately 2% of the emitted gas from the power plant.

The gas separation process is in two steps. First step is to separate the sour soluble gases, CO_2 and H_2S, from the less soluble gases H_2, N_2, CH_4 and Ar using an absorption/desorption or membrane system and then to use the difference in physical properties of CO_2 and H_2S to separate them in a distillation column.

Figure 2. Hellisheiði power plant, Iceland. In the foreground to the right is the gas separation station. Hellisheiði power plant is in the back.

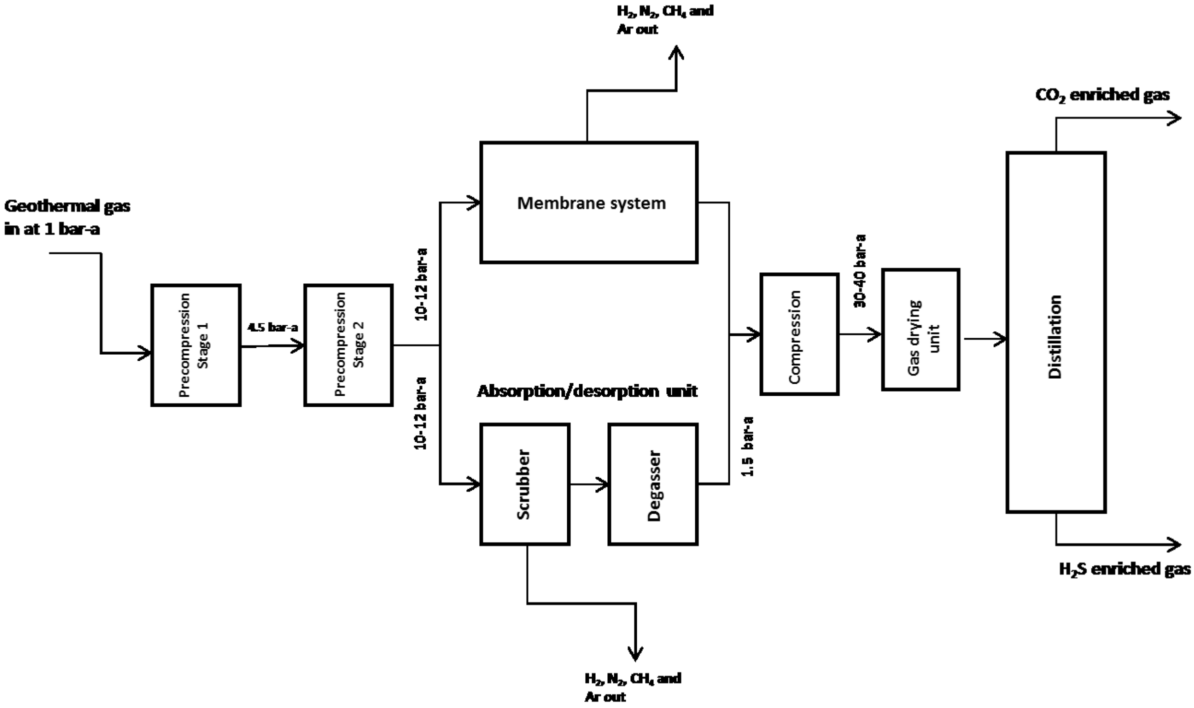

Figure 3. Simplified schematic overview of the pilot gas separation station operated with Hellisheiði power plant, Iceland.

3.1 General Description

Below is a general description of the major components of the gas separation station operated with the Hellisheiði power plant. The role of each component is introduced and their function is explained.

3.1.1 Pre Compressors

The role of the pre compressors is to pressurize the gas to get to operational pressures for the absorption/desorption and membrane systems. The gas is transported in polyethylene pipe from the power plant to the separation station and is at 1 bar-a pressure. The gas is compressed in two stages in the pre compressors. After the first stage the pressure is 4,5 bar-a and 10-12 bars-a after the second stage of compression. The gas is water saturated in all stages in the pre compressors and any condensation is collected in water traps and subsequently directed to waste.

