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Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource – The H2020 SURE Project

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ABSTRACT

Within the EC funded Horizon 2020 project SURE (Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource) the radial jet drilling (RJD) technology is investigated and tested as a method to increase performance of insufficiently performing geothermal wells. Radial jet drilling uses the power of a focused jet of fluids, applied to a rock through a coil inserted in an existing well. This technology is likely to provide much better control of the enhanced flow paths around a geothermal well and does not involve the amount of fluid as conventional hydraulic fracturing, thereby reducing the risk of induced seismicity considerably. RJD shall be applied to access and connect high permeable zones within geothermal reservoirs to the main well with a higher degree of control compared to conventional stimulation technologies. We investigated the technology over various spatial and temporal scales ranging from short term laboratory experiments to field scale applications. Here we give an overview about our work.

1. INTRODUCTION

In recent years, many sites have been explored and investigated for their suitability of an economic energy provision from geothermal heat. One major showstopper for the use of geothermal resources is the risk of a low-productive well, especially in low and medium enthalpy reservoirs but also in high enthalpy reservoir rocks (e.g., fracture or karst reservoirs) where the permeability distribution is often strongly heterogeneous. In order to increase the number of economically viable wells at such sites, the technology of enhancing a geothermal reservoir has been considered. Hydraulic or acid stimulation techniques adapted from the oil and gas industry have been applied to improve the performance of such enhanced or engineered geothermal systems (EGS) (Blöcher, 2012). It is obvious from developing EGS (Schindler, 2008) and magmatic (Valdez-Perez, 2014) systems that tapping into highly permeable zones like fracture systems (van Oversteeg et al., 2014) is generally key for achieving high flow rates. Sufficiently high flow rates have been reached by hydraulic stimulation technologies, which proved to be successful in establishing initial productivity increases (e.g., Zimmermann, 2010). The sustainability of EGS systems, however, remains to be proven. Another critical issue with hydraulic stimulation treatments results from the large amount of fluids injected to tap into high permeable zones. These injections may cause seismicity (e.g., Häring, 2008), which is mostly deemed unacceptable by the public. In addition, fluid volumes flowing back from the well after the stimulation have to be properly handled and disposed.

Another way to increase the productivity of a well is to drill multiple laterals from a single mother well bore (e.g., Bosworth, 1998). Multilaterals by conventional drilling are often done in the oil and gas industry and eventually combined with hydraulic stimulation treatments. Multilateral drilling, however, is usually too expensive for geothermal projects. In order to overcome this limitation, coiled tubing conveyed jet drilling assemblies have been investigated for multilateral drilling in geothermal reservoirs (e.g., Finsterle, 2013; Kolle, 2009). Until December 2014, although tested at the surface, such approaches have never been applied downhole within a geothermal project in Europe. Within the SURE project, the radial jet drilling (RJD) technology (e.g., Cinelli, 2013) was investigated and tested for a sustainable and efficient productivity enhancement in low productive geothermal wells. Radial water jet drilling uses the power of a focused fluid jet, which is capable of drilling multiple laterals of up to 100 m length out of the main well and thereby stimulating the well with full control on the operational parameters like initial direction of the lateral, length, fluid pressure. In contrast to hydraulic stimulation treatments, this technology can potentially provide a network of enhanced fluid pathways around a geothermal well to intersect with existing high permeable structures like fracture or karst systems within the reservoir, independent of the ambient stress field.

For RJD, a workover rig will install a 2 7/8” tubing with a 100 m 2 3/8” tailpipe to which a deflector tool (Figure 1, left) with decentralising springs is attached to the desired depth. Including a gyro service, the deflector tool can be oriented in the desired direction within the mother well. Through this tubing, a mini coil (1/2" Coiled Tubing) will be run to the depth of interest. Using the installed deflector tool, a 1" milling bit on a flexible chain attached to a positive displacement motor will create a first exit by milling a hole into the existing casing (Figure 1, left). Afterwards, the mini coil will be retrieved from the wellbore. In a second step, a 100 m long flexible high pressure hose will be run into the wellbore on the mini coil. This hose will exit the well through the previously created hole. By pumping water into this hose at a high pressure, the water exiting the hose through specially designed nozzles of very small diameter will deconsolidate the formation and create an open-hole lateral with a diameter of about 1-2" perpendicular to the wellbore (Figure 1, right).

