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1. Executive Summary

The main objective of work and investigation at the International Geothermal Centre in Bochum (GZB) within WP5 is trying to achieve a most complete understanding of water jet and rock interaction for a large variety of sedimentary and crystalline rocks which are being found in Geothermal reservoirs around Europe. Scope of this work is to introduce a drilling and stimulation technology for geothermal application/EGS that is not limited to only one single geological setting, but rather be applicable all over Europe or beyond in low to high enthalpy reservoirs. Experiments, carried out on surface with true scale jet drilling equipment (meso scale), are subdivided into four tasks and deliverables.

Therefore, D5.1 focuses on jet drilling experiments at ambient conditions and includes different subtasks:

1. Characterization of reservoir type rocks in collaboration with WP4
2. Jet drilling experiments on dry and saturated rock samples
3. Influence of operating conditions on jetting performance
4. Documentation of jetting process

In subtask 1 rock blocks from locations representing different types of geothermal reservoirs are selected and located at GZB drill site for further analysis, use in experiments and sharing with project partners. Tests are carried out to evaluate current, state of the art radial water jet drilling technology with regards to its applicability for existing and future geothermal well sites. Therefore, jet drilling experiments are performed on dry and saturated samples, labeled as subtask 2, and the created boreholes and laterals analyzed. In order to investigate the influence of operating conditions on the jetting process, the experiments of subtask 3 focus on a simple, single nozzle design (only one forward oriented orifice) and standardized rock specimen geometry to delimit uncertainties and inaccuracy of experiments of subtask 2. Parallel to this, the jetting process using the simple nozzle design by acoustic measurements, and for the radial water jet drilling technology with optical measurements as well. This refers already to subtask 4.

The experimental results presented in Section 3.1 reveal that the applicability of the currently available radial water jet drilling technology under atmospheric conditions is limited to very soft sandstone types. This is demonstrated by the measurement data in Section 4.1. The values for the jetability index clearly indicate that a geologic type by high porosity and permeability in combination with low values for mechanical strength is required in order to successfully erode material with a pure high pressure water jet at current state of available hydraulic energy at the bit. Especially for harder rock types, higher nozzle exit velocities and hence, nozzle pressures are needed as demonstrated in Section 4.2. With the current state of the art RJD technology, this is not feasible at

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atmospheric conditions on unsaturated rock. In order to identify the governing erosion mechanism the experiments presented in Sections 4.4 and 5.2 indicate that cavitation erosion is potentially the dominant erosion process. Submerged conditions enhance the erosion efficiency of the high pressure water jet, although the jet loses kinetic energy under water. This is demonstrated by comparing the experimental results from the Dortmund sandstone referring to the jetability measurements at atmospheric conditions and experiments at water flooded environment. Also, the influence of rock saturation on the erosion resistance via high pressure water is investigated. The experiments in Section 4.3 reveal that a lowering of the minimum threshold velocity can be achieved initiating the erosion process. The results of the acoustic measurements do show that variances in the emitted acoustic signals occur in the frequency spectra, referring to each individual nozzle type.

The work carried out in WP5 and the gained knowledge about the applicability, limitations and erosion mechanism of radial water jet drilling technology needs and gives mandatory input to all participants within the SURE project (Reinsch, Bruhn, & SURE consortium, 2016).

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2. Characterization of rocks in collaboration with WP4

2.1. Research of geothermal reservoir rocks

Work starts initially with review and research of rock types representing geothermal reservoirs located in Europe that are expected to show a broad variety of mechanical and geophysical characteristics. Also specimen from Iceland are added to the rock collection in order to directly investigate the applicability of the current jetting technology on geothermal well sites in that area, as is being planned during a field test in 2018. Therefore, the current collection includes rock types taken from the following locations:

- Permian volcanic sandstones, Flechtingen
- Granite, Raumünzach/Flossenbürg
- Carboniferous sandstone, Dortmund
- Triassic sandstone, Miltenberg
- Jurassic limestone, Drackenstein
- Devonian slate, Nuttlar
- Quaternary basalt, Mending
- Devonian limestone, Wülfrath
- Cretaceous sandstone, Rüthen and Bentheimer
- Triassic middle buntsandstone, Friedewald
- Devonian quartzite, Friedrichsdorf
- Basalt, Iceland Eyjafjörður

Scope of this rock collection is to perform experiments with the current radial water jet drilling technology as well as with new developed drilling tools. Next to this specimens out of this collection serve for basic research in the field of fluid structure interaction and for characterization of the mechanical and geophysical rock parameters.