3.1.2 Absorption/Desorption System

The absorption/desorption unit consists of an absorption tower (scrubber) that dissolves the soluble gases CO_2 and H_2S and a desorption tower that degasses CO_2 and H_2S from the solvent of the absorption tower. The solvent chosen for the system is water because OR was aiming at making the gas separation without organic solvents that might be harmful to the environment. Operational pressure of the absorption tower is 10-12 bar-a and for the desorption tower 1.5 bar-a. The absorption unit has a filling material to maximize the surface area between the solvent and the gas. The NCG is introduced into the absorption unit beneath the filling material. The water-soluble CO_2 and H_2S gases become dissolved in the water that drips down to the bottom unit while the H_2, N_2, Ar and CH_4 gases remain in its gaseous phase and move upwards and concentrate at the top of the absorption tower. The water is circulated in the absorption/desorption system to minimize water consumption of the pilot plant. The water flow and pressure of the system as well as water level in the adsorption tower are flexible and affect the performance of the system.

3.1.3 Membrane System

The membrane system has the same purpose as the absorption/desorption system that is to separate the sour gases (CO_2 and H_2S) from the rest of the geothermal gases (H_2, N_2, CH_4, Ar). The membrane system has not been tested yet and to the best of our knowledge it has not been used anywhere for separating geothermal gas.

3.1.4 High Pressure Compression System

The sour gas mixture coming from the absorption/desorption system at 1.5 bar-a is compressed before entering a drying unit and distillation column by two dual stage high pressure compressors. After the first stage the pressure is 4.5 bar-a and after the second stage 30-40 bar-a. Temperature of the gas after the first stage is 56-60°C and up to 150°C after the second stage. It is cooled down after both stages and is around 30°C exiting the high pressure compression system. The sour gas mixture from the absorption/desorption system is water saturated. Condensation occurring in the high pressure compression system is collected in water traps before entering the drying unit and diverted to waste.

3.1.5. Gas Drying Unit

The sour gas mixture is water saturated at 30°C and 30-40 bar-a when coming from the high pressure compression system. Drying the gas mixture is essential to be able to further process or transport the gas mixture. The water in the gas, if not removed, will condense in the distillation column resulting in a potentially highly corrosive liquid H_2S/water mixture leading to many operational difficulties.

The gas drying unit is a two column solid bed dryer filled with activated alumina. One column is used to dry the gas while the other is heated and purged with a hot sour gas mixture to remove the adsorbed water and re-generate the activated alumina. The dew point at atmospheric pressure after the drying unit is -68°C. At operational pressure of the distillation column (up to 40 bar-a), the dew point is -40°C.

3.1.6 Distillation System

Difference in volatility of CO_2 and H_2S can be used for physical separation of the gases by distillation. Operational pressure of the distillation system is between 30-40 bar-a and the gas is introduced to an intermediate level in the column. At the lower part of the column an H_2S enriched liquid fraction is collected, a fraction of the liquid evaporates on the heating elements, maintained at a temperature just above the boiling point of H_2S in order to decrease the CO_2 concentration of the liquid. Part of the liquid is removed from the column as a liquid stream maintaining a near constant liquid level. The top of the column has a cooling element where the temperature is set just below condensation temperature of CO_2 to provide a reflux that flows down providing cooling and condensation of the up-flowing gas stream thereby increasing the efficiency of the distillation column. The reflux (typical ratio of 2.5) is distributed by a distribution plate over filling material that increases the surface area between the liquid and gas phase.

4. OPERATION OF GAS SEPARATION STATION

Separation of geothermal gas into isolated streams of CO_2, H_2S and NGC (H_2, N_2, CH_4 and Ar) is an ambitious task and has not been done before in the geothermal industry. Operation and testing of the gas separation station started in January 2010. Testing period was longer than anticipated because of frequent technical and chemical problems. The causes of problems are mainly because of atmospheric contamination in the geothermal gas and moisture in the gas. This will be discussed in more detail below.

