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ThermoDrill - Fast Track Innovative Drilling System for Deep Geothermal Challenges

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ABSTRACT

Since 2015 an interdisciplinary team of experts from research and industry has set itself the ambitious goal of developing a fast and cost-efficient drilling system based on an innovative combination of conventional rotary drilling and water jetting. Deep geothermal drilling operations often have to cope with high formation temperatures (200°C static) and hard and abrasive rock types (granite, gneiss, sandstone). This causes an overall slow drilling progress, not only because of low penetration rates but also because of more trips required due to an increased material wear. Based on technical and financial data from real deep geothermal hard rock drilling operations in Europe it was concluded that by 50% faster drilling in crystalline rock, a cost reduction of 30% can be achieved which should greatly provide a boost for the deep geothermal industry. Numerous high-pressure fluid jetting experiments with jet pressures of more than 2.500 bars in various ambient pressure regimes (up to 425 bars) were performed and demonstrated that hard rocks can sufficiently be cut, even under high backpressures, if the right jetting parameters (jet pressure, stand-off distance, hydraulic jet power) are chosen. Based on these findings, two unique drill bit prototypes (8 1/2 in size) were built. A high-pressure body was designed and integrated into the frame of an existing roller cone bit. The high-pressure fluid jet assisted rotary drilling system including the two bit prototypes and a novel geothermal drilling fluid was successfully tested in crystalline rock, in full scale drilling experiments performed in a drilling simulator. In these experiments, a maximum increase in penetration rate of more than 70% was achieved. A first experimental field trial of the complete ThermoDrill system in a 1.3 km deep well was performed in May 2019. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 641202.

1. INTRODUCTION

In most areas in Europe, deep geothermal wells require depths of 4,000 to 6,000 meters to provide appropriate temperatures for heat and electricity utilization. Therefore, most of these wells will have to penetrate sediments as well as crystalline rocks at various depths causing several related problems, e.g. low rate of penetration, borehole instability, insufficient borehole cleaning, loss of drill fluid circulation, drill string failures due to high torque and drag, etc. Drilling deep geothermal wells is therefore rather costly and risky, with a significant amount of start-up capital during the earliest phases of exploration being required. Consequently, only a limited number of deep geothermal developments in Europe were realized in the past. Particularly the drilling process itself represents one significant cost driver when it comes to extended depths. It is therefore ThermoDrill's overall objective to develop an innovative and also economic hybrid drilling system consisting of conventional drilling in combination with high-pressure fluid jetting, to allow for minimum 50% faster drilling in hard rocks at a cost reduction of more than 30%.

The concept of combining mechanical and hydraulic rock destruction methods for increasing the rate of penetration (ROP) in deep drilling has already been discussed in the United States patent of Bobo (1963). The method described, involves a downhole multiplying pump to create a high pressure, which passes then through conduits to the nozzles for impinging around the periphery of the borehole. The left core in the middle of the borehole should then be easier to drill. The drilling mud not entering the multiplying pump along with the drilling mud exiting the nozzles transports the cuttings out of the wellbore. Later concepts, e.g. Veenhuizen et al. (1997), Kolle et al. (1987) and Shi et al. (2013), generally followed this initial idea.

To stimulate deep downhole conditions, high-pressure jetting experiments under different ambient pressure regimes had to be performed within this project. High-pressure jetting experiments performed by Reichmann (1977) on granite and Kolle (1987) on Sandstone, Limestone and Shale under back pressure, showed significant ceasing of the cutting action at elevated backpressures. Backpressure describes the pressure of the fluid layer between the nozzle outlet and the object to be cut. Knowing this, an extensive laboratory study to identify the appropriate parameters (jet pressure, stand-off distance, hydraulic jet power) for the future ThermoDrill system was conducted. The cutting performance under backpressures of up to 425 bars was especially investigated.

