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Extended Horizontal Jet Drilling for EGS applications in Petrothermal Environments

Simon Hahn, Volker Wittig and Rolf Bracke

International Geothermal Centre Bochum, Lennershofstr. 140, 44892 Bochum, Germany

simon.hahn@hs-bochum.de

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ABSTRACT

High pressure water jetting technologies are widely used in the (O&G) drilling industry. Especially in geothermal and hard rock applications, horizontal (radial) jet drilling as of today is, however, confronted with several limitations like lateral length, hole size and steerability. In order to serve as a serious alternative to conventional stimulation techniques high pressure jetting is experimentally investigated to gain fundamental knowledge about the fluid-structure interaction, to enhance the rock failing process and to identify the governing drilling parameters. The experimental program carried out at GZB is divided into three levels. In a first step jetting experiments are performed under free surface / atmospheric conditions, while logging fluid pressures, flow speeds and extracted rock volume. All process parameters are quantified with a self-developed jet-ability index and compared to the rock properties. In a second step experiments will be performed under reservoir type, pressure-controlled conditions. Therefore, a test bench is used that enables to set rock cores of up to 40 cm of length 15 cm of diameter under pressure until 200 bar while jetting with equipment and conditions of field standard. The experimental results from levels 1 and 2 allow to identify the governing rock failure mechanisms and to correlate them with physical rock properties and limited reservoir conditions. Results of the initial tests do show a clear dependency of achievable penetration depth on the interaction of jetting and rock parameters and an individual threshold of the nozzle outlet velocity can be noticed in order to successfully penetrate different formation types. At level 3 jetting experiments will be performed at simulated reservoir conditions corresponding to 5.000 m depth (e.g. up to 1.250 bar and 180 °C) on large samples with a diameter of 25 cm and a length of up to 3m using GZB´s in-situ borehole and geofluid simulator 'iBOGS'. Experiments will be documented by active and passive ultrasound measurements and high speed imaging.

1. INTRODUCTION

Radial water jet drilling (RJD) is a specific drilling technology that has been used in the oil and gas industry since many years successfully to access and stimulate petroleum reservoirs (Bruni, Biassotti, & Salomone, 2007). This drilling technology creates a micro borehole of just about one inch of diameter using a so called jet nozzle that exposes multiple high pressure water jets in different directions and orientations (Ragab, 2013). The task of the forward oriented jets is to erode the borehole front and the task of the backward oriented jets to widen the lateral and create pulling force (Ragab, 2013). By using only pure fresh water without additives and just about 1m^3 of volume it can be seen as a promising alternative for hydraulic fracturing (Buset, Riiber, & Eek, 2001). So far Radial water jet drilling has been used mostly in oil and gas reservoirs but just limited in petrothermal formations which are also found in hard rock formation types. At current stage of knowledge it is assumed that different erosion mechanism occur at the same time that while jetting and creating the lateral (Buset, Riiber, & Eek, 2001). These mechanisms are cavitation erosion, erosion due to shear forces and hydraulic fracturing on the pore scale at the borehole front. Cavitation erosion is a well know phenomena in the high pressure water jetting industry and scope of research since decades. When water is accelerated inside a nozzle, locally the occurring pressure of the fluid falls below the vapour pressure resulting in gas bubbles being created (Soyama & Takakuwa, 2011). These bubbles are then transported out of the nozzle within the high pressure water jet towards the target surface where they implode causing severe damage on that (Peng, Tian, Li, Huang, & Zhang, 2017). Material is eroded due to surface erosion when the excerted shear and compression force resulting from a passing by fluid are so high, that locally the strength of the target material is not high enough to prevent fragments to break out. Hydraulic fracturing at pore scale is considered to be the most effective erosion mechanism. It results from the stagnation pressure of the water jet that diffuses into the rock matrix where it increases locally the pore space. When the pore pressure is high enough the matrix fails in tension and the rock grains can be eroded with the shear forces (Buset, Riiber, & Eek, 2001). As it is not clear which of these mechanism is the governing one, an experimental procedure has been worked and conducted at the International Geothermal Centre in Bochum that is supposed to identify the relation between the operating conditions and a successfully created lateral. This experimental procedure is split in three different levels that are described in the following sections separately.

2. EXPERIMENTAL PROCEDURE

In the following sections the experimental procedures are described.