Compared to conventional hydraulic stimulation treatments with required fluid volumes of more than 1000 m³, only a fraction of the fluids is needed for RJD (< 10 m³). Thereby the environmental risk as well as the risk of induced seismicity is considerably reduced (Blöcher et al., 2016).

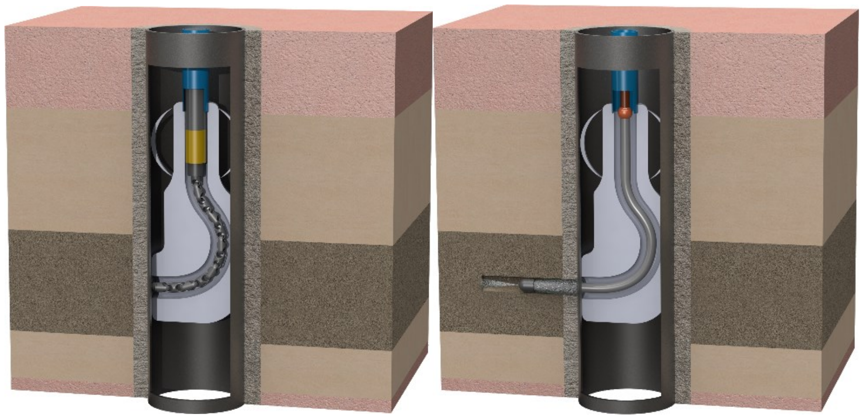

Figure 1: Deflector shoe with milling assembly to mill a hole into the casing (left) and deflector shoe with jetting assembly to jet into the casing (right). Reproduced from Reinsch & Blöcher 2016.

Within the SURE project, the RJD technology was systematically investigated and thoroughly tested for the application in different geothermal reservoir rocks, including hard rocks and high enthalpy reservoirs. For the different geothermal reservoir rock types, a specification of the parameters characterizing and controlling the jettability (i.e. the potential to drill a hole by the jetting approach) of the rock will be performed for the applied technical equipment. To qualify the technology for geothermal reservoir rocks in different geological settings such as deep sedimentary basins or regions with igneous host rocks, the jetting technology was investigated, eventually adapted, and tested at the micro- (µm-dm), meso- (dm-m) and macro-scale (m-km).

2. MICRO-SCALE

Rock physics measurements in the laboratory were performed to systematically investigate the dependency of the jettability of the rocks on their physical properties. The properties determined include elastic moduli, porosity and permeability and their dependence on (fluid) pressure and temperature (Bakker et al., 2019). To compare the properties of fractures generated by hydraulic stimulation with a well stimulated by RJD, several experiments were performed. A Punch-Through Shear (PST) was designed and demonstrated to characterize hydraulic-mechanical properties of fractures at laboratory scale (microfault) (Kluge et al., 2017a,b, 2019). From this test, major findings were that (1) permeability increases by faulting strongly dependent on rock type (0 to 3 orders of magnitude in sandstones and granites, respectively), (2) permeability of microfaults shows similar sustainability compared to displaced tensile fractures during effective pressure changes and (3) permeability in fractured sandstone cannot be fully recovered by pore pressure increase (Kluge 2017 a,b; Blöcher et al., 2019a, b). In addition, the stability of laterals in the simulated in-situ stress field were measured in the laboratory (Bakker et al., 2017, Medetbekova et al., 2018, Medetbekova et al in review a)). For a sandstone sample, it was found that the near-wellbore/lateral rock, was not damaged by the jetting process and that the lateral stability can be simplified using the Kirsch equation (Bakker & Barnhoorn 2019). For a chalk sample jet drilled with acid (15% HCl), near-wellbore rock showed damage up to about 4 cm radius surrounding the lateral hole, further away the damage gradually vanishes (Medetbekova et al. in review b). Moreover, numerical study on the lateral borehole stability showed that once the borehole is drilled, it can sustain the in-situ stress field; however the long term stability depends on the pressure decline rate around the wellbore (Medetbekova et al. 2017, Medetbekova et al. 2018). The results of these measurements are compared to the basic physical properties of the rocks to investigate predictive correlations.

