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Utilization of the Hottest Well in the World, IDDP-1 in Krafla

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ABSTRACT

Highly superheated wells like IDDP-1 in Krafla, Iceland reveal great new potential for energy production from near-magma geothermal resources. However, at temperatures exceeding 400°C and pressure above 100 bar, a number of challenges arise that need to be overcome for such an endeavor to succeed. Hydrogen chloride and silica in gaseous form in the steam phase calls for redesign of both well and surface equipment to enable utilization of such fluid in conventional geothermal steam turbines. The chemical composition of the steam sets limits to material selection for all equipment and requires “cleaning” of the steam before connection to the steam gathering system. The steam from IDDP-1 contained 100 mg/kg hydrogen chloride that formed hydrochloric acid when the steam condensed and 62 mg/kg silica was dissolved in the steam phase. The gaseous silica precipitated as solid silica below 80 bar pressure, causing a number of limitations to all design parameters and operational conditions. Wet scrubbing of steam from IDDP-1 proved to be the method of choice for mitigating acid formation and corrosion as well as formation of silica scaling.

INTRODUCTION

In 1975 the government of Iceland decided to start development of the geothermal resource at the Krafla volcano in north Iceland for electricity production of 60 MW. In December the same year, volcanic eruption started in the west part of the caldera that lasted for nine years. The repeated magmatic intrusion into the roots of the geothermal system left a long lasting impact on the fluid chemistry of the reservoir (Ármannsson, 1989) and resulted in slower development of the area than planned in the beginning. In 1977 the first 30 MW turbine started production, however the second turbine was not installed until 1999 after extensive exploration and drilling.

The first deep well in the Icelandic Deep Well Project (Friðleifsson et al., 2014) was drilled in Krafla (Elders et al., 2014). It produced superheated steam at wellhead pressure of 140 bar and temperature of 450 °C. The superheated steam was rich in hydrogen chloride gas and was highly corrosive when it condensed. It also contained dissolved silica and possibly gaseous sulfur, making it unsuitable for utilization without scrubbing (Hauksson et al., 2014).

Superheated steam rich in HCl has been observed in many of the wells drilled in Krafla (Einarsson et al., 2010), and in a number of other geothermal areas that have encountered highly superheated steam (Truesdell et al., 1989). By drilling IDDP-1 the understanding of the characteristics of the superheated zone of the Krafla geothermal system has improved. Before the flow test of IDDP-1 the existence of superheated steam zone containing HCl acid was known but temperature and the properties of the dry steam was not known due to down hole mixing with lower enthalpy fluid in previous wells. The testing of the IDDP-1 well showed a temperature higher than 450 °C, HCl concentration in the range of 100 mg/kg and the silica concentrations of 62 mg/kg measured in the steam indicated temperature of up to 550 °C (Hauksson and Markússon, 2013).

Figure 1: Flow test of IDDP-1. For the first hours during the flow test the steam is grey colored due to corrosion products.

The solubility of silica in superheated steam has been investigated up to high pressure and temperature (Fournier and Potter, 1982). However it was not realized before that it might affect the possible utilization of the superheated resource. Silica deposited very rapidly from the superheated steam when the pressure decreased in the flow test. The superheated steam also contained sulfur compounds that precipitated out when the steam was condensed. This will affect the usability of the steam. The rapid deposition of silica in the IDDP-1 well explains the prior experience of rapid blocking of wells that reached the superheated zone in Krafla. These wells were operated at low wellhead pressure and it is very likely that the silica in the superheated steam precipitated in the veins feeding the wells when pressure dropped. The following figure shows a conventional Krafla well. It is cased to 800 m depth and the production zone reaches to 2200 m depth.