Complementary investigations involved the design and testing of a novel geothermal drilling fluid as jetting fluid. Based on the findings of this study, two unique drill bit prototypes (8 1/2 in size) were built and equipped with high-pressure jet nozzles placed in specially designed nozzle holders. The high-pressure fluid jet assisted rotary drilling system, including the two bit prototypes and the novel geothermal drilling fluid was successfully tested in granite, in full scale drilling experiments performed in a drilling simulator. Further optimizations resulted from a first surface test of the ThermoDrill system, consisting of the drill bit prototype and a downhole pressure intensifier. The capability and on-site handling of the system was successfully tested under real drilling conditions in a 1.3 km deep well in Austria. The main knowledge gained from all these experiments performed within the ThermoDrill project is summarized in the sections here below.

2. HARD ROCK CUTTING EXPERIMENTS WITH HIGH PRESSURE JETS

From linear cutting tests performed at the very beginning of the project it was found that the pressure, the jet nozzle diameter and the traverse velocity are the most important parameters for successful cutting of granite. The experiments were performed on a reference rock, the Neuhauser granite, an intrusive rock of the Bohemian Massif. Furthermore, it became obvious that the difference in the cutting performance of abrasive and pure water jetting at higher traverse velocities is clearly decreasing. Although abrasive water jetting is superior in hard rock cutting, the complexity of supplying and mixing particles at depth, lead to the decision to continue testing with pure water only (Stoxreiter et al., 2018).

2.1 Experiments under atmospheric conditions

Between 2015 and 2017 water jet cutting experiments were performed under atmospheric conditions on selected hard rock samples from a quarry and from existing wells. The rock samples were extracted from sections of the wellbore where significantly low rate of penetration (ROP) values were measured during drilling. A review of drilling data performed within this project, lead to typical ROP values for deep seated granite between 2 and 5 meter per hour (Baujard et al., 2017). Slices of the selected core samples were embedded into mortar to enable sufficient jetting radii (figure 1).

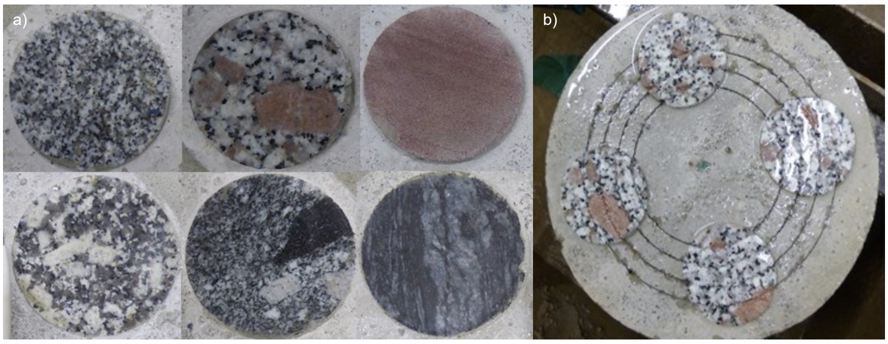

Figure 1: Neuhauser granite (Bohemian massif), Monzo granite (Soultz, 3894 m), Buntsandstein (Soultz, 1410 m), Falkenberg granite (Falkenberg, 93 m), Basel granite (Basel), KTB gneiss (Windischeschenbach, 1901 m) (a) and embedded core samples after jetting (b) (Stoxreiter et al., 2018).

The embedded samples were then placed on a motor driven turntable, turning at a velocity of 300-600 mm/s, which was the expected velocity for the final field application. The nozzle diameter used for jetting was 0.25 mm, the stand-off distance 11 mm, the jet pressure 4,000 bar with increasing cutting velocity from 400 mm/s to 700 mm/s from inner to the outer radius. Four radii with 15 mm spacing were jetted for every rock type using these parameters (figure 1b). The created kerfs were deep and narrow. The depth of the kerfs as well as the removed volume were measured using a laser scanner. Figure 2 summarizes the obtained results.

