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Multiple Fracture Stimulation Treatments to Develop an Enhanced Geothermal System (EGS) - Conceptual Design and Experimental Results

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ABSTRACT

Enhanced geothermal systems (EGS) are engineered reservoirs developed to extract economic amounts of heat from low permeability and/or porosity geothermal resources. To enhance the productivity of reservoirs, a holistic concept is necessary to actively make reservoir conditions from profitable using specially adjusted stimulation treatments, such as multi fracture concepts and site specific well path design.

The results of previously performed stimulation treatments in the geothermal research well GtGrSk4/05 at Groß Schönebeck, Germany are presented. The reservoir is located at a 4100-4300 m depth within the Lower Permian of the NE German Basin. The reservoir rock is classified by two lithological units from bottom to top: volcanic rocks (andesitic rocks) and siliciclastics ranging from conglomerates to fine grained sandstones (fluvial sediments). The stimulation treatments included multiple hydraulic stimulations and an acid treatment. In order to initiate a crossflow from the sandstone layer, the hydraulic stimulations were performed in different depth sections (two in the sandstone section and one in the underlying volcanic section). In low permeability volcanic rocks, a cyclic hydraulic fracturing treatment was performed over 6 days in conjunction with adding quartz in low concentrations to maintain a sustainable fracture performance. Flow rates of up to 150 l/s were realized, and a total of 13170 m³ of water was injected. A hydraulic connection to the sandstone layer was successfully created in this way. However, monitoring of the water level in the offsetting well EGrSk3/90, which is 475 m apart at the final depth, showed a very rapid water level increase due to the stimulation treatment. This can be explained by a connected fault zone within the volcanic rocks. Two gel proppant treatments were performed in the slightly higher permeability sandstones to obtain long-term access to the reservoir rocks. A total of 100 tons of high strength proppants were injected with 500 m³ of cross-linked gel. The subsequent production test in conjunction with flowmeter logging showed an improvement of productivity by a factor of more than 4. Due to assumed residual drilling mud (constituents: calcite, dolomite, aragonite) in the near wellbore vicinity, an acid stimulation was performed using a coil tubing unit. The following nitrogen lift test demonstrated another increase of productivity by 30 – 50%.

1. INTRODUCTION

Reservoir engineering is a key issue in the development of geothermal technology. Optimum economic utilization of reservoirs can be achieved with profound analysis of the geological system and adequate planning (including reservoir modelling), and understanding of the processes and interaction of the “borehole – reservoir” system. This is based on the long experience of the oil- and gas-industry, which should be directly transferable to geothermal exploitation (Baria et al., 1999; Tester et al., 2006; Falcone & Teodoriu, 2008).

Conventional geothermal resources cover a wide range of uses for power production and direct use under profitable conditions. A large scientific and industrial community has been involved in developing Enhanced Geothermal Systems (EGS) in unconventional reservoirs in the last 20 years (e.g. Gérard et al., 2006; Calcagno & Sliaupa, 2008). This concept involves different tracks for enlarging access to heat at depth by improving exploration methods, drilling and reservoir assessment technology for deep geothermal resources, and the stimulation of low permeability reservoirs.

Stimulation treatments must be performed to enhance the productivity of low permeability geothermal reservoirs by inducing artificial fluid pathways. Several concepts of stimulation treatments have been developed to enhance the existing productivity (e.g. Economides & Nolte, 2000), which can be summarized by the terms hydraulic fracturing (Sharma et al., 2004), thermally induced fracturing (Charlez et al., 1996) and chemical/acid stimulation (Nami et al., 2008). In hydraulic stimulation experiments, fluids are injected under high pressure into the rock to generate new fractures or extend existing fractures. These hydraulic fracturing stimulations can be categorized as waterfracs, gel-proppant fracs, and a combination of both called hybrid fracs (Sharma et al., 2004). The procedures are well known in the hydrocarbon industry (Shaoul et al., 2007a, 2007b) as well as in Hot Dry Rock (HDR) technology (Hettkamp et al., 2004; Baumgärtner et al., 2004; Schindler et al., 2008) and have also been applied in hydrothermal systems (Legarth et al., 2003; Legarth et al., 2005). Compared to hydrocarbon reservoir stimulation, the application for hydrothermal reservoirs requires a technique that is able to produce considerably higher amounts of fluids (Economides & Nolte, 2000).

The subjects which have to be addressed in conjunction with the EGS concept include quantification of reservoir parameters using laboratory experiments as well as borehole measurements to monitor the reservoir characteristics. The aim is to study the long-term hydraulic flow (Milsch et al., 2009), rock-fluid interaction, mechanical-hydraulic and thermal-hydraulic coupled processes (Blöcher et al., 2009), the recent stress field, and borehole stability (Moeck et al., 2008). In conjunction with operational work, the aforementioned issues support mitigation strategies to avoid reservoir and storage

impairment and hence lead to an increase in productivity and sustainability during later use.