2.2. Inventory and cataloging of rock collection

In order to facilitate the inventory and communication to project partners about available rock samples, the entire collection is catalogued including sample size, geometry, type and age, quarry location and contact details as well as, based on literature research, expected rock parameters. Entries concerning number of rock blocks, subsamples, their dimensions and properties are continuously updated.

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3. Jet drilling experiments on dry samples

3.1. Testing state of the art RJD technology under atmospheric conditions

Test setup and equipment

In order to test the current, available jetting technology, experiments are carried out on four different rock types representing possible quarry locations for MS6 (full scale quarry field test performed in late 2016) under unsaturated conditions. Measurement data of the jetability tests under 4.1, 4.2 and 4.3 reveal that only rather soft sandstone formation types are applicable for the current available radial water jet drilling technology due to the limitations in nozzle outlet velocity. Scope of the experiments in 3.1 is to test the applicability of the current jetting technology and required operating conditions that ensure successful penetration as well as gaining experience in the interaction of drill bit and formation type. Next to this also acoustic and seismic measurements are done in order to document the jetting process.

As already mentioned the initially selected rock types are chosen by their possibility of being selected for the full scale quarry test in November 2016. These formation types are:

- Triassic middle “Bunt” sandstone, Friedewald
- Carboniferous (Ruhr-) sandstone, Dortmund
- Cretaceius sandstone (“Gildehaus”), Bad Bentheim
- Cretaceous sandstone, Rüthen

Especially the sandstone from quarry location Dortmund is supposed to be one of the hardest from the collection, and the Gildehaus sandstone from Bad Bentheim quarry location the sample with the highest porosity. For the tests, blocks of various size and irregular shape are used. For the test themselves a test bench is manufactured that has the following tasks: guiding the high pressure hose with the nozzle (1), adjusting the standoff distance between nozzle and rock surface (2) and, if the nozzle can penetrate into the rock, allowing forward movement of the nozzle into the forming lateral. In the following figure 1 a sketch of the test bench with the rock specimen is shown.

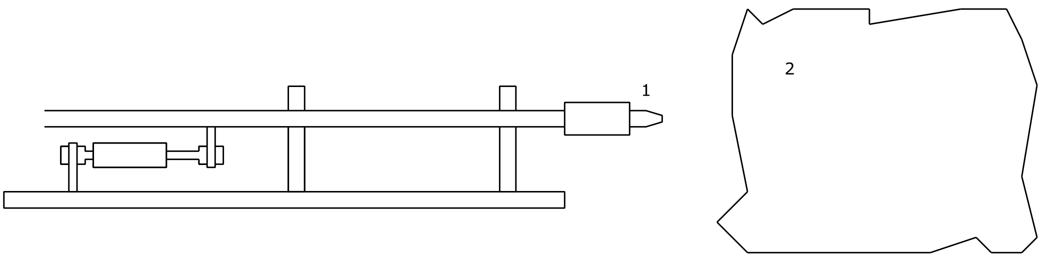

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figure 1 test bench and rock block

Currently two different nozzle designs are used for radial water jet drilling. Design 1 can be seen as static nozzle design, as it consists only of one fixed part which may be described as a lid screwed on a high pressure hose with openings in several directions. In the following figure 2 a sketch of this static nozzle design can be seen.