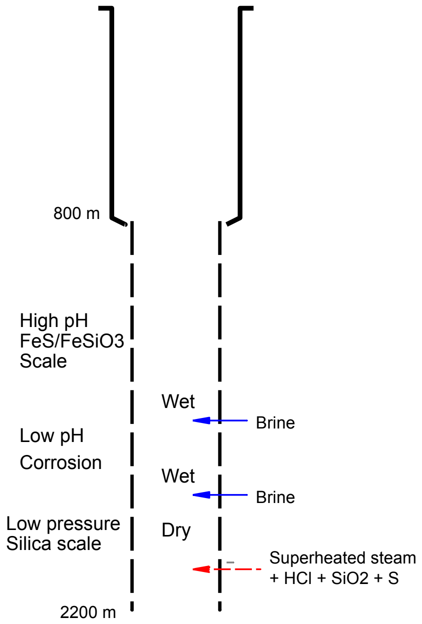

Figure 2: Conventional Krafla well

The deeper veins (>2000 m) feed superheated steam similar to the IDDP-1 steam into the well while the shallower veins (< 1800 m) feed alkaline brine into the well. The brine flowing from the new well was black colored ("black death") and contained suspended solids of iron-oxides, iron-sulfides and iron-silica compounds. The output of the wells dropped rapidly and in the end they only produced water and steam from the more shallow veins while the deep superheated veins were completely blocked.

HARNESSING THE SUPERHEATED STEAM ZONE

In 2009, a study was done to solve this problem and several options were proposed for the harnessing of the corrosive acidic fluid (Einarsson et al., 2010). Principally the three options proposed were deep casing and neutralization in surface equipment, neutralization in the well by various methods and in situ neutralization by water injection.

Silica deposition test from IDDP-1 steam (Hauksson and Markússon, 2013) showed (Figure 3) that the wellhead pressure needs to be kept above 80 bar in order to avoid silica precipitation in the well. This greatly affects the plans for the utilization of the deep superheated reservoir in Krafla. Now some of the options may not be feasible anymore because of this new information.

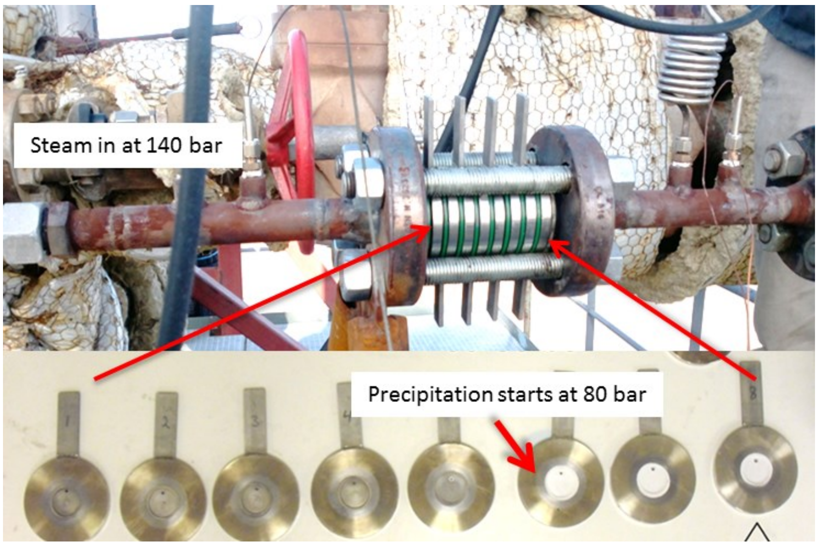

Figure 3: Silica precipitation experiment at the IDDP-1 well in Krafla. The upper part of the picture shows the experimental setup and the lower part show how silica precipitated on the orifice plates when the pressure dropped.

2.1 Deep casing drilling a well with casing down to the superheated steam zone and producing superheated steam that would be treated by surface equipment.

If the steam maintains superheat, the HCl will be of gaseous form and little corrosion of steel casing is to be expected. This was based among other things on experience from well KG-12 in Krafla where the liner depth was increased to 985 m and the shallow aquifers blocked of. This was partly successful and the well was used for many years despite rapid decrease in output the first months of operation. The steam became saturated after few years of operation and in the end the well became too low in pressure to be usable. The well KG-12 was operated at low wellhead pressure, which may explain the decline of production.