2. GEOLOGY OF THE GROß SCHÖNEBECK AREA

The Groß Schönebeck field is a key site for EGS research in the North German Basin. The field has two deep research wells forming a doublet of one injection well and one production well. This doublet has served as a down-hole geothermal laboratory. The geothermal reservoir is 4,100 - 4,200 m deep and is comprised of Upper Rotliegend of the Lower Permian sandstones deposited in fluvial environments at the southeastern flank of the North German Basin. The sandstone reservoir is underlain by Lower Rotliegend of the Lower Permian volcanic rock and capped by Upper Permian evaporites.

The main targets are the permeable sandstones of the Upper Rotliegend (Dethlingen Formation/Lower Elbe subgroup) and the volcanic rocks (andesites) of the Lower Rotliegend, where permeability is mainly due to connected fractures. It is intended to use this system of fractures to optimize the total productivity of the well. The Dethlingen sandstones represent an effective reservoir horizon with a porosity of 8-10%, and an in situ permeability of up to 16.5 mD (Trautwein, Huenges, 2005). The Elbe-Basis-sandstone in the lower part of the Dethlingen Formation exists in NE Brandenburg as well-sorted, middle- to fine-grained, poorly cemented sandstone. The effective reservoir thickness is approximately 80 m; due to the deviation of the well, the apparent thickness is 150 m. The fault pattern interpreted from 2D seismic profiles is characterized by major NW trending faults and NE to N trending minor faults. With regard to the current stress field, the NE trending faults bear the highest shear stress. Since critically stressed faults are described as hydraulically transmissive (Barton et al., 1995), the NE trending faults are expected as main fluid pathways in the reservoir (Moeck et al. 2008). The Gt GrSk4/05 well ends in the direct vicinity of a NE trending and W dipping minor fault (Moeck et al. 2008). Two gel-proppant fracs were carried out in the sandstone horizon. The design of the doublet system including the scheduled fractures is displayed in Figure 1. The well path of the deviated well Gt GrSk4/05 consists of an inclination between 37 to 49° in the reservoir rock with an orientation from 288 to 296°N alongside the minimum horizontal stress direction (Holl et al., 2004). The fracture propagation is consequently parallel to the direction of the maximum horizontal stress (18°N) and hence perpendicular to the well path orientation.

3. STIMULATION TREATMENTS

3.1 Hydraulic Fracturing Stimulation Treatment

The stimulation treatment was carried out between August 9 and August 14, 2007. When flow rates were high, a friction reducing agent was used in the well, which limited the maximum well head pressure to 580 bar. To avoid iron scaling of the injected water, acetic acid was added to set the pH to 5. When flow rates were high (150 l/s), low concentrations of quartz sand (20/40 mesh size) were added to support a sustainable fracture width. Transport of the sand in the fracture and the well was realized solely due to the high flow velocity, because a gel to support the transport was not an option due to the pH value restriction.

In total, 13,170 m³ of fluids and 24.4 tons of quartz sand were injected into the volcanic rocks. A maximum well head pressure of 586 bars was achieved at the maximum flow rate of 9 m³/min (150 l/s). The total duration of the treatment was 4.5 days, as shown in the stimulation schedule in Figure 2.

The stimulation treatment was accompanied by passive microseismic monitoring in the adjacent well E GrSk3/90. For that purpose, a seismic sensor was installed at a 3,800 m depth to locate and control the produced fractures (Kwiatek et al., 2008).

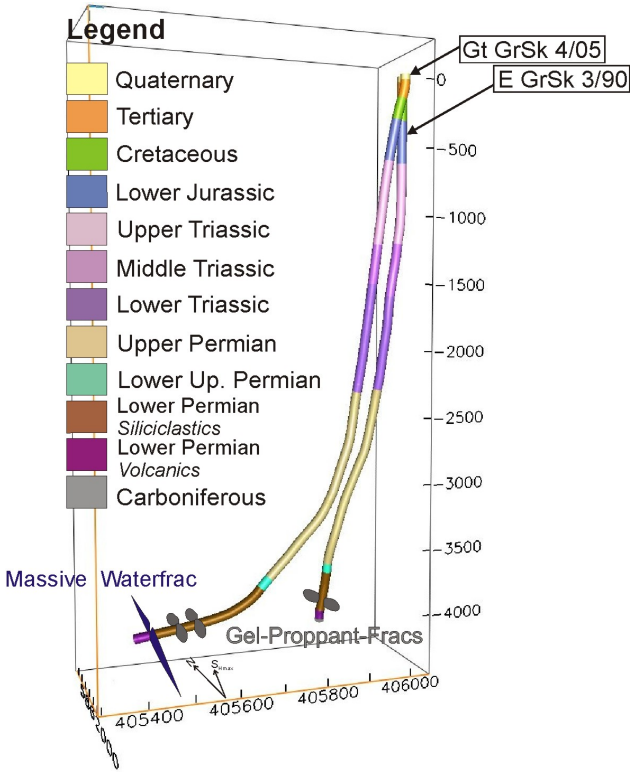

Figure 1: Alignment of the well path and the induced fractures of the doublet system at the Groß Schönebeck drill site.