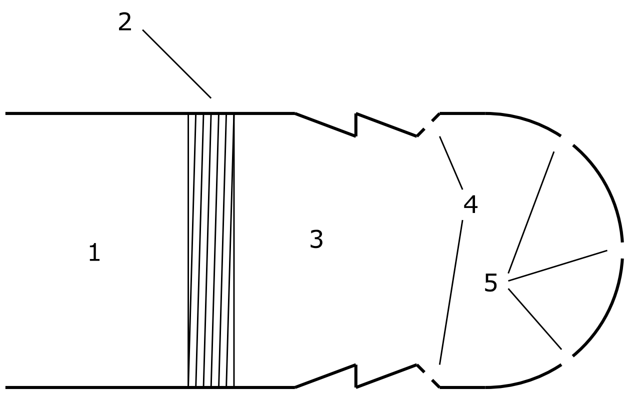

figure 2: schematic sketch of static RJD nozzle

The static RJD nozzle is made of one part (3) that is screwed with a thread connection (2) on a high pressure hose (1) having several, simple designed outlets in backward (4) and forward (5) oriented direction. The manufacturing quality of the outlets is quite poor as they are just simply drilled holes without any real nozzle like design specifications like diameter to length ratio and no further treatment of the inner surface. From literature referring to material erosion with pure high pressure water jets, it is known that specific design criteria, e.g. concerning to nozzle diameter to length ratio and inner surface roughness, affect the material removal rate (Soyama, 2011), (Li, Kang, Ding, Wang, & Fang, 2016). The main task of the backward oriented outlets (4) is to drive the nozzle, also called bit, into the formation and widen the borehole while the forward ones (5) mainly erode the formation in front (Bruni, Biassotti, & Salomone, 2007). In figure 3 this process is illustrated and figure 4 shows a photo of that specific static jetting nozzle design.

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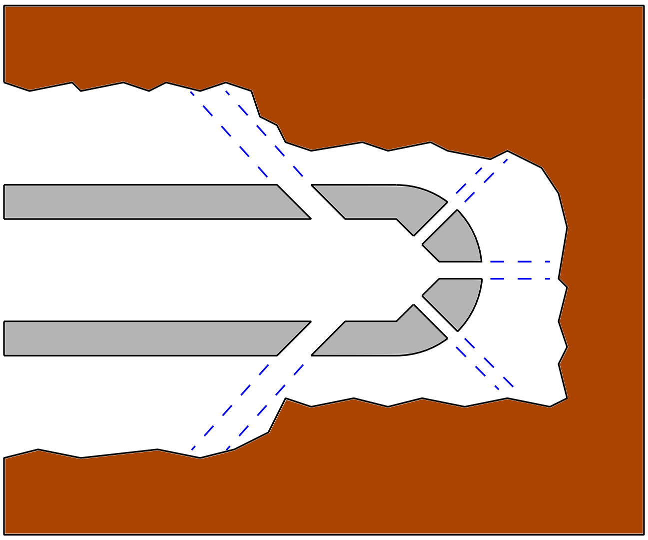

figure 3: jet drilling process with RJD nozzle

figure 4: static type RJD nozzle (first component on top, marked in red) during experiments with multiple adapters

Parallel to this static nozzle design representing the current industry standard, another type of nozzle design is investigated which is called ‘rotating nozzle’, due to its rotating movement of the nozzle body around an inner stator. This leads to a quasi-pulsating effect of the water (jet) striking on the surface of the rock, a more uniform and complete distribution of the high pressure water jet inside the borehole and thus, more regular, circular shaped laterals. During all conducted surface tests it shows better rock

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destruction and penetration results under same hydraulic conditions than the static nozzle design. Therefore, this new design can already be seen as an improvement of the current, static jet nozzle standard technology and may be applied, tested and used soon downhole as well. This so called rotating nozzle consists of three main components: a static inner part / stator (1), a rotating body / rotor with multiple outlets (2) and another static outer body (3). The following figure 5 illustrates this nozzle design and figure 6, figure 7 and figure 8