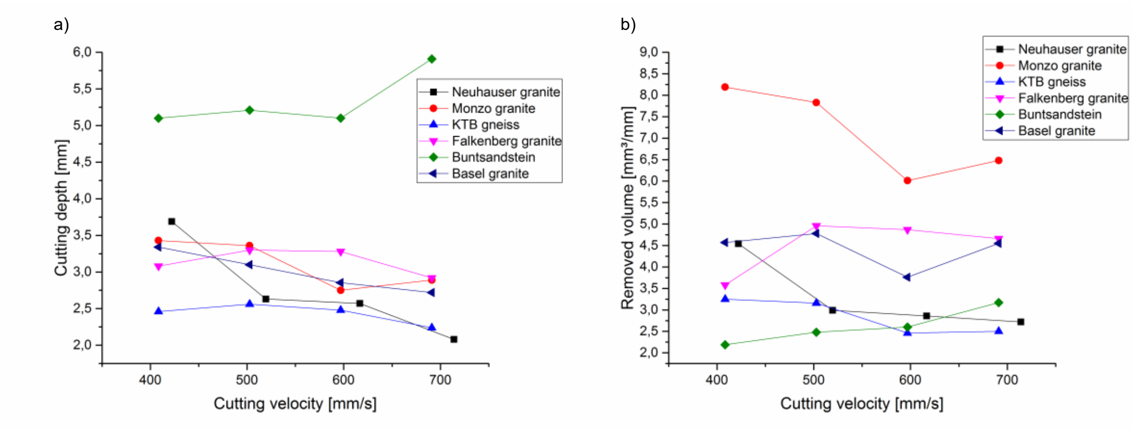

Figure 2: Water jetting under ambient conditions, cutting depth vs. cutting velocity (a) and removed volume vs. cutting velocity (b) (Stoxreiter et al., 2018).

The difference in cutting depth between all crystalline rock types (granite, gneiss) and the sedimentary rock type (Buntsandstein) becomes obvious. The depth of the kerf created in Buntsandstein is about twice as deep as the kerfs created in granite and gneiss, which relates to the compressive strengths of the rocks, 67 MPa for Buntsandstein and 220 MPa for the KTB gneiss (Emmermann, 1993). Contrary to this, the Buntsandstein with nearly continuous rectangular slots shows the smallest removed volume while the Monzo granite shows the biggest removed volume due to irregular large breakouts.

Buntsandstein and Monzo granite, both originate from different depths in Soultz (figure 1). While drilling, average ROP values of 5 m/h were observed in the Buntsandstein and 2 m/h in the granite formations (Vidal et al., 2015). Comparing these ROP values to the cutting depths created by jetting in these rock formations, the conclusion could be drawn that the effort required to loosen the Buntsandstein and granite is very similar, regardless of whether mechanical or hydraulic techniques are used.

2.2 Experiments under downhole conditions

In order to identify the jetting parameters required to obtain a satisfying cutting result even under back pressures of up to 450 bar, jetting experiments with varying parameters were performed inside a specially built pressure vessel. The pressure vessel was designed for cylindrical rock samples with a diameter of 220 mm, which is close to the gauge diameter of an 8 ½” bit. The height of the samples was 90 mm. The turning table was mounted on a cylindrical roller bearing and connected to the coupling, spur gear and motor via a sealed shaft. The rotational speed from 0-120 rpm was controlled by a frequency inverter. Nozzle holders with different lengths enabled stand-off distances from 2-15 mm. Two nozzle types with diameters from 0.7 mm to 1.5 mm were used for these experiments, the R-nozzle (nozzle discharge factor 0.66) and the K-nozzle (nozzle discharge factor 0.72). The pressure inside the vessel was controlled by a control valve. The jetting pressure was recorded at the cutter head (figure 3a).

More than 100 kerf radii were jetted on Neuhauser granite, which was selected as reference rock type. The stand-off distance, nozzle diameter and jet pressure respectively hydraulic jet power were varied in a reasonable range. The influence of back pressure, cutting velocity and multiple cutting of the same kerf were examined as well. In order to validate that the cutting performance is not influenced by using mud as jetting and surrounding medium instead of water, jetting experiments were also performed using polymer-potassium carbonate based and sepiolite based mud. The cutting depth and the removed volume were again measured using a laser sensor.

