# FINAL REPORT

## DRG-H3
## Utilization of superheated geothermal fluid – power conversion, chemistry and material challenges

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| Project ID: | **13-5-006** |
| Coordinator: | Guðrún Sævarsdóttir |
| Start date: | 01.11.2014 |
| Duration: | 3 years (+ 6 months) |
| Partners: | Reykjavik University, University of Iceland, HS-orka, Landsvirkjun, Mannvit |

# 1 Intoduction

The aim of the work is to develop technological solution that offer the best thermodynamic utilization of the high enthalpy fluids from IDDP. The fluid may be expected to contain impurities and dust, in the case of IDDP1 the steam contained high percentage of volatile chloride and dry silica. High volatile chloride present in the fluid makes it mitigation a necessity before utilization.Presence of gaseous silica in superheated steam makes chances of scaling in components if superheat is tried to recover from steam before separation. Therefore in order to utilize the superheated steam it is necessary to overcome the above mentioned constraints.

The work in H3-was divided in two parts,

1. Corrosion testing, done in a simulated geothermal environment

2. Development of technology for utilization and mitigation for a high temperature geothermalfluid from IDDP, divided into three stages:

a. Modeling thermophysical properties of real fluid mixtures

b. Cycle modeling and exergy analysis

c. Developing mitigation techniques, experimental verification

# 2 Project summary

## 2.1 Corrosion testing in a simulated geothermal environment.

the supervision of Sigrún Nanna Karlsdóttir. The thesis is delivered along with this report and there a thorough description of the scope, procedures and results is provided. The abstract and conclusions of the thesis are given below [1].

### 2.1.1 Abstract

Corrosion testing was done in a simulated geothermal environment at 350°C as well as at 180°C with a pressure of 10 bar for both temperatures. The chemical composition of the steam included H2S, HCl and CO2 with a pH of 3 and was formulated to represent the conditions in the IDDP-1 well. Testing was done in three flow through reactors having an internal diameter of 11.7mm and a total length of 300mm. Four materials were selected for testing, P265GH a carbon steel commonly used in high temperature installations, 254 SMO a high grade austenitic stainless steel as well as two nickel alloys, Inconel 625 and Hastelloy C276. Testing was done for 1 and 3 week exposures except for the carbon steel which was tested for 48 hours and 1 week. The carbon steel showed high corrosion rates at 180°C and very high rate at 350°C. All of the corrosion resistant alloys performed well at

180°C. At 350°C localized damage was seen for the 254 SMO and Inconel 625 samples. Hastelloy C276 performed the best at the higher temperature although the CR was higher than acceptable for such an alloy. Some difficulties occurred during testing including momentary blockages of flow as well as dissolution of the ceramic insulation material that likely affected the results which should be viewed as a worst case scenario in the operation of a geothermal plant.

### 2.1.2 Conclusions

This experiment has shown that damage can be seen on even high end corrosion resistant alloys in high temperature acidic geothermal steam. Carbon steel had high rates of corrosion for both the lower temperature test at 180°C as well as in the higher temperature test at 350°C and should not be used in the conditions simulated here. Both 254 SMO austenitic stainless steel as well as the nickel alloy Inconel 625 showed localized damage at the higher temperature although they performed very well for the lower temperature test. Only Hastelloy C276 showed no signs of localized damage although the corrosion rate was higher than acceptable (>0.1 mm/yr) and comparable to the other two CRAs.

Running the simulated geothermal environment in the laboratory was a challenge and did not go without incidents. The confined space of the reactors and the materials used in sample mounting undoubtedly affected the results of the test. The results should be considered representative of a worst case scenario in the operation of a well where there is no protective scale and possible fluctuations in operation as well as the possibility of dew point acidic droplets with a high concentration of Cl.

To gain a better understanding for a particular alloy further testing would be recommended for a longer period of time. In future testing improvements should be made to the experimental setup to enable smoother operation at a steady flow and pressure. With improvements to equipment and procedures simulated corrosion testing for geothermal environments are possible at these high temperatures and can be a valuable tool for material selection in future deep drilled and acidic geothermal wells.