The IDDP-1 was drilled to 2100 m depth and the casing reached down to 1950 m. The production zone contained only superheated steam and shallower water dominated aquifers were blocked of. Testing of the IDDP-1 well proved that it could be operated without silica scaling if wellhead pressure is kept above 80 bar. Also corrosion was not severe when the steam was superheated but repeated shutdown caused condensation in the well and accelerated corrosion of the casings and wellhead. After intermittent testing for two years the well had to be closed because of master-valve failure (Einarsson this volume).

2.2 Neutralization in the well neutralization of the superheated steam in the well by mixing it with alkaline water, either injected into the well or coming from shallower aquifer into the well and thus protecting the casing and wellhead from corrosion damage.

Most of the old acid wells in Krafla had a casing of 800 m and water flowed into the well from the shallow 200 °C hot aquifer neutralizing and scrubbing the acid steam from the deep aquifer. Tests were conducted in order to control the ratio of superheated steam and water by changing the wellhead pressure. It proved to be difficult and unpredictable.

The old wells with water and superheated steam aquifer clogged rapidly. Clogged wells have been reamed but have clogged rapidly again. The well casing and liner has been damaged in such operations. Different reaming technology such as use of tubular coil with jet stream and acidizing may be a better approach as such an operation will also clean the inflow veins. The possibility of using wells without liners or liners made of corrosion resistant material was evaluated and the possibility of injecting NaOH solution into wells was studied in detail.

This approach is not considered feasible anymore. The reason is that the well must be operated at wellhead pressure higher than 80 bars and the neutralization of acid in the well must occur at temperatures higher than 300 °C. This will put much strain on the materials of the injection equipment. When water is mixed with the superheated steam, silica will precipitate and may clog the well. Drilling of a well that produces correct ratio of alkaline water and steam for in-well mitigation may be difficult. Finally the operation of two phase well at wellhead pressure higher than 80 bars will also be difficult or even impossible.

Injecting water into the superheated zone

By injecting water into the superheated zone the steam will condense and the acid in the steam may become neutralized. This was proposed already in 1981 as a way to reduce the acidity in the deep zone and since 2002 alkaline separator water has been being injected down to 2200 m depth in well KG-26. Neutralization of the superheated zone by this injection has not been detected.

This approach is still valid and such injection can become more widespread and increased. Water is now also injected into the IDDP-1 well and into well KJ-39.

Recently Thermochem, (Hirtz et al. 2013) conducted a study of this possibility based on their experience in HCl mitigation in the Geyser field in USA. They suggested the injection of 357 l/s for one year to fill fractures and then 23 l/s of water for production of 23 kg/s of steam for 50 years from a reservoir 0.75 km^2. The reservoir temperature was expected to drop from 330 °C to 240 °C during the resource operating time of 50 years.

It should be cautioned that maintaining superheat in deep cased production wells might become impossible if injection is conducted at the same time. During transition of the zone from being superheated to a two-phase system the reservoir condensate may become very acidic.

PURIFICATION OF STEAM FOR TURBINE

The superheated steam produced from the reservoir will contain acid gas, which will be highly corrosive when it condenses, making it unsuitable for utilization in a turbine without purification.

Three methods have been proposed for purification of the superheated steam i.e. heat exchanger, dry scrubbing and wet scrubbing.

3.1 Heat exchanger

By heat exchanger the energy will be transferred to another medium, which will be harmless to the turbine. It may be possible to use the steam at high temperature and thus get better efficiency than if the steam is saturated and scrubbed with water.