Atmosphere gas mixes with the geothermal gas at normal operating conditions in the condensers after the turbines in Hellisheiði power plant. The percentage of atmosphere gas can be up to 30% in the gas mixture. Geothermal gas and atmosphere gas mixtures can be explosive if certain conditions are met. Excessive explosion tests were carried out on geothermal gas/atmosphere gas mixtures to map the explosion risk in the gas separation station. The result indicated that the risk of explosion was only present in lower geothermal gas/atmosphere gas ratios than present in the gas separation station, i.e. the volumetric percentage of air needs to exceed 50% of the mixture. Oxygen in the geothermal gas however made the gas very problematic for processing in the separation station. Corrosion and scaling in the absorption/desorption unit resulted in frequent operational problems. Aqueous water containing dissolved hydrogen sulphide and oxygen as is the case in the adsorption tower is very reactive. The oxygen readily oxidises the hydrogen sulphide to either solid elemental sulphur clogging up pipes and control valves or to sulphuric acid, lowering the pH-value of the water in the adsorption tower making it highly corrosive. Atmosphere contamination in the geothermal gas also decreases the efficiency of the adsorption/desorption unit as higher ratio of the poorly soluble gases (H_2, N_2, O_2, CH_4, Ar) increases their concentration in the sour gas stream. To prevent these problems, turbine units needed considerable amendments in order to deliver almost atmosphere free geothermal gas for further processing in the gas station.

The geothermal gas is moisture saturated at 40°C when extracted from the condensers. Water condensation in the pipe transporting the gas from the power plant to the gas station stopped the gas flow and halted operation. To amend this the pipe to the separation station was heated using hot water. Some of the water is then condensed in the pre compressor pumps before the adsorption/desorption unit but in the adsorption/desorption unit it becomes water saturated again at 12-14°C. Distillation of this water saturated gas proved to be very problematic. The waters condensed to the bottom of the distillation column forming a highly reactive mixture of H_2S and water. The operation of the distillation column had to be stopped because of severe corrosion and scaling problems (Figure 4). Elemental sulphur precipitated in the distillation column and severe corrosion problems were encountered. After two months of testing, heating and cooling elements in the column were broken beyond repair. Operation of the distillation was abandoned and separation of the experiment of sour gases into streams of enriched H_2S and CO_2 stopped. The initial plan of injecting enriched streams of H_2S (>90% H_2S) in the SulFix project and enriched stream of CO_2 (>98% CO_2) in the CarbFix project changed and in both cases a gas mixture of H_2S and CO_2 was used for injection. Operation of the distillation column was only been tried in water saturated geothermal gas. Drying the gas proved to be an essential part of the gas separation process. Separating CO_2 form H_2S proved to be impossible unless if the CO_2 and H_2S mixture is water saturated.

Figure 4. Heating element from the bottom distillation column in the pilot gas separation station in Hellisheiði power plant, Iceland. The yellow colour is elemental sulphur. Rust colour on the cooling element on the right of the picture is where drops of liquid H_2S/water mixture fall on the heating element.

5. GAS COMPOSITION FROM THE GAS SEPARATION STATION

Three kinds of gas composition have been separated in the station (Table 1). The composition of the gas from the Hellisheiði power plant has changed somewhat during the testing phase as new turbines have been installed along with starting production from new regions of the geothermal area. This has changed the overall composition of the gas in the Hellisheiði power plant.

Raw geothermal gas is the gas coming from the condensers of the power plant. Gas from top of the adsorber is the gas that does not dissolve in the water in the absorber unit and is primarily the less soluble gases (H_2, N_2, CH_4, Ar and O_2). Gas from the desorption unit is the sour gas that dissolved in the waters of the absorber unit and got released in the desorption unit. Top of the distillation column should provide CO_2 enriched gas and the bottom of the column provides H_2S rich gas. The distillation column was only tested on the first gas composition as it permanently broke down as discussed above before it could be tested on other gas compositions.

6. SULFIX II

The operational and practical experience gained from the pilot scale gas separation station described above and in the SulFix and CarbFix projects is the foundation of an up-scaled gas separation station and injection that will be commissioned in the summer of 2014. This up-scaled gas treatment and re-injection is called SulFix II. The design of the SulFix II station is focused on primarily dissolving the H_2S in the geothermal gas. H_2S is slightly more soluble in water than CO_2 and therefore preferentially removed from the gas stream in water.