## 2.2 Mitigation and utilization

The project assigned was developing method for effective and efficient utilization of superheated steam obtained from deep drilling. The major challenges includes dealing with acidic Chlorine and gaseous and Silica present in the superheated steam. An efficient way to clean steam without losing considerable amount of superheat using the boiling point elevation property of salt solutions is proposed. The scrubbing technique used for such system is venturi scrubbing. A comparison of thermodynamic performance for a power plant cycle using Sodium Chloride solution for scrubbing and conventional wet scrubbing was done for the case of IDDP-1 [1]. The results shows improved efficiency and work output using scrubbing with salt solutions. The efficiency could be increased further using salts with higher boiling point elevation than Sodium Chloride used. One of such salt is Potassium carbonate which was used for analysis and final experimental studies as discussed later.

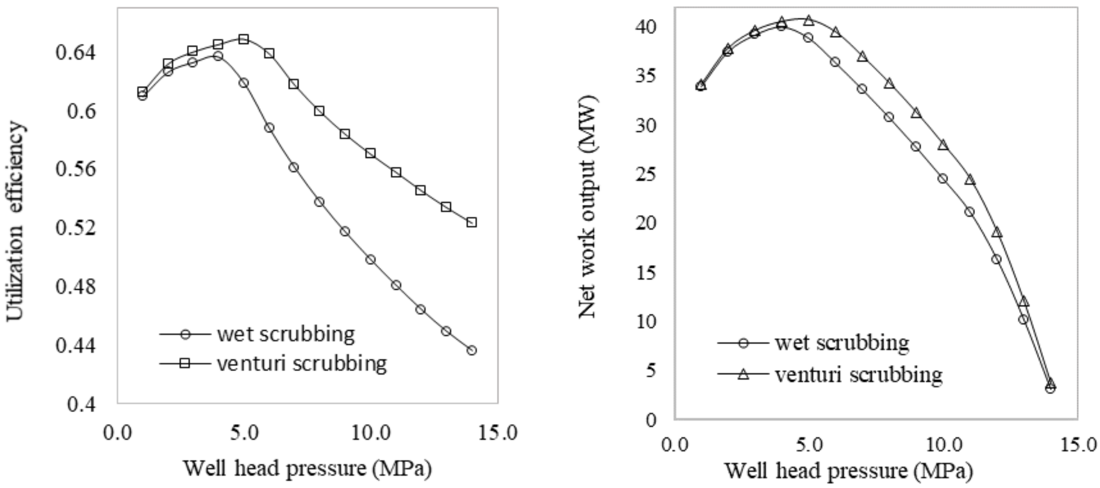


**Figure 1** Variation of Utilization efficiency and Net work output with well head pressure using single separation for IDDP-1 case study

Efficient utilization of superheated steam for power generation not just require scrubbing technique but also thermodynamic cycle selection. Thermoeconomic analysis for different cycles using various scrubbing techniques was made for IDDP-1 case study [2, 3]. Result shows heat recovery system as a thermoeconomic optimized method for power generation. The work is focused on development of salt solution for scrubbing combined to heat recovery system.  Application of heat recovery system poses problem related to scaling caused by dusty silica present in the superheated steam after precipitation from gaseous phase. In order to do computational study about the deposition of silica particles in superheated steam flowing through a heat exchanger unit, a solver was developed in OpenFoam an open source software. The solver developed can be used for future applications related to design and analysis of power plant components with superheated steam flow with silica particles present in dispersed phase. Results of silica deposition in superheated steam are shown in the studies [4].