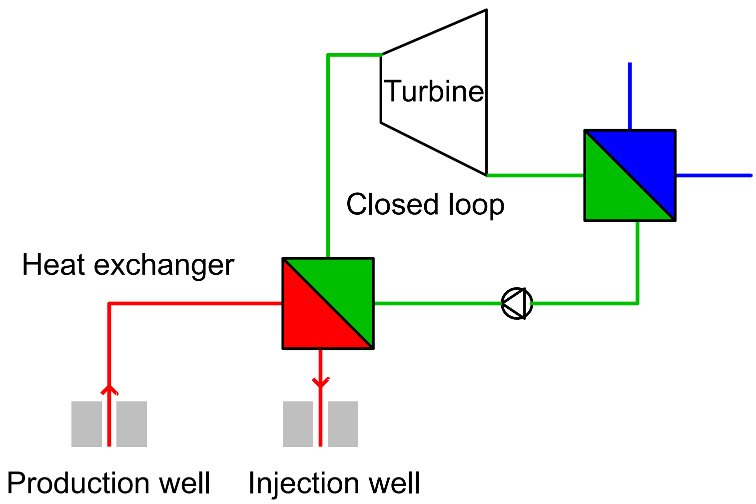

Figure 4: Heat exchanger and closed loop power cycle

High temperature condensation will pose a great challenge to material selection for heat exchanger tubes. The condensing acid steam will be very corrosive, especially the earliest condensing part. Also the silica in the steam may cause scaling problems.

This was tested during flow testing of the IDDP-1 well (Karlsdóttir el al., 2013). A test unit with eight different types of heat exchanger tubes was used without prior removal of silica, sulfur and acid gases. The steam condensed in the tubes at an outlet temperature of about 270°C. The operation was problematic and discontinuous due to a need for frequent cleaning and replacement of flow controlling orifices. Common materials such as stainless steel showed both corrosion and cracking but the high alloy materials (e.g. Inconel 625) showed little corrosion. The possibility of using a heat exchanger for the acid steam was not ruled out but further experimentation was deemed necessary.

3.2 Dry scrubbing

By contacting the superheated steam with dry alkaline material the acid may be captured and pure high temperature superheated steam produced for better energy efficiency than is possible by wet scrubbing.

A dry steam scrubbing process has been developed at The Geysers in USA (Hirtz, 2009) and allows mitigation of high-Cl steam without significant superheat loss. The process demonstrated in full-scale well tests involves flowing high-Cl and superheated steam through a dry packed bed of calcium carbonate (limestone). The neutralization reaction takes place in the absence of an aqueous environment, with the byproducts being $CaCl_2$, CO_2 and H_2O (g). Periodic washing and replacement of the limestone substrate is necessary, but with properly sized reaction vessels these processes can be performed at intervals of several weeks or months, depending on the Cl concentration of the steam and the flow rate of the well.

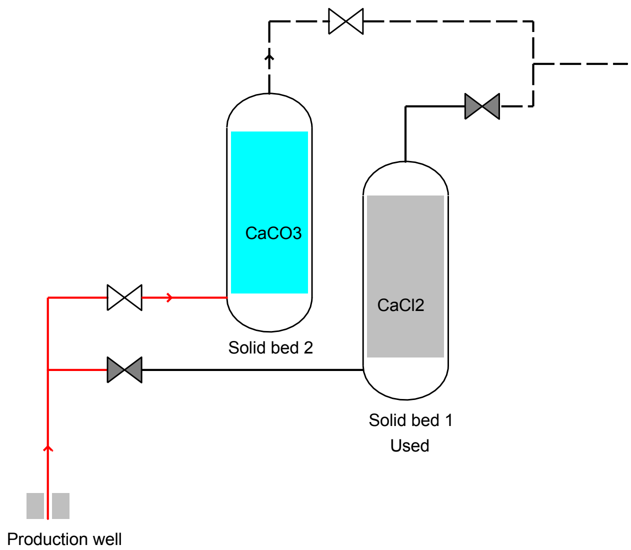

Figure 5: Dry scrubbing process

Thermochem undertook a study in 2011 on the available options for scrubbing superheated steam (Hirtz, 2011). The primary uncertainty in the calcium carbonate scrubbing process is the efficiency of HCl removal at high temperature. Since then further information has been collected but it still remains to test the effect of silica in steam on this process before it can be considered a realistic candidate for treating superheated steam from the Krafla reservoir.