Table 1. Composition of gas in gas separation station, Hellisheiði Iceland. Volume percentage

Gas composition 1

Type of gas	CO_2 (%)	H_2S (%)[a]	H_2 (%)	N_2 (%)	CH_4 (%)	Ar (%)	O_2 (%)
Raw gas	53,3	18,6	25,03	1,38	0,32	n.d.	0,15
From top of absorper	14,7	2,0	81,84	3,52	1,00	n.d.	0,19
After desorption unit	70,6	25,7	1,53	0,23	0,04	n.d.	0,07
Top of distillation column	86,5	9,6	1,26	0,50	0,02	n.d.	0,13
Bottom of distillation column	10,6	91,1	0,01	0,00	0,00	n.d.	0,16

Gas composition 2

Type of gas	CO_2 (%)	H_2S (%)[a]	H_2 (%)	N_2 (%)	CH_4 (%)	Ar (%)	O_2 (%)
Raw gas	45,0	27,0	26,5	1,04	0,37	n.d.	0,040
From top of absorper	8,0	1,05	86,6	3,12	1,18	n.d.	0,064
After desorption unit	62,0	36,5	1,41	0,06	0,038	n.d.	0,035

Gas composition 3

Type of gas	CO_2 (%)	H_2S (%)[a]	H_2 (%)	N_2 (%)	CH_4 (%)	Ar (%)	O_2 (%)
Raw gas	61,3	21,0	15,8	1,47	0,26	n.d.	0,24
After desorption unit	75,2	23,5	1,14	0,12	0,032	n.d.	0,00

[a] Calulated value. 100-(sum of other gases) = H_2S (%)

Schematic of the gas injection scheduled to start operation in the summer of 2014 is shown in Figure 5. The gas separation station takes 400g/s of the gas form Hellisheiði power plant, pressurizes it to 5 bar-a and dissolves 98% of the H_2S along with 57% of the CO_2 in 36 kg/s condensate water (Table 2) in an absorption tower. Prior to use in the absorption tower the condensate is cooled from around 45°C to 20 °C. The cooling increases the solubility of the geothermal gases is the water. The gas loaded condensate water is then injected back into the geothermal reservoir through one of the re-injection wells currently operated in the Húsmúli re-injection zone next to the Hellisheiði power plant. The gas loaded water has a pH value around 4 and is corrosive to carbon steel in the injection well casing. To prevent corrosion of the casing the gas loaded water is put in a stainless steel pipe that goes 750 m into the well. The casing goes down to 700 m below the wellhead. Geothermal brine with pH between 9 - 9.5 is injected between the casing and the pipe with the gas loaded corrosive water. This setup prevents the gas loaded low-pH water to corrode the well casing.