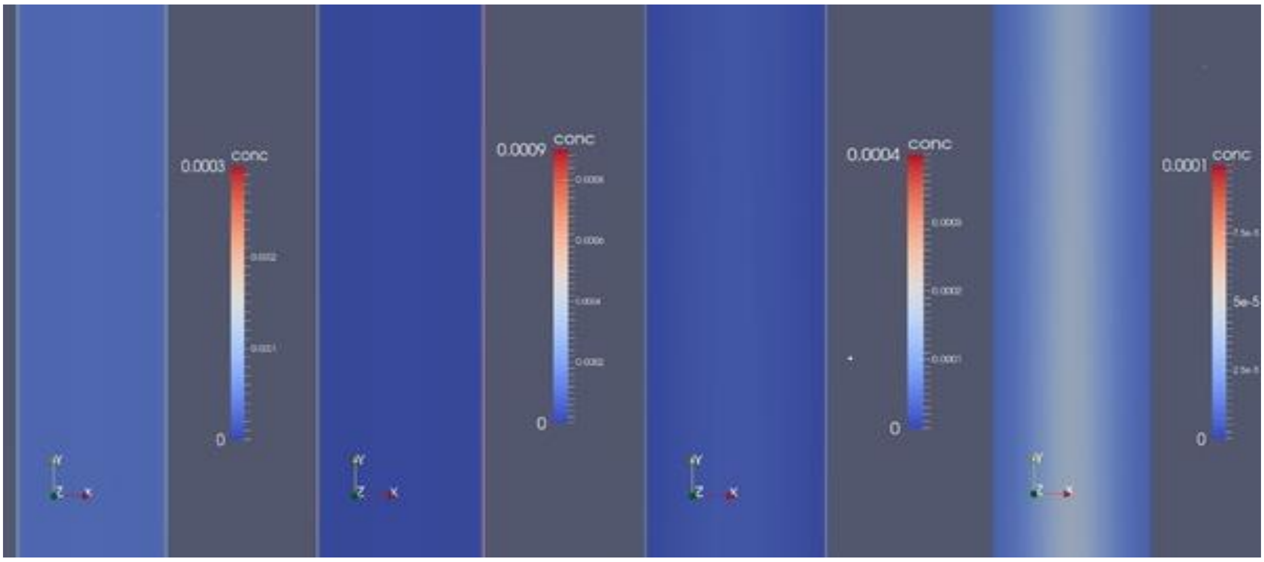


**Figure 2** Particle concentration profiles obtained from computation for different dimensionless particle relaxation times (a) 0.5 (b) 2.0 (c) 7.8 (d) 60

In order to validate the results obtained from computational work for deposition of silica particles in superheated steam, experimental studies were done. A laboratory scale test facility was designed and constructed. The setup facility built is used for two major purposes: Measuring deposition of silica present in superheated steam and measuring scrubbing performance using salt solution injection. A schematic of the setup is shown in Figure 3. Comparison of experimental and simulation results is shown in figure 4. Results will be explained in literature [5].

