Improving Geothermal System Performance Through Collective Knowledge Building and Technology Development

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ABSTRACT

Despite years of experience with geothermal systems, the geothermal sector still faces a significant number of underperforming doublets, posing a strong limitation on a region's growth of geothermal energy utilization. A key operational challenge in geothermal energy production is restricted flow. Major obstacles for geothermal flow are scaling (mineral deposition), clogging (solid micro-particle deposition), corrosion and inefficient injection strategies. These issues result in high and mostly unforeseen costs for workovers, and additionally reduce production. In order to overcome these challenges, the consolidation and sharing of knowledge, including validated strategies for prevention and mitigation needs to be in place.

Based on experiences from operating geothermal sites within the EU, the project PERFORM will establish a single knowledge database containing information on operational, chemical and physical aspects of geothermal energy production. The database enables the sharing of experiences from operating geothermal doublets located in various countries and comparing the performance of the different geothermal reservoirs.

One of the tasks will focus on building and advancing predictive models that allow for pinpointing the most likely sources, location and causes of failure, as well as for injectivity improvement purposes. The integrated models will provide forecasts for scaling, productivity, and injectivity on short- and long- time scales, supporting early warning and planning of mitigation measures. Coupled thermo-hydro-mechanical-chemical (THMC) simulators will allow for evaluation of injection temperature on flow and energy output.

Data and knowledge gathering and technology demonstration is planned for eight geothermal plants across Europe. Demonstration of new and improved, cost-effective technologies will allow for the reduction or even elimination of flow-obstructive scaling, clogging, and resistance to fluid (re-)injection. The technologies include low-cost cation/metal extraction filters, self-cleaning particle removal appliances, H_2S removal technology, corrosion management and soft-stimulating injection procedures (thermal and CO_2-injection).

The PERFORM project will integrate the knowledge database, predictive modelling and advanced technologies into a design and operation toolbox, which will be tied to economical calculations. The toolbox will enable stakeholders and specifically geothermal operators to plan future operations, mitigate existing obstructions, and optimise production/injection procedures, to ensure maximum energy production.

1. INTRODUCTION

In many geothermal plants both productivity and injectivity decline over time. One of the main reasons for reduced injectivity is clogging the reservoir rock pores thus reducing the permeability (Gallup, 2009, Hesshaus et al., 2013, Blöcher et al., 2016). Moreover, the overall performance of a geothermal plant decreases if clogging occurs in other parts of the installation such as the production and injection wells, pipes, or on the heat exchanger. The clogging material may be either particles from the reservoir, mineral precipitation (scaling), or corrosion products. Suspended particles additionally may cause erosion corrosion (Corsi, 1986).

Mineral scaling in the reservoir is reported to occur in geothermal systems under a wide range of temperature and chemical conditions and may involve precipitation of carbonates, silica, metal compounds (oxides, hydroxides, sulphides, sulphate) and clays (e.g. Regenspurg et al., 2010). Research on selective induced

precipitation by the injection of fluids highlights the potential to control chemical reactions in the reservoir (Nasr-El-Din et al., 2004, Wasch et al., 2017). A recent review article on “Operational issues in Geothermal Energy in Europe” (Schreiber et al, 2016) addressed the operational barriers caused by scaling, corrosion, gas content and poor injectivity, stating that there is still a lack of solutions. Finding solutions for increasing the injectivity by preventing clogging and promoting good permeability at the injection side, significantly reduces operational costs by decreasing shut-down times for cleaning and filter changes. It also ensures the longevity of a geothermal plant by preventing reservoir damage. All these aspects add high value to the operation of geothermal plants.

Several methods are known to avoid or mitigate injectivity/productivity problems: (i) particles can be filtered out, the precipitation process can be hindered either by (ii) adding chemicals (such as inhibitors) or (iii) by removing part of the chemical reactant from solution. Further (iv), corrosion induced precipitation could be avoided by selection of corrosion resistant materials, and (v) the reservoir performance on the injection side can be optimized by various fracking and stimulation techniques such as acidification. There is a common need to evaluate and improve methods that avoid the application of large amounts of chemicals as well as reservoir fracking, and instead promote simple low-cost filtration and soft-stimulation techniques.

2. INNOVATIVE TECHNOLOGIES

The project PERFORM focusses on developing and using new and improved technologies to prevent scaling and damage to the geothermal reservoir. In the following section, we introduce a range of technologies and methods according to their current status and innovation potential.