3. MESO-SCALE

Rock blocks large enough to be jetted with real scale jetting technology were collected for testing in the laboratory. Material from the same blocks was also used for the microscale experiments. That way the active jetting experiments performed under ambient (Hahn and Wittig, 2017) as well as in-situ reservoir conditions (Hahn et al., 2019) can be related to the microscale investigations and to the basic rock properties determined at the smaller scale. Similar to results from literature, it was found that jet-drilling without acid works best on sedimentary rocks with a high porosity (Hahn et al., 2019). For hard rocks, e.g. basalts, high pressures need to be delivered to the jetting nozzle (Hahn et al., 2019). Jetting experiments were also performed under differential stress conditions inside a true-triaxial cell. It was found that applying differential stress does not increase the rate of penetration (ROP) compared to experiments under atmospheric and hydrostatic pressure conditions. However, comparing jetting into and perpendicular to the direction of the main horizontal stress shows that ROP values are highest into the direction of the highest stress for the investigated sandstone samples (Hahn et al. 2019). Based on the learnings from this work, different jetting and bit designs were tested and designed to overcome current limitations in the jettability of harder rock types (Gradzki et al. 2019). Another integral part of meso-scale investigations is a drilling experiment in a quarry, where a special logging tool was developed and applied to measure the laterals geometry as well as seismic acquisition during the jetting activity was investigated (Reinsch et al., 2018).

4. MACRO-SCALE

Finally, RJD was analysed for a field application in Klaipeda, Lithuania. A limited productivity increase was observed for this experiment (Nair et al., 2017, Petrauskas et al., 2017). A second experiment was performed in Iceland. These field tests were planned to serve to validate and improve the model predictions made on the basis of laboratory testing. The experiment in Iceland was performed in early summer 2019. Although the final evaluation of the field experiment was not finished when writing this contribution, it can be said that the field test did not show improvements of inflow into the well. The reason is partially due to difficulties with the jetting equipment during the operation. Further tests are needed to extend the RJD technology to stimulate geothermal wells in magmatic environment where hard rock formations are found. The project results show that high pressures generating high exit velocities at the jetting nozzle are needed in order to penetrate basalt, one of the main rock type found in Iceland (Hahn et al., 2019). Furthermore, a method for mapping drilled laterals would give confidence and feedback for targeting during jetting operations (Kaldal et al., 2020).

5. INTEGRATION

Conceptual models to simulate the experimental results at all scales investigated play a key role in the interpretation and understanding of the experimental results and of the RJD technology in general (Xiang et al 2019). Specific numerical tools were developed to simulate the rock destruction process at the grain scale, taking into account the physical parameters and properties determined in the laboratory (Chen et al 2019). Two main rock breakdown and erosion mechanisms were identified: a) pressure fluctuations in front of the nozzle introduce a water hammer effect creating shock waves at the rock-fluid interface weakening the inter-grain joints. b) a water driven bursting effect suggesting that fluid driven into the pore space close to the rock-fluid interface leads to a bursting of the grain cementation/bonding of the surrounding pores (Xiang et al. 2019). Although it was found that the Kirsch equations are suitable to assess the lateral stability in a first approach, such results might be too simplistic to take into account progressive deformation and stress redistribution effects (Latham et al., 2019). Based on the model results, a safe window for orienting the laterals within the ambient stress field was investigated for different stress regimes (Latham et al., 2019).