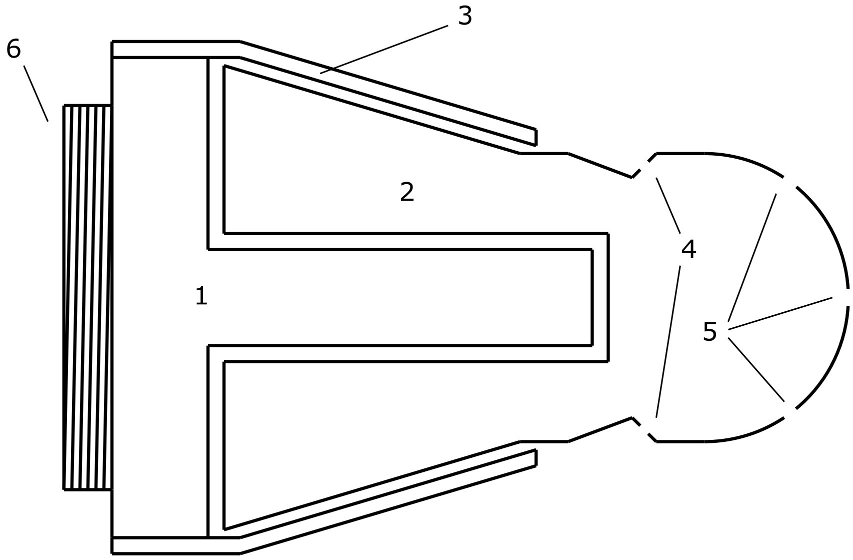

figure 5: schematic sketch of rotating nozzle design

figure 6: rotating body

figure 7: static inner part

figure 8: static outer part

The rotor / inner rotating part (2) is connected via hydro bearing to the stator / static inner (1) and outer (3) body of the nozzle. This rotating body also has forward (5) and backward (4) oriented nozzles that have the same tasks like those of its static counterpart from before. The complete rotating nozzle is screwed via threaded connection / NPT (6) onto a high pressure hose. The operating conditions during the experiments cover flow rates ranging from 15 to 25 l/min, resulting in pump pressures ranging from 200 to 230 bar, which can be assumed as well as pressure drop at the nozzle as a shortened high pressure hose is used. The fluid / water is being pumped through high pressure hoses with field specifications (here: Parker Tough hose, 200

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MPa), that is shortened for testing to < 10 m in order to minimize pressure losses. Higher lengths of the hose result in higher pressure losses that unnecessarily require pump pressures but not increase the flow rates. Hence, the test setup represents real hydraulic field and jetting conditions as being applied at typical jetting operations.

Test results and data evaluation

In the following Table 1 results of the jetting experiments with the mentioned nozzle designs are listed. It can be clearly seen that the best jetting performance with the currently available technology can be achieved with specimens from the sandstone of Bad Bentheim/Gildehaus quarry location. Rate of penetrations of up to 4 m/h are possible with a flow rate of 20 l/min and a bit pressure of 230 bar using the rotating nozzle design. With this setup a hole of 118 mm depth with a diameter of 35 mm can be created within about 3 min in the Bad Bentheim/Gildehaus sandstone. Furthermore in case of successful penetration into the rock, the diameter of the horizontal borehole, also called lateral, has an almost constant value of 33 – 35 mm. During the test series the static nozzle is not able to create boreholes, and thus laterals, under the experimental conditions. No rock sample is penetrated successfully using the static design as no bore hole is created at the surface of the rock block and thus allowing for the jetting nozzle to enter further into the rock. In the following figure 9 and figure 10 the borehole front of the static and rotating nozzle can be seen.

Table 1: test results with current RJD technology

Sandstone	Flow Rate (l/min)	Pressure at bit (bar)	ROP (m/h)	Nozzle Type
Friedewald	20	230	0.46	rotating
Bad Dürkheim	20	230	0.25	rotating
Gildehaus	20	230	**4.28**	rotating
Rüthen	20	230	0.144	rotating

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figure 9: jetted borehole in Bad Bentheim/Gildehaus sandstone with rotating nozzle design

figure 9 shows the photo of the complex borehole geometry of the rotating nozzle. The shape of the hole is symmetric which is achieved by the rotating movement and hence the rotating penetration of the high pressure water jet. Furthermore several stages within the borehole can be seen that result from the different orientations of the forward and backward oriented outlets and will be discussed further under 3.2.