2.1 Particle filters

For removing particles either filter bags or cartridges are commonly used at most geothermal sites in Europe. However, filter changes cause a lot of expensive down-time of the geothermal plant. Although self-cleaning filters are commercially available they are generally not purpose fit for geothermal application and create large amounts of waste water. For particle removal, the self-cleaning, cost-efficient particle filter systems (AMIAD-AMF and HydroGeoFilt) will be advanced towards geothermal utilization by deploying them in a side-line at geothermal sites. The filters will reduce operational costs by having less shut-down times for cleaning and replacing while at the same time diminishing or avoiding wastewater**.**

2.2 Cation filters

The innovation is to selectively remove problematic elements from the thermal water, rather than using large amounts of costly and potentially environmentally harmful substances to reduce scaling. In geothermal plants located in the Permian Basin (North Germany, Belgium, Netherlands, Denmark) or in the Upper-Rhine Valley, carbonate-, sulphate- and various metal scaling occurs in different plant stages (Eggeling et al., 2013, Regenspurg et al., 2015, Wanner et al., 2017). Precipitation occurs due to oversaturation of certain salts due to changes in the chemical equilibria. Since salts are composed of a cationic and an anionic part, uncontrolled precipitation can be avoided if the cation (often a heavy metal) is removed from the solution by a sorption technique down to concentrations below mineral saturation. Commercial polymer-based ion exchange technology (e.g. Dow, Mitsubishi) is expensive and is not tailored to geothermal brines. Various sorption techniques are known from groundwater purification or from scientific studies but have never been applied at geothermal conditions (e.g. Bailey et al., 1998). Based on those reviews, three types of materials, all well known for their high sorption capacity for heavy metal removal (Zeolites, Chitosan, Fe-oxides) and major cation removal (FACT) are selected:

- Zeolites: Mineral group of natural or synthetic highly porous, hydrated alumosilicates with net negative charge and exchangeable cations suitable especially for removing heavy metals (Erdem et al., 2004).

- Chitosan: Chitosan is a bio-based sorbent obtained by deacetylation of chitin (poly(β-(1→4)-N-acetyl-D-glucosamine), which can be derived from shells of crabs and shrimp and which is the second-most abundant polymer in the world. Studies have shown a large capacity for cation adsorption, especially for heavy metals (Çelik et al., 2017; Bailey et al., 1998). By electrospinning chitosan fibre mats, this material can be synthesized with extremely large surface areas and thus used as adsorptive filter material suitable for geothermal application (Çelik et al., 2017).

- Magnetic iron oxide nanoparticles: Iron oxides are known for their high surface area and adsorption capacities for both cations and anions (Cornell and Schwertmann, 2001). Different iron nanominerals are used for water purification in waste water treatment (Xu et al., 2012). Magnetic iron oxides (e.g. magnetite Fe_3O_4) are of special interest for geothermal application since they can be easily magnetically separated (Dave and Chopda, 2014).

- FACT Filter: The formation of calcite represents a major problem at many geothermal sites. For the removal of Ca^{2+} the Filtration Assisted Crystallization Technology (FACT) has already been developed and patented by TNO (PCT/NL2004/000709). FACT is a hybrid process based on heterogeneous crystallization and filtration. FACT has the potential to be cheaper and more efficient than conventionally available water treatment technologies. FACT has been tested in pilot plant experiments at industrial ground- and process water streams at a scale of up to 5-10 m^3/hour and the method has been applied at temperatures up to 60 °C.

2.3 H_2S removal by flocculation

Flocculation (controlled precipitation) combined with filtration can be used to remove unwanted components from thermal water. One component that represents a problem in many geothermal sites such as in the Molasse Basin is the toxic and corrosive gas hydrogen sulphide (H_2S). A new and promising technique of H_2S removal is via addition of Fe(II) chloride. The reaction between Fe(II) and sulphide resulted in the precipitation of pyrite (FeS_2) that can be readily removed from the fluid by above ground particle filtration. This technique has already been successfully applied in biogas treatment (Dezham et al, 1988) and has proven to be feasible in pilot at geothermal sites. Monitoring and quantification is necessary to characterize the reaction precisely and enable full deployment of the technique.

2.4 CO_2-(re)injection and pH control

Rather than diverting to harsh reservoir fracking to improve injectivity the innovation is to utilize gentle and low-cost techniques to overcome low injectivity and reservoir scaling such as low-concentration CO_2-(re)injection. CO_2-(re)injection will be tested site-specifically and systematically on reservoir rock both off- and on-site.

CO_2 is commonly degassed in the surface installations of geothermal doublets together with methane and other gaseous hydrocarbons (Veldkamp et al., 2014). The degassing of CO_2 changes the pH and leads to precipitations of scales (mainly $CaCO_3$). By dissolving CO_2 in the brine, the gas partly dissociates forming hydrocarbonic acid. This shifts the pH value of the brine to lower values and therefore CO_2-(re-)injection can prevent $CaCO_3$ precipitation and may even allow carbonates to dissolve in the well-near region thus increasing the injectivity of the well. Models on CO_2 degassing during production have indicated a high scaling potential, specifically $CaCO_3$ scaling (Wasch 2014, Alt Epping et al., 2013). The high scaling potential within doublets due to gas release as observed especially in the Netherlands, highlights the possibilities of preventing scaling and enhance injectivity via CO_2 (re)-injection. Although numerous experiments and studies have been performed on CO_2 injection, they have focused only on high concentration CO_2 injection for CO_2 storage purposes (Randi et al., 2017). The work in PERFORM will focus on dissolved CO_2 injection.