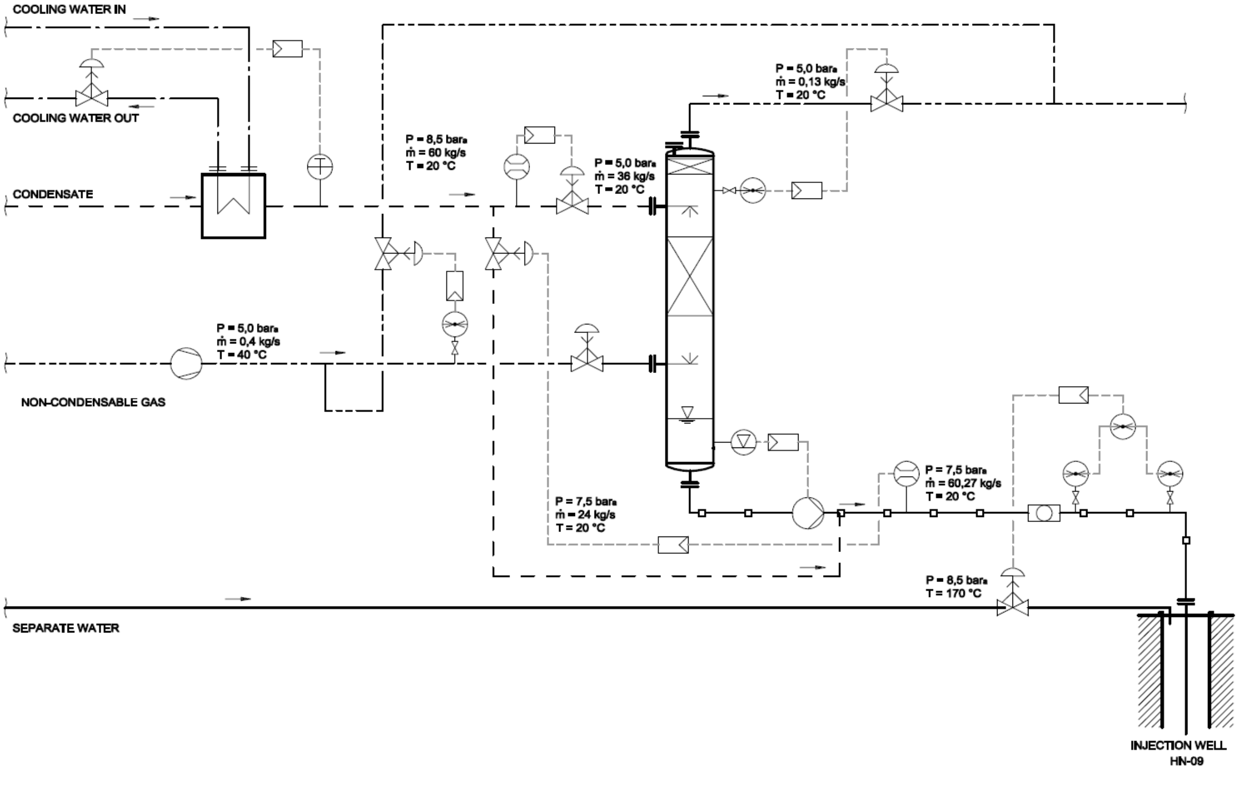

Figure 5. Schematic of SulFix II gas separation and injection Hellisheiði Power Plant, Iceland.

The reservoir temperature in the reinjection zone is 200-270°C. Tracer elements will be co-injected with the gas and arrival of the injected geothermal gas back into the production field will be extensively monitored. Studying fate of the re-injected H_2S in the geothermal reservoir is an important part of the SulFix II project and the success of this abatement method of re-injecting the H_2S back to where it came from depends on the extent of H_2S mineralization in the reservoir.

Table 2. Gas flow in SulFix II gas separation and re-injection

	Inlet gas kg/s	Top of scrubbing Tower kg/s	Dissolved in water kg/s
H_2S	0,11	0,0023	0,1079
CO_2	0,2757	0,1186	0,1571
H_2	0,0064	0,0063	0,0001
N_2	0,0056	0,0056	0,0001
O_2	0,0009	0,0009	0
CH_4	0,0006	0,0006	0
Total	0,3992	0,1343	0,2652

7. SUMMARY AND CONCLUSIONS

Following an increase in the atmospheric concentration of H_2S in communities around the Hellisheiði power plant after its commissioning in 2006, Reykjavík Energy put more effort in lowering the gas emissions from its power plants. The abatement method Reykjavík Energy has been aiming at is to dissolve the gases in waste waters form the power plant and re-inject them back into the geothermal reservoir. An important step towards dissolving the gas is to separate insoluble gases (H_2, N_2, CH_4 and Ar) from the more soluble H_2S and CO_2. A pilot scale gas separation station was build where geothermal gas was to be separated into streams of the insoluble gases (H_2, N_2, CH_4 and Ar) and more soluble sour gases (CO_2 and H_2S). CO_2 and H_2S were then to be separated by distillation. Individual part of the station could be operated separately. Operation of same parts of the station was successful while other parts like distillation of CO_2 and H_2S mixture were not successful. The gases from the pilot gas separation station were used in the SulFix and CarbFix experimental re-injection projects.

Based on the experience in the pilot gas separation station and the SulFix and CarbFix gas injection projects, an industrial scale gas separation station capable of dissolving around 15 % of the H_2S along with some CO_2 from the Hellisheiði power plant was built and will be commissioned in the summer of 2014. Building and operation of this gas separation station is a part of a plan set up by Reykjavík Energy to considerably lower the H_2S emissions from its power plants and is a clear evidence of its determination to react to the new regulation in Iceland on the H_2S concentration in atmosphere in inhabited areas in Iceland. Further steps will subsequently be taken based on the experience of this industrial scale gas injection in Hellisheiði to make sure that the H_2S concentration in air in communities affected by the Hellisheiði power plant is lowered.