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figure 10: Bad Bentheim/Gildehaus sandstone, comparison of boreholes rotating (left and right) and static nozzle design (middle)

Comparing the jetting boreholes of the rotating and static nozzle bit in figure 10 it can be seen, that the static nozzle is not able to create borehole that is large and uniform enough to serve as an entrance for the bit and the high pressure hose under these ambient, atmospheric pressure conditions. The four forward oriented outlets create single micro boreholes that are not connected to each other. Thus the area they cover is much too small for guiding the rest of the following jetting bit through.

Discussion

The measured data clearly indicate that the Gildehaus/Bad Bentheim sandstone is most suitable for the currently available radial water jet drilling technology under atmospheric condition. Even though the established database of the experiments is low in number of tests and possibilities of repeatable measurements, the values for rate of penetration do show a very clear difference. But one must kept in mind that these tests are just valid for atmospheric conditions. Normally at reservoir depth three

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components act together that influence the performance of a drilling action in general, independent of the formation type. These are temperature in the reservoir, the in-situ stress field and the state of the rock, saturated or unsaturated. These three factors are knowingly neglected in these first test series at this stage. By comparing the achieved penetration rate per unit time as well as the amount of water needed to create the laterals it can be clearly seen that it is far less than those rates reported in literature (Ragab, 2013). This difference might arise from the different interaction between the high pressure water jet at atmospheric and downhole conditions. In literature several erosion mechanism are described that are assumed to erode the borehole wall (Buset, Riiber, & Eek, 2001) but at current state of knowledge, none of the mentioned ones is clearly specified as the governing one. Consequently the influence of the downhole conditions on the jetting performance compared to surface conditions cannot be estimated.

Based on these observations and experimental results the decision to execute the scheduled quarry test in the quarry located near Gildehaus/Bad Bentheim is made.

After completion of the test series some dedicated boreholes and laterals, mainly of Gildehaus/Bad Bentheim and Friedewald sandstone, are cored and inspected concerning their shape and size via CT scan and thin section analysis and therefore sent off to project partners.

3.2. Investigation of borehole and lateral geometry

The borehole and thus, its geometry, has been generated by use of static and rotating jet drilling nozzles. Therefore, respective sketches are illustrated in figure 11 and , showing schematically the flow field in front of the borehole wall, the resulting shape of the cavity and the different working principles of both nozzles.

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Borehole and lateral shape of the rotating nozzle design

The rotating nozzle is explained in figure 11 showing on the left a technical sketch of the bit including the high pressure water jets passing through forward and backward oriented outlets indicated by the blue dashed lines. On the right side of figure 11 a two dimensional projection of the cavity is shown including the moving direction of the various nozzle outlets.