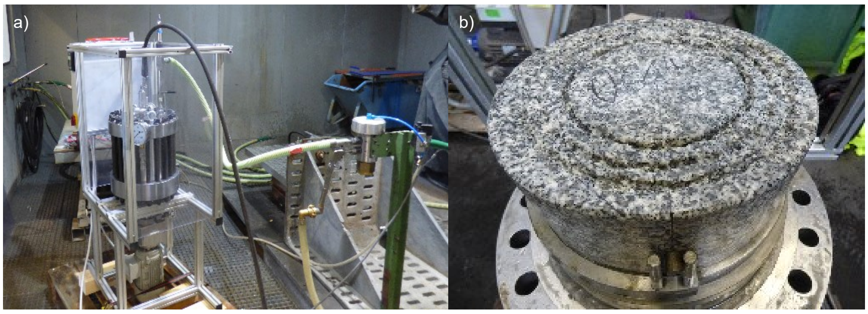

Figure 3: Set-up for jetting under back pressure at the high-pressure laboratory of URACA GmbH & Co. KG in Germany (a) and example of a jetted rock sample using 85 kW hydraulic jet power, 3 mm stand-off distance and 150 bar back pressure (b) (Stoxreiter et al., 2018).

The stand-off distance is one of the critical parameters for jetting under backpressure. This was already projected by Cheung & Hurlburt (1979) and Kolle (1987). The pure water jet cutting K-nozzle showed a significantly greater allowable stand-off distance than the R-nozzle (figure 4a). With 1.4 mm nozzle diameter a maximum distance of about 11 mm from nozzle outlet to rock surface was acceptable at a backpressure of 425 bar. It appeared that the shape of the internal flow path of the nozzle has also an impact on the jet cutting performance, besides the obvious influence of the backpressure.

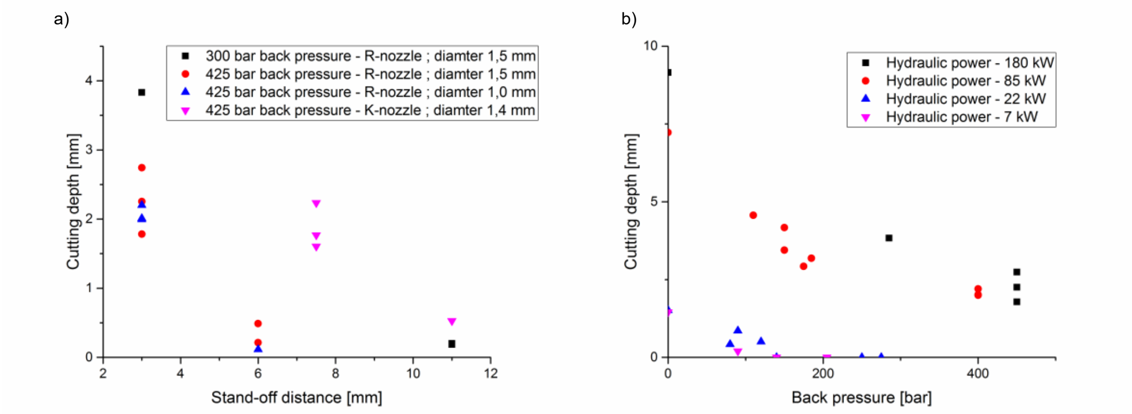

Figure 4: Cutting depth vs. stand-off distance at different backpressures and using different nozzle types (a) and cutting depth vs. backpressure dependent on the hydraulic jet power with 3-4 mm stand-off distance (b) (Stoxreiter et al., 2018).

The second important property of the jet is the hydraulic power. The cutting depth also strongly depends on the applied hydraulic power of the jet. This is clearly visible in the obtained data (figure 4b) and was already ascertained by Rehbinder (1980) in the past. For the purpose of defining the requirements for the downhole pressure intensifier in ThermoDrill it was obviously interesting to see, that even under high backpressure, a jet with 85 kW hydraulic power and a jet with 180 kW hydraulic power have nearly the same cutting performance at 3 mm stand off-distance.

The jetting experiments performed with superimposed cuts showed that at elevated backpressure, the cutting depth was not significantly increased by jetting the same kerf several times. The most likely reason for this is that after cutting the first kerf the stand-off distance is increased by the already existing kerf depth. No significant difference in cutting performance was observed when drilling fluids were used for jetting. Common drilling fluids may have a minor positive influence on the jetting performance at higher backpressure.