3.2 Hydraulic Stimulation of Sandstone Sections

The stimulation treatment in the sandstones of the lower Dethlingen was carried out from August 18 - 19, 2007. The intended interval of 4204 - 4208 m was isolated with a bridge plug at 4300 m and then perforated with large hole perforations (20 per meter, circumferential). The proppants were transported by a cross-linked gel with high viscosity. Two kind of high strength proppants were applied: coated and uncoated. Both had a diameter of 0.4 - 0.8 mm (20/40 mesh size). The coated proppants were used at the end of the treatment to support the sustainable fracture opening in the vicinity of the well bore.

The treatment began with an injection test with flow rates between 0.3 m³/min and 0.57 m³/min. In total, 250 m³ were injected into the reservoir at a maximum well head pressure of 416 bar.

Subsequently, a leak off test was carried out to obtain the fracture gradient (0.16 bar/m). Then a step-rate test followed to calculate the friction and tortuosity at the perforation. Finally, the gel-proppant treatment was performed, in which 95 to of proppants and 280 m³ of cross-linked gel were injected into the Lower Dethlingen formation with a flow rate of 4 m³/min. The schedule of these treatments is given in Figure 3.

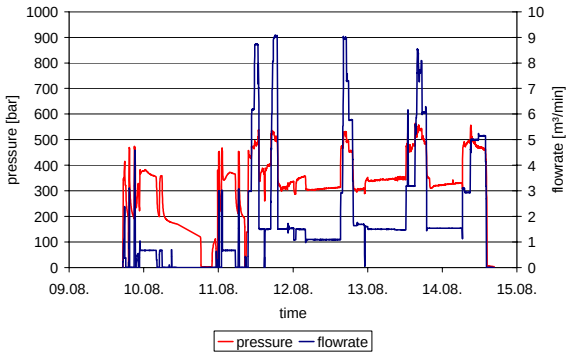

Figure 2: Schedule of the stimulation treatment in the volcanic rocks.

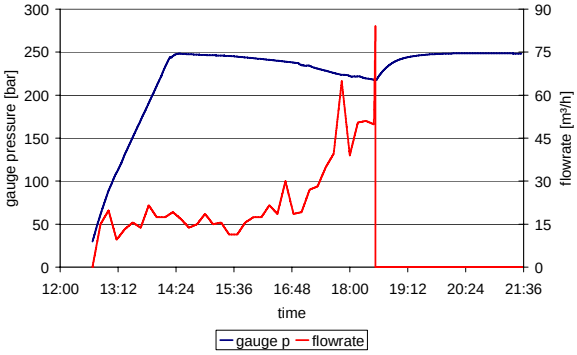

Figure 4: Schedule of production test after acid stimulation of the reservoir rocks. In the beginning, the coil tubing was positioned at 2350 m.

The second gel-proppant treatment was carried out from August 23 - 24, 2007 in the sandstones of the Upper Dethlingen. The treatment was similar to the previous ones. The bridge plug was set at a 4123 m depth, and the interval above was perforated from 4118 - 4122 m. The treatment started with an injection test with flowrates ranging from 0.3 - 0.62 m³/min and a total volume of 170 m³. The leak off test analysis yielded a fracture gradient of 0.15 bar/m. In the following stimulation treatment, 113 tons of proppants and 310 m³ of cross-linked gel were injected at flow rates ranging from 3 - 3.5 m³/min.

3.3 Acid Stimulation

The acid treatment was performed in conjunction with well cleaning from April 22 – 24, 2009 using a coil tubing (CT) unit (2”, 5000 m on a reel) to obtain the best positioning of the acid in the geothermal reservoir between 4360 m and 4100 m measured depth (MD). It was the aim of this treatment to dissolve the residual drilling mud (constituents: calcite, dolomite, aragonite) in order to achieve better access to the post perforated sections and enhance the productivity. Approximately 10 m³ of hydrochloric acid (7.5 % concentration) were placed in the post perforation sections above 4360 m MD for 30 minutes and then flushed out.