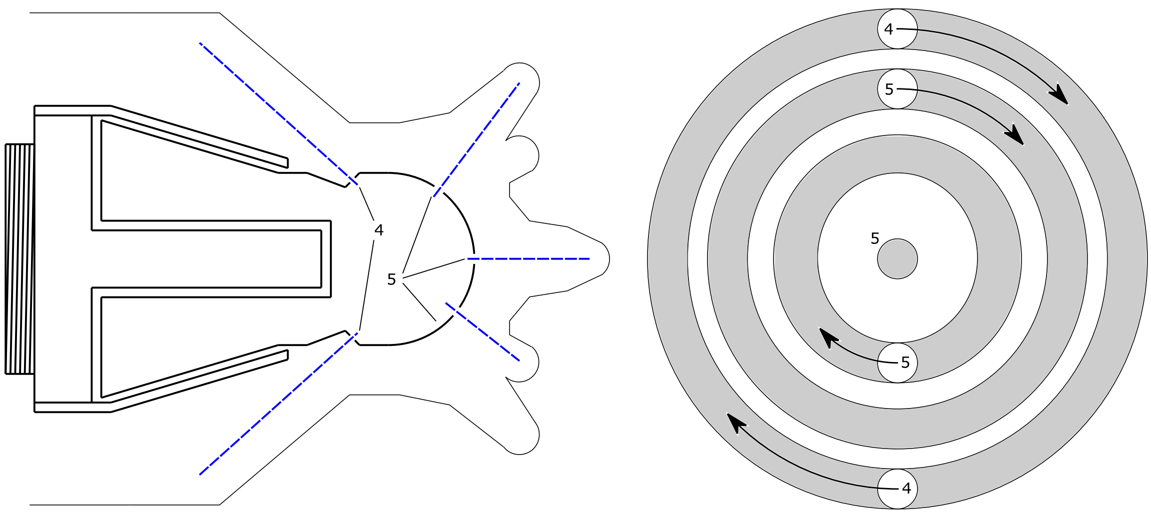

figure 11: mechanism and borehole shape of rotating nozzle design

It can be seen in figure 11 that the rotating nozzle creates a wellbore of a complex shape towards the front with a rather round trajectory borehole wall, resulting from the rotating movement of this bit. Each one of the high pressure water jets exposed from the rotating body is not only acting on a single point at the borehole wall. Each jet follows a circular path at the wall, erodes material and hence, does create a cylindrical borehole with symmetrical shape. Therefore, the backward oriented outlets (4 in figure 11) widen the borehole and create the forward movement of the bit. Therefore they create a helical pattern along the lateral walls, while the forward oriented outlets erode material in the front.

Similar to the design of a tri- or roller cone bit the forward oriented nozzles of the rotating nozzle design are also not distributed symmetrically around the rotation axis.

One outlet is directly set along the center line and ejects its water jet straight forward onto the rock, parallel to the rotation axis of the body. The next jet has an offset to the side of the center nozzle and exposes its water jet with a certain angel towards the borehole symmetry axis. The third outlet is located a bit more offset and thus, also erodes material away next to the midpoint of the borehole. In figure 11 these outlets are all labeled no. 5, and their circular path can be seen as the moving direction is indicated by arrows. Due to the different orientation angles of these forward outlets their respective depth of penetration varies, and the borehole wall does not show an

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even, plane surface. Each orbit of the forward outlets is characterized by a certain depth and orientation at the borehole wall, where the centered outlet reaches the highest depth. All nozzle outlets together therefore cover a cumulative area in the borehole that in the end is of round shape, and the material being equally eroded in the wellbore. In figure 9 a photo of such a complex borehole geometry is shown that is created in the sandstone rock sample of Gildehaus/Bad Bentheim quarry location.

Borehole and lateral shape of the static nozzle

In figure 12 a sketch of the wellbore shape resulting from a standard, static nozzle with multiple outlets is shown. The basic working principle of this nozzle is comparable to that of the rotating one: the forward oriented outlets erode the material in front of the bit to ensure that the nozzle can move at all into the formation, while the backward oriented outlets widen the borehole, produce a forward thrust and thus, create the lateral (left side figure 12). Due to the fixed position and orientation of the outlets, the lateral and borehole geometry has a star shaped pattern, which is illustrated on the right side of figure 12 (Ragab, 2013).