2.1 Jetting Experiments at Atmospheric Conditions

The scope of this type of jetting experiments is to evaluate the induced erosion of material from different rock types under variable operating conditions. For this purpose a set of parameters is defined that is changed during the test procedures that enables one to quantify the material being removed independently from the erosion mechanism in a newly developed index named the 'jet-ability index'. The index relates the applied hydraulic energy applied on the rock surface to the removed volume of rock mass and it is defined by:

$$J_i = \frac{exctraced\ rock\ volume}{applied\ hydraulic\ energy} = \frac{(mm^3)}{(J)}$$

The experiments focus on the use of a single nozzle that has just one forward oriented outlet. As described already in the introduction a typical self-propelling radial water jet drilling nozzle has multiple forward and backward oriented outlets that release each a high pressure water jet towards the borehole front or lateral wall. Each of these outlets are defined by their own diameter and cross sectional area for the fluid being exposed through it. The exit speed of the water jet at each outlet is defined by the cumulative area of all nozzle outlets instead of the individual bore diameter. According to its cross section the volume flow changes for each outlet but not the exit speed. This leads to the basic assumption for the jet-ability tests: the rock extraction process is more related to the amount of kinetic jet energy applied on the target surface than of mass flow passing the nozzle exit. Therefore, the operating conditions refer to the nozzle exit velocity and the standoff distance between nozzle outlet and rock surface that is changed in 5 steps during each test, ranging from 1.5 to 5.0 times the nozzle diameter. For comparison reason two different nozzle outlet diameters are used. In order to ensure repeatable measurements each test series is repeated at least three times using rock specimen of cylindrical shape with a diameter of 120cm and a thickness of 5cm. Sandstones from Gildehaus (GI, IGSN GFTRE0065), Bad Dürkheim (BD, IGSN GFTRE0035) and Dortmund (DO, IGSN GFTRE0099) quarry locations are used during the tests.

2.2 Jetting Experiments at Reservoir Type Conditions

In deliverable D5.1 (Hahn & Wittig, 2017) radial water jet drilling experiments are performed under atmospheric conditions and with unsaturated specimen which does not represent downhole conditions in a real reservoir. In depths of several hundred meters of depth the formation is usually saturated with reservoir fluid, oil or water, and a differential stress field is acting. Both of these attributes and their effect on the jetting performance can be tested simultaneously to some extent in the 'iBOGS mini'. This experimental device is a pressure vessel of about 12.5 cm of diameter and 50 cm of height that can handle entire rock specimen of approximately the same dimensions. Furthermore, it enables to use real field RJD equipment by guiding the jetting nozzle with a hydraulic feed system while it is penetrating into the rock. The feed system acts as inlet of the vessel which has also two outlets where one of them acts as a safety line and the other one as pressure control line. Backpressure and therefore pore pressure can be generated by closing the outlet valve in the pressure control line enabling to induce also mechanical stress in the saturated specimen according to the Biot factor of each rock type. In the following figure 1 a phot of the specimen including a rock specimen is presented. Each specimen is saturated before testing by submerging it in a water tank for long enough time and a flat surface is generated on top and bottom of the core. Again specimen from Gildehaus (GI, IGSN GFTRE0065), Bad Dürkheim (BD, IGSN GFTRE0035) and Dortmund (DO, IGSN GFTRE0099) quarry locations are investigated. The experimental operating conditions are chosen according to real field operating conditions including flow rates of up to 25 l/min and a static and rotating nozzle design is used. Pressure and flow rate is supplied by a triplex pump that can deliver up to 900 bar and after each experiment the achieved rate of penetration is evaluated.

2.3 Experiments at Simulated Reservoir Conditions

The experiments at simulated reservoir conditions are currently in the planning phase as the in-situ borehole and geofluid simulator is in its final construction phase. The planed experiments will be performed again with specimen from Gildehaus (GI, IGSN GFTRE0065), Bad Dürkheim (BD, IGSN GFTRE0035) and Dortmund (DO, IGSN GFTRE0099) quarry locations in order derive comparable experimental results over all 3 test levels. First results are expected for Q2 in 2019.

Figure 1: 'iBOGS mini' autoclave being used for jetting experiments under reservoir type conditions.

3. RESULTS

The results of the experiments are divided in 2 parts according to each experimental setup.

3.1 Jetability Index Derived from Free Surface Experiments

During the experiments at free surface conditions more than 100 tests are conducted and robust statistics are applied in order to derive the jetability index for each rock type. In the following table 1 the indices are listed next to the physical rock parameters of each tested type.

Table 1: Jetability index and rock parameters: Jetability Index J_i, porosity *por.*, permeability *k*, unconfined compressive strength *UCS*, tensile strength *TS*

Parameter	GI sst	BD sst	DO sst
J_i, in (mm^3/J)	2.9e-3	2.7e-3	7.1e.4
por., in (%)	23.7	19.5	8.7
k, in (m^2)	6.3e-13	4.5e.14	1.9e-18
UCS, in (MPa)	53	30	68
TS, in (MPa)	3.5	2.9	7.2