Wet scrubbing

Scrubbing geothermal steam with water is common practice in many geothermal fields and considerable experience exists in this field. Tests were done in which superheated steam from the IDDP-1 well was scrubbed with various mixtures of condensate and alkali (Hauksson and Markússon 2013, Hauksson et al., 2014). The IDDP-1 steam contained acid gas and was highly corrosive when it condensed. The acid gas in the steam could effectively be scrubbed from the steam with brine, condensate or cold ground water. The steam from the IDDP-1 well also contained sulfur in gaseous form, which could only be scrubbed from the steam with alkaline water. The superheated steam from the IDDP-1 well contained both silica dust from the well and dissolved silica, which precipitated out of the steam as particles when the pressure was reduced. The silica particles were effectively washed from the steam with wet scrubbing. The scrubbing water then contained particles which might deposit in scrubbing equipment and clog injection wells if it would be mixed with injection brine.

By the wet scrubbing experiments during flow testing of the IDDP-1 well it was demonstrated that pure steam could be produced by scrubbing the steam with brine from the present plant. For this, sufficient alkaline brine must be available from other wells. Modification of the scrubbing process, by prescrubbing with small amount of water and subsequent scrubbing with alkaline brine, was proposed in order to remove the silica and most of the acid. The small prescrub water stream would contain most of the silica particles, which would be disposed of separately, see fig. 4.

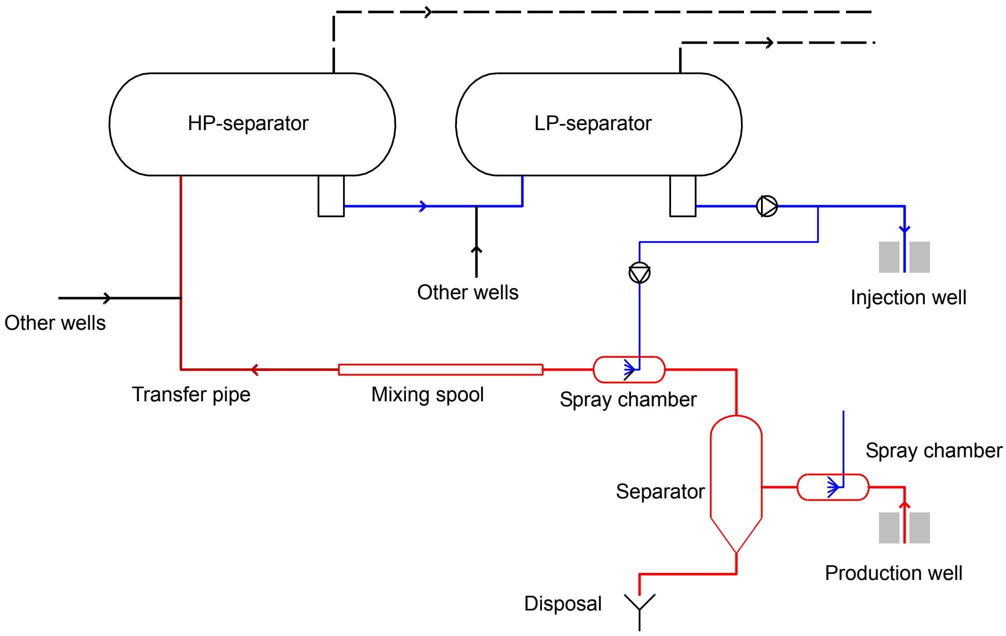

Figure 6: Proposed wet scrubbing of superheated steam for the Krafla plant.