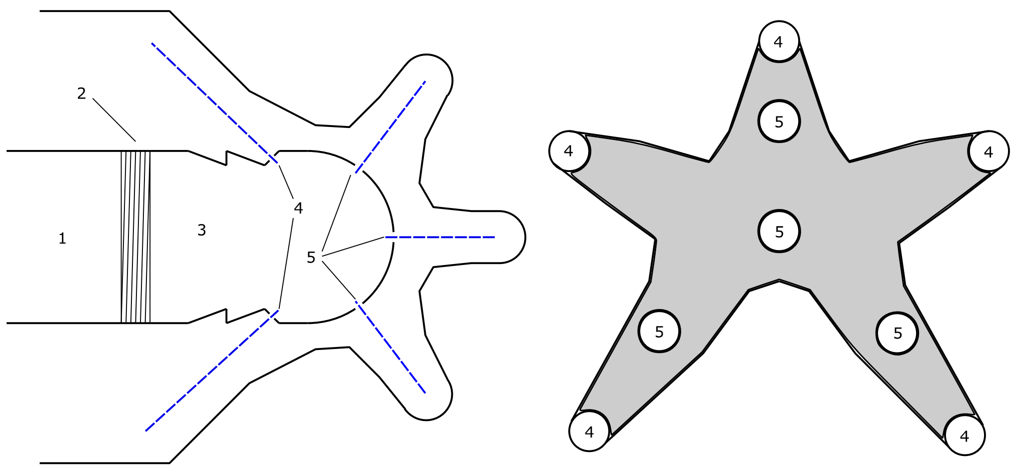

figure 12: mechanism and borehole shape of static nozzle design

This star shape form figure 12 results mainly from the different orientations and location of each of the outlets. Concerning the forward oriented outlets (5) it can be seen that one is set directly at the center, exposing its water jet straight forward into the rock parallel to the center axis of the bit (3). Three other forward oriented outlets are equally distributed in triangular position (120° spacing) at the front face with an offset to the center one. Due to their location and orientation the ejected water jets the shape of the borehole front is triangular, which can be seen in figure 10. The five backward oriented and inclined jets (4) widen the borehole. Due to their number, location and (backward) orientation within the nozzle the initially triangular shape of the borehole front is

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enlarged and changed into a five star shape pattern. Furthermore, just like with the rotating jet nozzle, the backward set outlets also create the necessary thrust to push the complete jetting bit into the rock. The amount of thrust depends on the number and distribution of the backward oriented outlets as well as the annular space in the lateral between jetting bit and borehole wall (Wang, et al., 2015).

Comparison rotating and static nozzle

The experiments with the radial water jet drilling technology at ambient conditions show that the rotating nozzle design is already more advanced than the static one. One main reason lies within the rotating movement of the nozzle body which creates a uniform penetration of the rock surface at the borehole front and wall by the forward and backward oriented outlets. Due to that they cover a wider area in the wellbore and the borehole front is eroded almost uniformly. As a result of the rotating movement of the nozzle body the load applied at the borehole wall is of oscillating character. At an initial time step the high pressure water jet attacks one discrete point on the borehole wall. At the next time step the body rotates by a certain angle and the water jet attacks the neighbouring point at the borehole wall. This procedures is repeated until a circle of 360° is fulfilled. Consequently the load on the rock surface is of pulsating character related to the rotational frequency of the nozzle. It is commonly know from engineering science that load application with oscillating characteristic leads to failure of a specimen even if the absolute amplitude of the load itself is much smaller compared to a static one. Consequently the design and therefore the working principle of the rotating nozzle differs from the static one, resulting in higher material erosion efficiency. One must kept in mind that the rotating nozzle design is initially not designed to create wellbores in rock formations. Consequently a better understanding of erosion mechanism of this design bears huge potential for improving the current available radial water jet drilling technology, namely the static nozzle design that is commonly used in the industry.

Another advance of the rotating nozzle refers to the form of the laterals. Due to their almost round shape, the stability of these laterals is increased as the tension, applied by vertical and horizontal stresses, is more uniformly distributed, instead of showing extreme local concentrations along the borehole wall. In contrast, the laterals created by the static nozzle design are affected by a non-uniform stress distribution, mainly in the corners and edges of their star shaped borehole wall. An earlier collapse of such a star shaped lateral compared to a round one produced by a rotating nozzle might be result.

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In terms of contact area with the surrounding formation the static nozzle design is of advantage compared to the rotating design. Due to the complex form the cumulative area is larger where fluid passes by and hence the drainage area of the lateral is higher compared to laterals created by the rotating nozzle design.