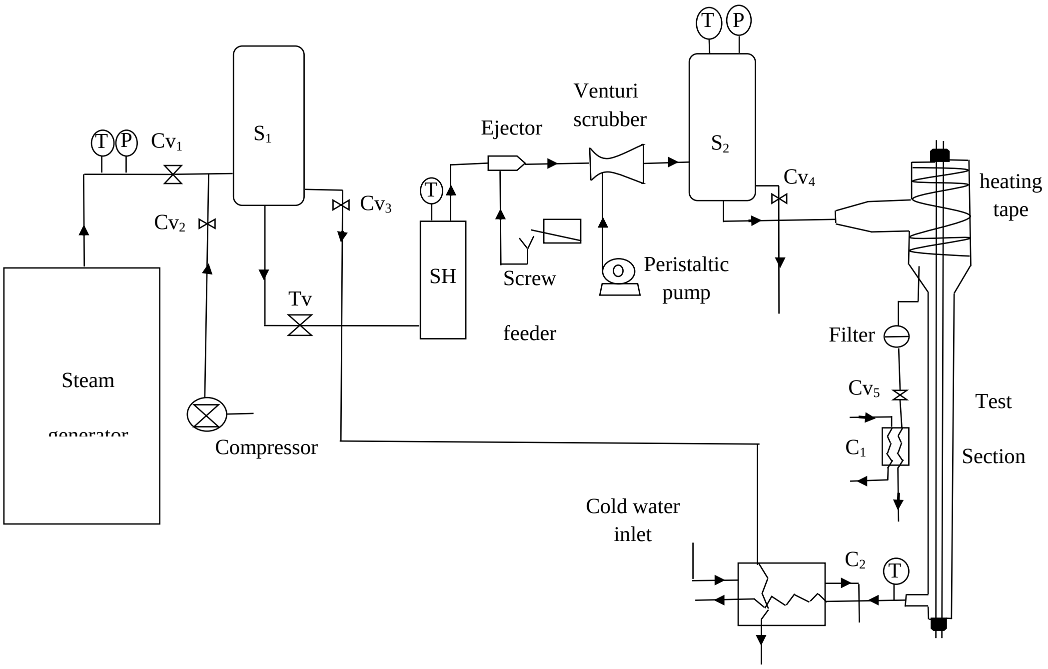


**Figure 3.** Schematic diagram of the experimental setup

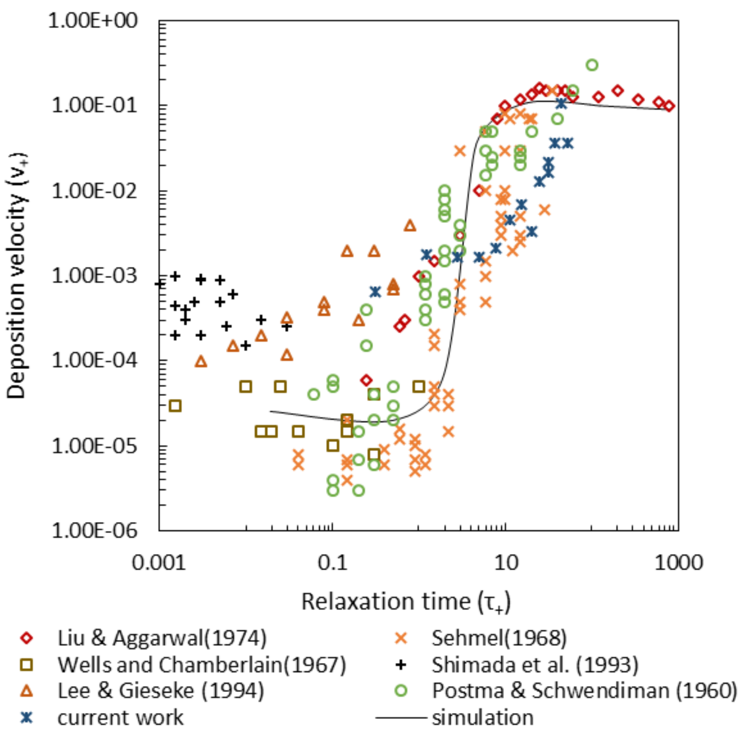


**Figure 4** Variation of non-dimensional deposition velocity with non-dimensional particle relaxation time

In the second phase of testing, experiments were carried out to measures the performance of salt solution in superheated steam. From literature studies it was concluded to use Potassium carbonate solution as a potential salt for superheated steam cleaning. The results of superheat obtained with different concentration are shown in figure below and discussed in literature [6].

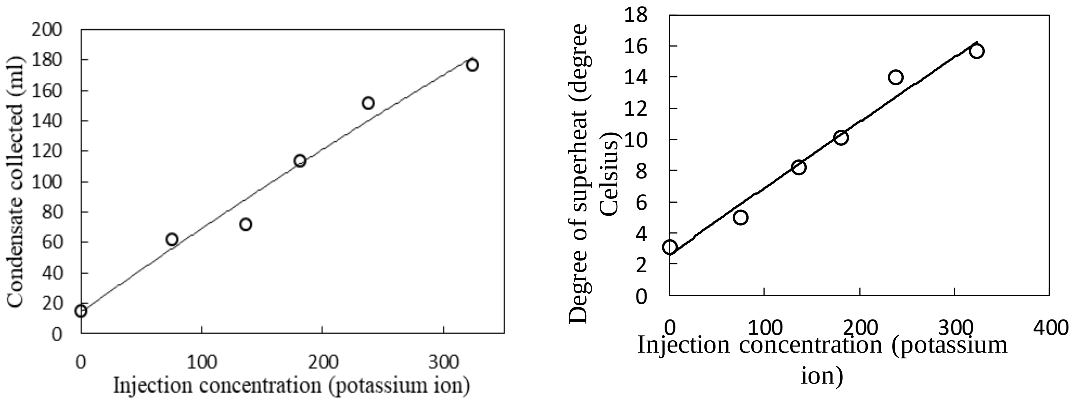


**Figure 5** Variation of Condensate collected and degree of superheat obtained for salt injection at different concentration

The experimental results show Potassium carbonate as potential option for the cleaning superheated steam. Experiment to measure scrubbing performance using Potassium Carbonate were carried out in the third phase of the experiment. Results of the analysed samples are yet to be obtained from Laboratory (ISOR).