The presented results show that the sandstone from Gildehaus quarry location shows the highest possibility to be eroded with a pure water jet while having the highest value for the jet-ability index of 2.9e-3 (m^3/J), followed by the sandstone located in Bad Dürkheim quarry with a value of 2.7e-3 (m^3/J). The sandstone from Dortmund quarry location has the lowest value for the jet-ability index with just 7.1e-4 (m^3/J), which is almost factor 10 less compared to the others. Considering the jet-ability index and the rock parameters, it can be noticed that the sandstones from Bad Dürkheim and Gildehaus quarry location are almost comparable to each other in terms of porosity, permeability and mechanical strength. In contrast to that, the Dortmund sandstone has the highest mechanical toughness, indicated by the highest values for uniaxial compressive (UCS) and tensile strength of all three tested sandstones. It also shows the lowest values for porosity, permeability and jet-ability. This combination of physical rock parameters and measurement results leads to the conclusion that the combination of high porosity and permeability with low values of mechanical strength enhances the erosion process via high pressure water jet at atmospheric conditions. Next to this for each tested rock type a certain threshold velocity, or minimum amount of hydraulic energy, can be determined at which the erosion process starts. The experimental results show that the erosion process for the Dortmund sandstone does not start unless a nozzle outlet velocity of 180 m/s is reached. The sandstone rock types from Gildehaus and Bad Dürkheim quarry location need at least 100 m/s of nozzle exit speed to be eroded. Furthermore it can be stated that the standoff distance within the tested range and under atmospheric conditions does not have a major effect in the erosion process. This can be explained by the relatively low diffusion angle of 1° of the used nozzles indicating that almost no kinetic energy is lost due to diffusion of the jet. The influence of the nozzle outlet diameter on the jetting performance has also not been detected as a predominant factor within the tested range. The differences of the nozzle exit velocities are negligible as well as the differences in the diameters of the produced cavities in the specimens.

3.2 Rate of Penetrations Derived from Pressure Controlled Experiments

The experimental series of pressure controlled experiments includes more than 20 experiments and the results are presented in the following table 2 and table 3, showing only some dedicate experiments.

Table 2: Experimental results pressure controlled experiments for rotating nozzle design: rate of penetration ROP, volume flow rate Q, nozzle pressure p_{nozzle}, vessel pressure p_{vessel}

Parameter	GI sst	BD sst	DO sst
ROP, in (m/h)	100	100	0
Q, in (l/min)	26.5	26.0	27.0
p_{nozzle}, in (bar)	450±20	450±20	450±20
p_{vessel}, in (bar)	0	0	150

Table 3: Experimental results pressure controlled experiments for static nozzle design: rate of penetration ROP, volume flow rate Q, nozzle pressure p_{nozzle}, vessel pressure p_{vessel}

Parameter	GI sst	BD sst	DO sst
ROP, in (m/h)	0	0	0
Q, in (m^3/h)	26.5	26.5	27.0
p_{nozzle}, in (bar)	500±20	500±20	500±20
p_{vessel}, in (bar)	150	150	150

The experimental results of the test series at pressure controlled experiments show, that the rotating nozzle design works best, especially for the sandstone rock types from Gildehaus and Bad Dürkheim quarry location and under 0bar of ambient pressure. Rate of penetrations of up to 100 m/h can be achieved. Further experiments at higher ambient pressures are needed to investigate the performance of the rotating nozzle design also under simulated downhole conditions. The sandstone from Dortmund quarry location is not accessible with the rotating nozzle design even if a back pressure of up to 150 bar is applied on the rock specimen. The static nozzle design does not seem to work at all for all 3 tested sandstone rock types. During the test series various vessel pressure are tested, ranging from 0 to 150 bar. At no pressure stage notice able rate of penetrations can be achieved. Also the observed cavities after each test show that as they are much too small in diameter in depth for the jetting nozzle to enter. In the following figure 2 a photo of a successful jetting experiment is presented. It shows a specimen of Gildehaus sandstone rock type that has been penetrated with the rotating nozzle design. The diameter of the created lateral is about 40 mm and the shape of the lateral wall itself is of curvy form resulting from the spinning back thrusters of the used jetting bit. The depth of the lateral is about 30 cm and it is created within less than 5 seconds of operation time.

Figure 2: Photo of Gildehaus specimen after experiment with rotating nozzle design.

4. CONCLUSIONS

The experimental outcome of the experiments at atmospheric conditions show that jetting into a high permeable rock with low values of mechanical strength bears the highest potential for successful jetting. The experiments under pressure controlled conditions seem to underline this assumption. In both experimental setups it was comparably easy to penetrate into the sandstone rock types from Gildehaus and Bad Dürkheim quarry location. A single cavity could be produced with much less hydraulic power compared to the sandstone from Dortmund quarry location. Furthermore, even under increased pore pressure it was not possible to jet in that tough sandstone with a radial water jet drilling nozzle. These observations are quantified in terms of the jet-ability index and measured rate of penetrations. Concerning the governing erosion mechanism no clear statement can be made evaluating the experimental observations presented here. At least one can state that increasing the pore pressure, and hence, inducing mechanical stress in the specimen, does not enhance the erosion of rock by a pure high pressure water jet. Otherwise the experiments relating to the Dortmund sandstone with 150 bar of vessel pressure would have resulted in successful jetting operations delivering a measurable rate of penetration. Further experiments being conducted in the iBOGS will subsequently focus on that point.

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