3. JET-ASSISTED ROTARY DRILLING EXPERIMENTS IN A DRILLING SIMULATOR AND IN THE FIELD

Based on the results from the hard rock cutting tests described above, full-scale drilling experiments were performed with a high-pressure fluid jet assisted rotary drilling system in 2018. The system consisted of novel drill bits with high-pressure components and were performed at the drilling simulator test bench of Mines ParisTech in Pau, France (Stoxreiter et al., 2019). Further optimizations and developments lead to a first downhole field test of the ThermoDrill system in 2019.

3.1 Experiments in the drilling simulator

In order to perform the tests, a high-pressure tubing had to be integrated into the existing drilling test bench. A mobile URACA Jet Power 300-1000 pump with a maximum flow rate of 55 L/min at 250 MPa provided the required hydraulic power for jetting.

As reference bit, a standard TCI (Tungsten Carbide Insert) bit (IADC 627Y) was used. A bit type, that is typically used in deep granite formations. The two innovative prototype bits were developed with a high-pressure conduit/plenum system integrated into the bit body. Jetting occurred through one or two extended high-pressure nozzles (figure 5). Depended on the prototype bit used, low pressure circulation of mud was still possible through one or two low-pressure nozzles.

For all these tests, a stand-off distance for the extended nozzles of the bit of 6-8 mm was chosen. Standard high-pressure nozzles made out of hardened steel with a nozzle discharge factor of 0.97 were installed in the extended nozzle holders of the bit. Depending on the jetting pressure required, the one-nozzle bit was equipped with a 1.3 mm or 1.5 mm diameter nozzle, while the two-nozzle bit was equipped with 0.9 mm or 1.1 mm diameter nozzles. Neuhauser granite was again used as reference rock. Besides fresh water, sepiolite and xanthan gum based muds at a density of 1.1 g/cm³, possessing the same low shear rate viscosity (3 rpm=10lbf/100 ft², 6 rpm=12 lbf/100 ft²), were used for drilling and jetting.

The results of the drilling simulator tests using fresh water are summarized in figure 5. The rotational speed was set to 60 RPM and the flowrate for cutting transport was 600 L/min.

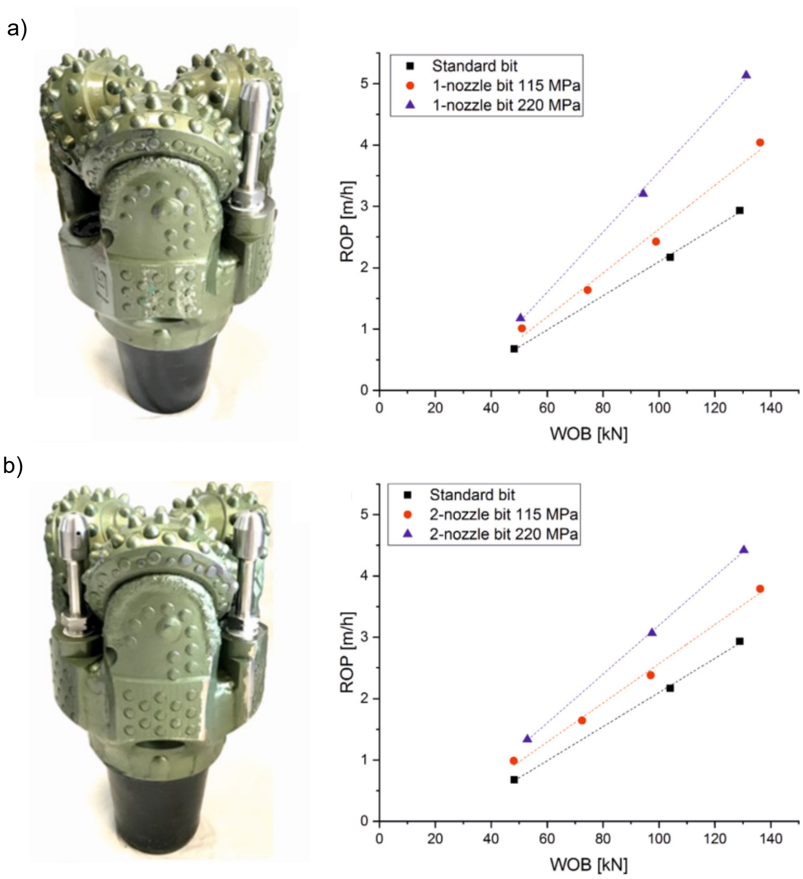

Figure 5: Drilling performance of the 8 ½" one-nozzle bit prototype (a) and drilling performance of the 8 ½" two-nozzle bit prototype (b) (Stoxreiter et al., 2019).