To assess the performance increase from an RJD stimulation, flow models were developed for the connection between lateral and reservoir (Salimzadeh et al, 2018a, 2018b; Peters et al, 2018, 2019a, 2019b, Egberts and Peters, 2019). From the models, it was e.g. concluded that the RJD laterals can be very effective in enhancing injectivity/ productivity and/or heat production from the fractured reservoirs. The best performance of the RJD laterals in enhancing injectivity/productivity was observed in low fracture density cases in which the main wellbore was not directly connected to the fractures. In the high fracture density case, the RJD laterals can be effective in heat production by providing access to the hot rock. In low permeability reservoirs where the flow mainly occurs through the fracture network, the RJD laterals should connect to the fracture network in order to be effective (Salimzadeh et al., 2019). In addition, results for the net energy production rate showed higher sensitivity to the lateral lengths in low fracture density cases and in cases where the well was not connected to the fractures. The laterals can in principle remove the dependency of the net energy rate to the position of the wells with respect to the fractures by creating direct connections between the wells and the fractures (Salimzadeh et al., 2019). In order to gain the best performance of laterals in fractured reservoirs it is important to direct RJD laterals in the direction outside the area between the injection and production wells aiming at enhancing the effective volume of the reservoir (Torres et al., 2020).

For accurate simulation of the radial well configuration in reservoir scale simulators, the upscaling of the well modelling was investigated and accuracy of the simulation evaluated by comparing to semi-analytical solutions. With correct representation of the well in the well model and sufficiently fine grid (5-10 m), accurate simulation of the radial well was possible in reservoir scale simulation. These models were used to estimate the performance in sedimentary formations. Increase in well flow due to stimulation with radials was found to be best in cases were the orientation of the original well was poor with respect to the anisotropy in the permeability. To arrive at realistic estimates of flow increase, several aspects of the radial flow were investigated in more detail. It was found that including the uncertainty in the lateral path which is quite large because the radials are not steered, is important to take into account. This is especially true in thin reservoirs and layered reservoirs. Also important is the flow inside the laterals. Because the laterals have a small diameter and flow rates are high in geothermal applications, pressure drop in the laterals should be accounted for planning the radial well design. In complex reservoir, the radial well design has plenty of scope for optimization. The optimization problem is challenging though, because of the discrete variables and the many sources of uncertainty to include.

Based on the results from the reservoir simulations, strategies to optimize the lateral placement, taking into account the cost for the jetting operation as well as the reservoir geometry were developed (Peters et al, 2019c).

6. CONCLUSION

From the laboratory experiments at the micro- and meso-scale, a conclusive data-set could be generated for mechanical and hydraulic rock properties of geothermal reservoir rocks. Also, data to compare hydraulic stimulation techniques with the radial water jet-drilling stimulation technology was gathered. The jetting experiments helped to understand the underlying rock destruction mechanism acting during radial water jet drilling in porous rocks. For hard and low porosity rock formations, water jet drilling is still possible if jetting pressures are sufficiently increased. As this is difficult with the current state-of-the-art jet drilling equipment, especially the pressure rating of the flexible hose, different jet-assisted drilling technologies and nozzle designs were investigated and tested.

A major concern when assessing the performance increase due to a radial jet drilling stimulation is the geometry of jetted laterals. To assess the geometry, we successfully tested a small diameter sensor in the quarry. It proved possible to flush the memory sensor into existing laterals using backwards directed nozzles only. Unfortunately, this sensor could not be tested in the field application. From the geometry data of the quarry it was seen that the lateral path can be very curvy. In the quarry, we found fractures with apertures up to 3 cm and a very heterogeneous lithology that heavily influenced the lateral path. Although the conditions in the quarry cannot be translated to downhole conditions, it is advisable to stabilize the jetting bit to increase the chances of a far reaching lateral.

The uncertainty in the lateral path, lateral stability and pressure drop in the laterals need to be taken into account when assessing the benefits from a radial jet drilling operation. A too simple simulation approach leads to a gross overestimation of what can be achieved with laterals. Although RJD is an innovative stimulation technology with a high potential for geothermal applications, it has still some technical challenges that need to be addressed in future work.

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