Concluding the results of the experiments, following layout for the power plant with scrubbing unit is proposed for the superheated steam obtained deep drilling. The steam is assumed to be have chemical characteristic similar to IDDP-1 whose characteristics were taken as base of this work.

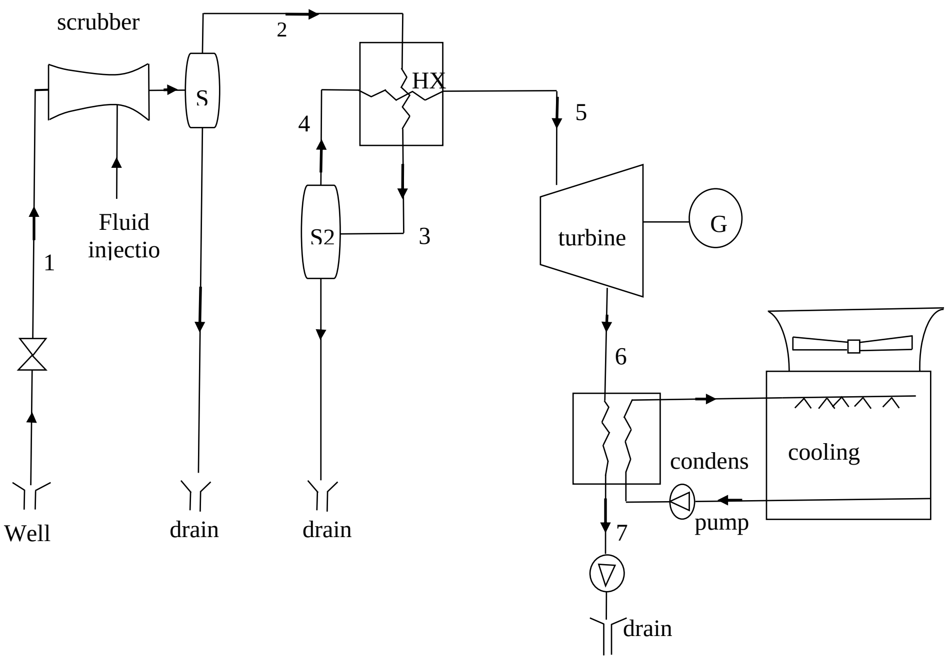


**Figure 6** Schematic of the proposed Cycle for superheated steam utilization

The overall acheivments of the work are summarised as:

1. Computaional solver development in OpenFoam applicable to superheated steam with silica present in dispersed phase.
2. Building up test facility for studying superheated steam and particle flow.
3. A Novel idea for cleaning superheated steam without exergy destruction applicable for superheated steam application.