A linear relation between the weight on bit (WOB) and the rate of penetration (ROP) was observed for both bit prototypes at different jetting pressures. An increase of more than 70% compared to the standard roller cone bit was observed for both bit types, but at different WOB. At higher WOB the one-nozzle bit showed higher ROP. The application of different fluid types had no significant influence on the drilling performance, however erosion on the high-pressure nozzle was observed when using the sepiolite based mud. Fluid jetting had a strong impact on the xanthan gum fluid as it was strongly degraded while the sepiolite remained unchanged.

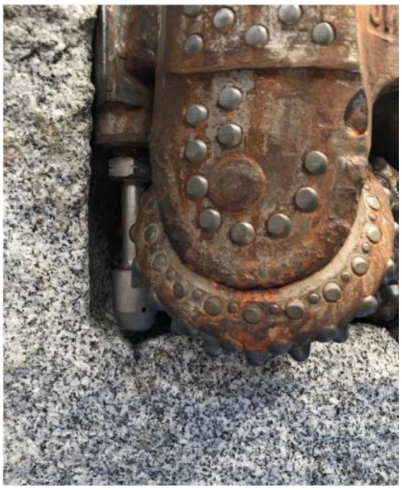

Figure 6: One-nozzle bit integrated in a drilled rock sample (Stoxreiter et al., 2019).

3.2 First field test using the ThermoDrill system

The application of the rotary-assisted drilling system in a borehole, required also the development of a novel downhole pressure generation tool. The so-called downhole pressure intensifier (DPI) was designed to deliver a high-pressure flow of 50 L/min at 2500 bar and was manufactured at the beginning of 2019.

In May 2019, a field trial was performed in a 1.3 km deep well in Austria using Drilling Rig E200 (figure 7a). The reference bit was first run to determine the baseline for later comparison of the ROP. The DPI was then directly connected to the one-nozzle jet bit, and the assembly was picked up in one piece. The extended bit nozzle, equipped with an optimized high-pressure nozzle made out of hard metal was screwed into the bit and the DPI was run in the hole (figure 7b and 7c). The ThermoDrill configuration was easy to handle and the installation did not consume any additional rig time compared to standard BHA handling.

Although the formation consisted of marlstones, which was not the optimum formation for the bit type selected, a very encouraging ROP increase was observed at the same drilling parameters. Further analysis of the results is currently ongoing.

Figure 7: Drilling rig E200 used for field testing (a), 1-nozzle bit prototype with the downhole pressure intensifier connected (b) and extended nozzle on the bit prototype with a stand-off distance of 9 mm (c).

4. CONCLUSIONS

The ThermoDrill consortium has impressively demonstrated its capabilities within the past four years of research and development. Finding the right parameters for successful jetting under high backpressure was the first big challenge to overcome. Innovative solutions and developments, like the design of the pressure vessel, the two bit prototypes and the downhole pressure intensifier have led the project to where it stands today.

From the hard rock jetting experiments, it was found that the stand-off distance and the hydraulic power of the jet are the most critical parameters for hard rock jetting. The results from testing in the drilling simulator demonstrated a more than 70% increase in drilling velocity in granite when using ThermoDrill technology with a surface pump and water or drilling fluid. This result was even exceeded during the field test which showed a remarkable increase in drilling velocity.

The increase in drilling velocity mainly results in a reduction of rig time, which has a significant impact on the cost of a well. In order to reach the full potential of the jet-assisted rotary drilling system, the lifespan of the downhole pressure intensifier and all other components like the high-pressure nozzle has to be further investigated. If the number of trips required to drill a well can also be reduced significantly, cost savings of up to 30% for the full wellbore construction become realistic.

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