2.5 Injection temperature optimisation

Soft stimulated enhanced injectivity can be obtained by injecting a cold fluid in the relatively hot reservoir. Pressure and temperature changes due to the cold-fluid injection may cause (re-)opening of flow paths (fractures) and hence the injectivity enhancement. Meanwhile lowering of the reservoir fluid temperature during cold-fluid injection may enhance scaling and induce seismicity (Wassing et al., 2014; Candela and Fokker, 2017). The injection of cold water should therefore be performed by monitoring changes in the chemical composition of the injection water and by modelling of the underlying thermo-hydro-mechanical-chemical (THMC) processes in the reservoir to make better forecasts. Injection temperature reduction has already been attempted at the Honselersdijk geothermal site with promising results and will be further tested in laboratory experiments and field tests.

2.6 Corrosion tests – Galvanic corrosion and CO_2 corrosion

Electrochemical or galvanic corrosion and specifically the reaction of carbon steel casing with either dissolved Pb or Cu can result in the formation of massive native Cu or lead precipitation as observed in Groß Schönebeck (Germany; Regenspurg et al., 2015) or at Danish (Mathiesen et al., 2018) and Dutch sites. This kind of clogging can be avoided by selecting higher alloyed casing materials that do not cause a reduction reaction of dissolved heavy metals. Moreover, better understanding of the corrosion mechanisms of carbon steel can possibly solve problems in existing plants. Clogging by corrosion products may be caused by reactions with noble elements (Pb or Cu). On the other hand, corrosion may also be caused by less complex mechanisms that are easier to handle when identified, such as oxygen ingress, CO_2 corrosion or inappropriate surface condition of the supplied steel casing. Thus, a variety of measures can be taken to control corrosion, including material upgrading, applying corrosion inhibitors, optimising operational conditions or simply enforcing stricter requirements to casing materials.

3. PROJECT METHODOLOGIES

The project PERFORM will establish a single and shared knowledge database, build predictive models and demonstrate new and improved, cost-effective technologies which will reduce or even eliminate flow-obstructive scaling, clogging, and resistance to fluid (re-)injection at eight geothermal plants across Europe. The applied methodologies are described in the following sections.

3.1 Geothermal database

A large amount of data and in-depth knowledge resides with individual operators across Europe for a range of geothermal reservoir types. The goal is to develop a knowledge base that integrates the geological, geochemical, geomechanical and operational data from underperforming doublets (and when available from well-performing doublets for comparison), by aggregating the data and experiences at supra-national level. The database enables sharing the experiences from operating geothermal doublets located in various countries and comparing the performance of the different geothermal reservoirs.

Figure 1: Flow-through apparatus FluMo-2 (left) and mobile bypass (right) for off- and on-site tests and demonstrations.

Several chemical and physical data will be collected from seven geothermal demonstration sites Pijnacker Nootdorp (NL), Honselersdijk (NL), Gross Schönebeck (DE), Insheim (DE), Oberlaa (AT), Thisted Varmeforsyning (DK), Sønderborg Fjernvarme (DK) and Margretheholm (DK). Based on the collected data, a user-friendly database will be built along with a web application. The likely inhomogeneous datasets will be systemized, validated and stored adequately using a relational database created as a PostgreSQL database. PostgreSQL will be fitted with the PostGIS extension. The database will be included in the EGDI (EuroGeoSurveys' European Geological Data Infrastructure) system to ensure that the data still are accessible after the PERFORM project has ended. It is the intention that the database shall serve as a catalogue for new geothermal plants, where possible problems and mitigation actions can be studied in the planning phase prior to investing in the expensive establishment of boreholes and topside equipment. This will ensure the best possible investment plan and reduce planning costs.

3.2 Models

The key to enabling long-term doublet performance is predictive modelling of thermo-hydro-mechanical-chemical (THMC) processes affecting injectivity and scaling. Predictive models enable pinpointing the most likely sources and causes of failure, as well as the possibilities for injectivity improvement. Existing models for the reservoir, wellbore and top-side facilities need to be coupled and populated with actual data. The objective is to advance the models towards a readiness level that can provide realistic predictions of injectivity and provide the required input parameters to facilitate the choice of standard versus new mitigation measures. The integrated models will provide predictions for scaling, productivity, and injectivity on short- and long- time scales, supporting early warning and planning of mitigation measures. An example of how the integrated model could provide insights in controlling and optimizing the operation of doublets is shown in Wasch et al. (2019).