# 3 Project Management

The project management followed a stepwise sequence such that outcomes from the previous step taken was made as a decision making criteria for the next step. The overall objective of the work defined was developing method for effective utilization of superheated steam obtained from deep drilling similar to IDDP-1. To start with the problem, thermodynamic analysis of the different power cycles using different scrubbing methods proposed in literature were done. Based on the results, power plant with heat recovery system was chosen as a base cycle for further development. In order to take economic aspects into consideration, thermoeconomic analysis for the different power cycles using scrubbing were also done. The study also concludes power cycle with heat recovery and wet scrubbing as an optimum option. Though the heat recovery system delivers better solution to the problem, the system however involved two major issues: loss of exergy due to wet scrubbing and scaling occurring due to silica precipitated from the gaseous phase present in superheated steam which could lower the thermal output with time. To overcome the exergy loss due to wet scrubbing, application of salt solution for scrubbing was proposed. Thermodynamic analysis were done for the comparison, showing improved efficiency. The next step decided was to study deposition process of silica present in superheated steam flow. To begin with, it was decided to do a computational study. The problem however came regarding lack of computational solver applicable for the current case. It was then decided to build up solver for study of such system which could be used in future for similar applications. OpenFoam, an open source software was used as a platform for the purpose. The model was developed and the computational results for air and particle flow showed consistency with that of experimental results from literature. Results of simulation for steam and particle flow gave very much insight of the different characteristics of particle and flow which control the deposition of particles on the wall. To verify, next step decided was to do experimental validation of the computational results obtained. In order to achieve this it was required to have a facility for testing superheated steam with particle flow such that different variables of the flow could be controlled as per the requirement. Due to unavailability of such facility around as per the knowledge of the project team members, it was decided to build up such facility in the University premises. A consideration was made with regard to the design of setup such that it should offer facility for other tests to be made with regard to scrubbing performance of salt solutions. The building however poses challenge with regard to the cost of setup. To overcome this, different possible components were borrowed from related companies. A complete setup was build fulfilling the required conditions for the experiment. The experiment was divided into three phases. Verification of computational results was done in the first phase of the experiment. The second phase of experiment involved studying salt solution droplets in superheated steam flow. The tests however required measurement of salt concentration from the condensate samples. Due to unavailability of testing facility required in the University, samples were analysed at ISOR. The final phase of the experiment consists of performance analysis of scrubbing using salt solution. Qualitative analysis shows good scope of utilization of such salt solution to scrubbing without losing superheat. Experiments for quantitative analysis were done and samples are under analysis.

# 4 Student involvement

*< if applicable, inform about the student involvement in the project. Are graduate students involved in the and in so what are their names and degrees?>*

Graduate Student: Vijay Chauhan

Degree: Master in Science, working towards a PhD.

Graduate Student: Tindur Jónsson

Degree: BSc, obtained MSc.

Graduate Student: Alberto Mereto

Degree: BSc, obtained MSc.

Graduate Student: Daniel Neil Caddy

Degree: BSc, has not finished MSc.

# 5 Publications and disseminations

[1] Chauhan V, Harvey WS, Saevarsdottir G. Chlorine mitigation for geothermal power plants using venturi scrubbers, ECRES – 4th European Conference on Renewable Energy Systems, Istanbul, TURKEY, 28-31 August 2016: 333-339.
[2] Mereto A, Gudjonsdottir M, Chauhan V, Saevarsdottir G. Thermoeconomic analysis of geothermal power cycles for IDDP-1 chloride mitigation, GGW 2016.
[3]Tindur Jónsson, "Corrosion Testing in a Simulated High Temperature Geothermal Environment" 60 ECTS MS. thesis submitted in partial fulfillment of a Magister Scientiarum degree in Mechanical Engineering at the University of Iceland, September 2015
[4] Mereto A, Gudjonsdottir M, Chauhan V, Saevarsdottir G. Thermoeconomic analysis of geothermal power cycles for IDDP-1 chloride mitigation, Masters Thesis, Reykjavik University, January 2016.
[5] Chauhan V, Gudjonsdottir M, Saevarsdottir G. Modelling deposition in superheated steam flow with silica in dispersed phase, GGW 2016.
[6] Chauhan V, Gudjonsdottir M, Saevarsdottir G. Silica particle deposition in superheated steam in an annular flow: Computational modeling and experimental investigation. (*To be submitted*)
[7] Chauhan V, Gudjonsdottir M, Saevarsdottir G. Computational modelling and experimental investigation of salt solution droplets in superheated steam. (*To be submitted*)

# 6 Cost statement

*<explain and justify the cost of the project, also fill in the GOERG - cost statement excel sheet provided by GEORG>*

The main costs inferred in the project were:

Salary of PhD student: 36 mm*400=14.400 kKr

Salary of MSc student: 9 mm* 300=2.700 kKr

Experimental costs:  1.320 kKr

Travelling costs: 2.580 kKr

Costs covered as in-kind funding from participants: 8.670 kKr