4. PRODUCTIVITY INCREASE AFTER STIMULATION TREATMENTS

A total of four stimulation treatments were performed in the Groß Schönebeck GtGrSk4/05 well. The three hydraulic stimulations in well GtGrSk4/05 were carried out separately in two sandstone sections and the volcanic rocks. To determine the success of these stimulation treatments, a

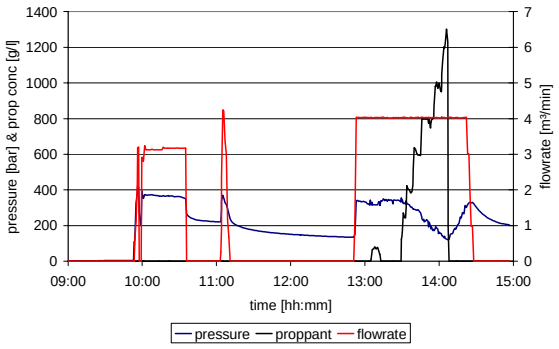

Figure 3: Schedule of the gel-proppant treatment in the Lower Dethlingen sandstones starting with a leakoff test and a step-rate test.

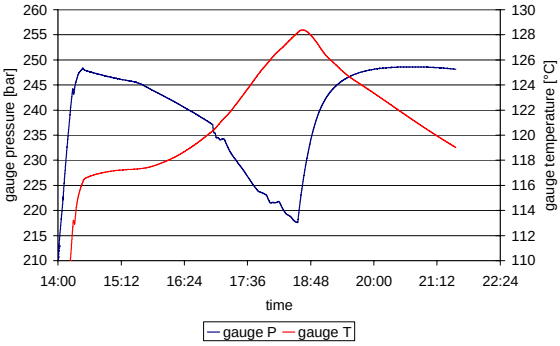

Figure 5: Gauge pressure and gauge temperature changes (at 2350 m depth) during the production test.

production test was carried out for all sections together. The individual contribution of each section was determined by flow meter profiling (Zimmermann et al., 2008). The corresponding productivity index increased from 2.4 m³/(h*MPa) before stimulation to 10.1 m³/(h*MPa) after stimulation.

After the acid stimulation, another production test was carried out to determine the improvement of productivity. For that reason, the coil tubing was lifted up to 2350 m depth, and nitrogen was injected to lift the water. A pressure-temperature memory gauge was installed at the bottom of the coil to measure the pressure and temperature below the coil in order to allow a reliable calculation of the reservoir pressure.

The flowrate was calculated from tank volume change in 10 minute intervals. In total, 140 m³ of water were produced during approximately 4 hours, as shown in Figure 4. The bottom-hole pressure was calculated from the gauge, assuming a 90 % share of formation water below the gauge and recalculating the density of this water from the change of the gauge temperature. The changes of the gauge temperature and pressure with time are shown in Figure 5.

The productivity index, which was calculated from the change in flowrate and associated change in bottom-hole pressure, reached a value between 13 - 15 m³/(h MPa). Since the lift test was quite short and stable conditions could not be achieved, the obtained productivity index should be treated as a first estimate, which has to be verified in a more suitable long term test. This is scheduled for the end of 2009 in conjunction with long term communication experiments between both wells.

CONCLUSION

Some lessons were learned from the experiences of the stimulation methods applied at the Groß Schönebeck field used to develop an EGS. The achievements of the hydraulic fracturing treatment and the gel-proppant treatments indicated that the stimulation methods should be designed individually depending on the reservoir rock properties, stratigraphic sequences, and structural geological setting to achieve best results.

If hydraulic fracturing is performed, the sustainability of fracture openings must be assured. In case of generating mostly tensile fractures without shear displacement, supporting procedures like adding meshed sand or proppants should be performed to keep the fractures open. This is especially the case for production wells with reduced formation pressure during production. During the stimulation treatments, the propagation of fractures and the final extension can be controlled by the flow rate, the treatment duration, and the utilization of fluids with different viscosities (linear or cross-linked gels). This opens the possibility to control the propagation of the fracture in height and length and leads to an optimal connection to the reservoir rocks. Designing a special concept of the well path, including sub horizontal sections in the reservoir and special alignment according to the stress field, offers the possibility for multiple fracture treatments in a well to develop the geothermal field.

Due to the performed hydraulic stimulations, the productivity of the well was enhanced by more than a factor of 4. The subsequent acid stimulation dissolved the residual drilling mud in the vicinity of the well bore and led to a further increase of well productivity by 30 – 50 %.

The well doublet is now prepared for a future thermal water loop and subsequent installation of a binary geothermal power plant. Technical and scientific challenges were successfully met with the strategy to define the applied stimulation design and with the stimulation operation itself. The stimulation treatments and the considerations about the well path design can, in principle, be applied to other environments with modifications. Hence, the results provide essential knowledge for developing future stimulation strategies in deep sedimentary geothermal systems like those in the Central European Basin and elsewhere.

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