Numerical modelling will be applied to study the technologies of CO_2-(re)injection and pH control and cation filters and their chemical effect in the geothermal installation and chemical/mechanical effect in the reservoir. Predictive numerical modelling using geochemical codes (PHREEQC v3, Parkhurst and Appelo, 2013; TOUGHREACT, Xu et al., 2006), wellbore models (OLGA, LedaFlow), mechanical software (FLAC3d) and coupling codes (TOUGHREACT-Flac3, Gan and Elsworth, 2016) will be performed to constrain and support the interpretation of the results of the laboratory and field experiments. The most suitable thermodynamic databases for the actual problem in hand will be chosen based on a benchmark modelling study that also facilitates a qualitative assessment of the uncertainty of the model results.

3.3 Experiments and field tests

Demonstration of new/improved, cost-effective technologies is paramount to enable reduction or even elimination of flow-obstructive scaling, clogging, and resistance to fluid (re-)injection. Experiments are performed for the different technologies including both batch and flow loop set-ups. New technologies to prevent scaling or particle clogging (cation and particle filters, CO_2 re-injection) and thermal stimulation need to be tested and demonstrated at actual geothermal sites. The technologies are applied in bypasses at geothermal systems under continuous monitoring. To provide insights into possible geochemical effects when modified brine depleted in cations is injected into the reservoir, laboratory experiments will be conducted. The effect on the reservoir quality of applying the different cation removal filters will be tested. A series of laboratory core flooding experiments will be conducted at reservoir conditions using state-of-the-art equipment.

The project consortium possesses a range of experimental equipment that allow for off- and on-line filter tests and demonstrations. The flow-through fluid monitoring apparatus FluMo-2 was specifically

developed at GFZ for simulating and monitoring reactions of a fluid and material interactions under near-geothermal conditions (Fig. 1). The mobile bypass has been developed and constructed by Hydroisotope and can be easily transported and connected to different geothermal sites.

3.4 Operational advice toolbox

Ultimately, optimization of production and injection procedures is necessary at demonstration sites to ensure a maximum energy production when needed. An investigation into injection temperature decrease is necessary, as it would create more energy output and improve cost-effectiveness. A workflow will be developed to show the usage of integrated models to provide operational decision supports. Operational advice needs to be tied into a toolbox and take into account economical calculations for field cases.

The economic performance of a doublet will be assessed using DoubletCalc-GeoElec tool that calculates the cashflow and economic performance in terms of Net Present Value (NPV), delivering the LCOE over the full lifetime of the doublet (Fig. 2). The necessary inputs for the tool: (i) a set of parameters containing the major reservoir quality parameters, (ii) a simplified well design and (iii) doublet and pump properties, will be taken form the geothermal sites involved in this project.

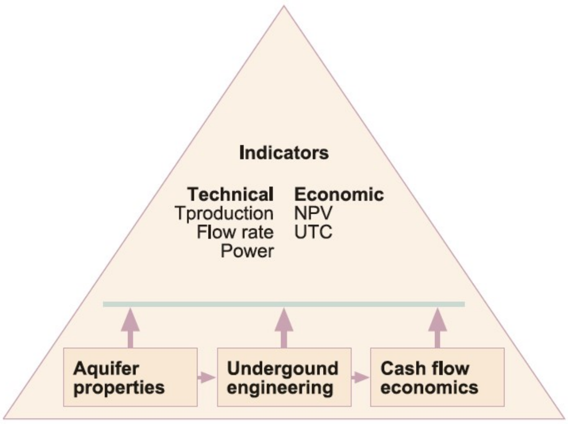

Figure 2: Integrated value-chain model capable of assessing the impact of uncertainty in technical and economic parameters based in key performance indicators.

4. SUMMARY AND OUTLOOK

The overarching target of PERFORM is to improve geothermal system performance, lower operational expenses and extend the life-time of infrastructure by the concept of combining data collection, predictive modelling, innovative technology development and in-situ validation. The targets are:

- To create a collective knowledge database, enabling efficient evaluations of the causes for poor flow and injectivity;
- To develop integrated models providing forecasts for scaling, productivity and injectivity on short- and long- time scales supporting early warning and planning of mitigation measures;
- To develop innovative technologies to prevent site-specific scaling, clogging and enhance injectivity, including an evaluation of injection temperature that apart for increasing flow will also increase the energy output;
- To optimise production and injection procedures at demonstration sites, thus ensuring maximum energy production on demand by proving a design and operation toolbox for the operators.

The outcomes of the project will include a set of best practice guidelines for cost-effective flow optimization in geothermal doublets, which will be shared with all geothermal operators. The optimizations will potentially increase the energy output by ~30 % and would thus result in accelerated growth of geothermal energy production.

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