REFERENCES

Aradóttir, E. S. P., Sigurdardóttir, H., Sigfússon, B., and Gunnlaugsson, E.: CarbFix: a CCS pilot project imitating and accelerating natural CO_2 sequestration. *Greenhouse Gas Sci Technol.,* **1**, (2011), 105-118.

Aradóttir, E.S.P., Gunnarsson, I., Sigfússon, B., Gíslason, S.R., Oelkers, E.H., Stute. M. et al.: Towards Cleaner Geothermal Energy: Subsurface Sequestration of Sour Gas Emissions from Geothermal Power Plants. *Proceedings*, World Geothermal Congress, Melbourne, Australia, (2015).

Arnórsson, S., Angcoy, E., Bjarnason, J. Ö., Giroud, N., Gunnarsson, I., Kaasalainen, H., Karingithi, C. W., and Stefánsson, A.: Gas chemistry of volcanic geothermal systems, *Proceedings,* World Geothermal Congress, Bali, Indonesia, (2010).

Franzson H., Gunnlaugsson, E., Árnason, K., Sæmundsson, K., Steingrímsson, B., and Harðarson, B. S.: The Hengill Geothermal System, Conceptual Model and Thermal Evolution. *Proceedings* World Geothermal Congress, Bali, Indonesia, (2010).

Giggenbach, W. F.: Geothermal gas equilibria, *Geochimica Cosmochimica Acta,* **44**, (1980), 2021-2032.

Gíslason, S.R. and Oelkers, E.H.: Carbon Storage in Basalt. *Science* **344**, (2014), 373-374.

Gíslason, S.R., Oelkers, E. H., Sigfússon, B. Matter, J., Stute, M., Gunnlaugsson, E. et al.: Solubility and Mineral Storage of CO_2 in Basalt. *Mineralogical Magazine* **77(5)**, (2013), 1178.

Gunnarsson, I., Sigfússon, B., Stefánsson, A., Arnórsson, S., Scott, S.W., and Gunnlaugsson, E.: Injection of H_2S from Hellisheiði Power Plant, Iceland, *Proceedings,* 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2011).

Gunnarsson, I., Aradóttir, E. S., Sigfússon , B, Gunnlaugsson, E., and Júlíusson, B. M.: Geothermal gas emission from Hellisheiði and Nesjavellir Power Plants, Iceland, *Proceeding,* Geothermal Research Council, (2013)

Júlíusson, B.M., Gunnarsson, I., Matthíasdóttir, K.V., Markússon, S.M., Bjarnason, B., Sveinsson, Ó.G., Gíslason, Th. and Thorsteinsson, H.: Tackling the Challenge of H_2S Emissions, *Proceedings*, World Geothermal Congress, Melbourne, Australia, (2015).

Matter, J., Stute, M., Hall, J.L., Mesfin, K.G., Gíslason, S.R., Gunnlaugsson, E. et al.: Quantification of CO2-fluid-rock reactions using reactive and non-reactive tracers, *Abstract V41A-2753 presented at 2013 AGU Fall Meeting*, (2013).

Olafsdottir, S. and Gardarson, S. M.: Impact of meteorological factors on hydrogen sulfide concentration downwind of geothermal power plants, *Atmospheric Environment,* 77, (2013),185-192.

Scott, S., Gunnarsson, I., Stefansson, A., Arnorsson, S., Gunnlaugsson, E.: Gas Chemistry of the Hellisheidi Geothermal Field, SW-Iceland, *Proceedings,* 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA. 2011.

Stefánsson, A., Arnórsson, S., Gunnarsson, I., Kasalainen, H., and Gunnlaugsson, E.: The geochemistry and sequestration of H_2S into the hydrothermal system at Hellisheiði, Iceland, *Journal of Volcanology and Geothermal Research*, **202,** (2011), 179-188.

Thorsteinsson, Th., Hackenbruch, J., Sveinbjörnsson, E. and Jóhannsson Th.: Statistical assessment and modeling of the effects of weather conditions on H_2S plume dispersal from Icelandic geothermal power plants, *Geothermics*, 45, (2013), 31-40.