CONCLUSIONS

Wells with several times the output compared to normal wells can both decrease cost and limit visual impact by decreasing the number of wells providing steam for the power plant. The most likely scenario for future utilization of the deep superheated reservoir in Krafla is likely to be either wells with deep casings to mask off any low enthalpy fluid that might cause acid formation and corrosion in the wellbore or reinjection deep into the superheated reservoir, possibly below the production area. The hostile fluid chemistry of the superheated system in Krafla, with respect to utilization is manageable with simple acid/base chemistry of the wet scrubbing method along with controlled pressure drop to remove solid silica. Direct utilization of steam with enthalpy around 3200 kJ/kg is more demanding and the risk is higher than conventional wells on all levels, but so is the gain if successful. Production from such wells still poses a number of challenges in regards to well and surface equipment such as valves. Work is being carried out both in terms of preparation for IDDP-2 (Fridleifsson this volume) and for further production at Krafla site.

REFERENCES

Armannsson, H., Benjamínsson, J., Jeffrey, A.: Gas changes in the Krafla geothermal system, Iceland. Chem. Geol. 76, (1989), 175-196.

Einarsson, K., Pálsson, B., Gudmundsson, Á., Hólmgeirsson, S., Ingason, K., Matthíasson, J., Hauksson, T., Ármannsson, H.: Acid Wells in the Krafla Geothermal Field. In: Proceedings World Geothermal Congress 2010, Bali, Indonesia. (2010)

Elders, W.A., Friðleifsson, G.Ó. and Pálsson, B.: Iceland Deep Drilling Project: The first well, IDDP-1, drilled into magma. Geothermics, 49, (2014), 1.

Fournier, R. O., Potter, R. W.: An equation correlating the solubility of quartz in water from 25°C to 900°C atpressures up to 10,000 bars.Geochimica et Cosmochimica Acta, 46, (1982), 1969–1973.

Friðleifsson G.Ó., Elders W.A. and Albertsson A.: The concept of the Iceland deep drilling project. Geothermics, 49, (2014), 2–8.

Hirtz, P., Buck, C., Kunzman, R.: Current Techniques in Acid-Chloride Corrosion Control and Monitoring at The Geysers. In: Proceedings, Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program, Stanford University, p. 83–95. (1991).

Hirtz, P.: Krafla Geothermal Power Station – Initial HCl Scrubbing Process Evaluation and Design for Well IDDP. Report Prepared by ThermoChem for Landsvirkjun., p. 41. (2011).

Hirtz, P., Beall, J., Pingol, A.: Injection Study for Superheat Management and HCl Mitigation of the Krafla High Temperature Reservoir. Report prepared for landsvirkjun by Thermochem October 15, 2013,. 36 p. (2013).

Hauksson, T., Markússon S.: Wet Scrubbing of IDDP-1 Steam, Pilot Test Results. IDDP-1 Flow test 2010-2012. Landsvirkjun LV-2013-050, p. 119-170. (2013).

Hauksson, T., Markússon S., Einarsson K., Karlsdóttir S.N., Einarsson Á., Möller A. and Sigmarsson Þ.: Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland. Geothermics 49, (2014), p. 76–82.

Hauksson, T., Markússon S.: Silica in superheated steam of the IDDP-1 exploratory geothermal well in Krafla. Experimental study. IDDP-1 Flow test 2010-2012. Landsvirkjun LV-2013-050, p. 299-332. (2013).

Karsldóttir, S.N., Einarsson, Á., Ragnarsdóttir, K., Möller, A.: Corrrosion testing of heat exchhanger tubes in steam from the IDDP-1 exploratory geothermal well in Krafla, Iceland. IDDP-1 Flow test 2010-2012. Landsvirkjun LV-2013-050, p. 233-263. (2013).

Karsldóttir S. N.: Failure analysis of a stem from a IDDP-1 valve. IDDP-1 Flow test 2010-2012. Landsvirkjun LV-2013-050, p. 265-280. (2013).

Truesdell, A.H., Haizlip, J.R., Ármannsson, H., and D‘Amore, F.: Origin and transport of chloride in superheated steam. Geothermics, 18, 295-304. (1989).