By comparing both nozzle design it can be generally stated that the geometry of the nozzle outlets themselves is of poor manufacturing and design quality. From the literature it is known that certain nozzle designs cause different erosion rates under varying operating conditions. It turned out that for single nozzles a certain diameter to length ratio is optimum (Soyama, 2011). This does not seem to be considered in the state of the art nozzle design, regarding the static and rotating one. Especially the static nozzle shows a rather simple as the outlets are simply drilled in the front face of the bit without following any design specifications. It is commonly assumed that cavitation erosion is one of the main erosion mechanism in radial water jet drilling (Buset, Riiber, & Eek, 2001), (Li Z. , 2013). Based on this assumption both nozzle designs, the rotating and the static nozzle, bear huge potential in terms of optimizing the design of the outlets in order to increase the potential of cavitation erosion for material removal in the wellbore.

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4. Influence of operating conditions on jetting performance

4.1. Jetability experiments on sandstone rock types

The scope of the jetability tests is to judge and evaluate the induced erosion or removal of material from different rock types under various operating conditions. For this purpose a set of parameters is defined that is varied in test procedures enabling to quantify the material removal rate independent from the erosion mechanism in a newly developed index.

The tests focus on the use of a single nozzle with the following geometry: a typical self-propelling radial jet drilling nozzle has multiple forward and backward oriented outlets that release a high pressure water jet into the borehole. Each of the outlets is defined by its own diameter and hence, its own cross sectional area for the fluid. The exit speed of the water jet at each outlet is not defined by the individual bore diameter, but by the cumulative area of all nozzle outlets. As the exit speed stays constant at each nozzle outlet, only the volume flow changes for each outlet, according to its cross section. Hence, the basic assumption of the jetability tests is that 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.

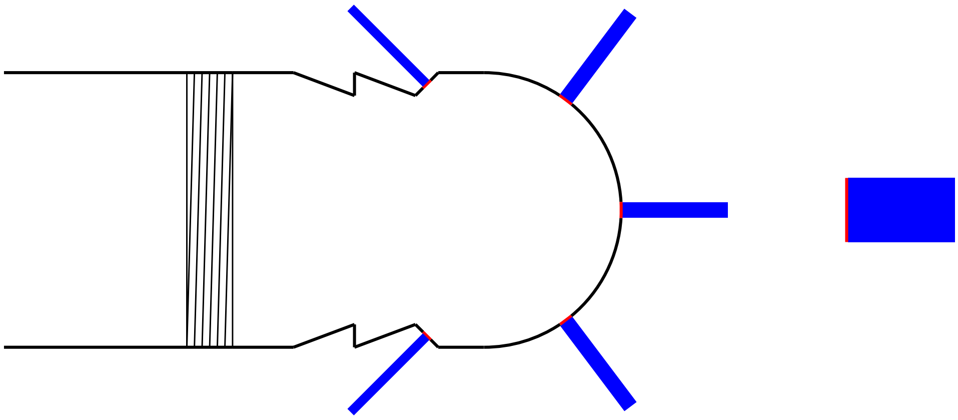

figure 13: relationship of multiple outlet areas to one cumulative area

figure 13 shows on the left hand side of the sketch a static radial water jet drilling nozzle with multiple outlets ejecting water jets with the same exit velocity. But in combination with the corresponding outlet areas, different mass flow rates exit the nozzle. On the right hand side of figure 13 the cumulative outlet area with the corresponding mass flow is shown. Consequently a design for the single nozzle is used, mainly depending on the orifice diameter that allows to adjust the same amount of kinetic jet energy on the rock surface that can be compared to radial water jet drilling nozzles. The operating

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conditions for the jetability experiments refer then to the exit velocity of the jet and the standoff distance between nozzle outlet and rock surface. For comparison two nozzle diameters are used in order to proof the dependency on nozzle outlet diameter.

Test setup and equipment

In order to ensure repeatable measurements, rock specimens are prepared that have the form of a slice with a diameter of about 120 mm and a thickness of 50 mm. In the following figure 14 a sketch of a rock specimen can be seen with dimension and target zones for the high pressure water jet to attack on.
The two main functions of the test bench are to hold the rock specimen in place and adjust the standoff distance between rock surface and nozzle outlet. For this purpose the test bench is equipped with a clamping device for the samples and a translatory steering device for the nozzle including high pressure hose. A technical sketch of the test bench can be seen in figure 15 and a photo is presented in figure 16.

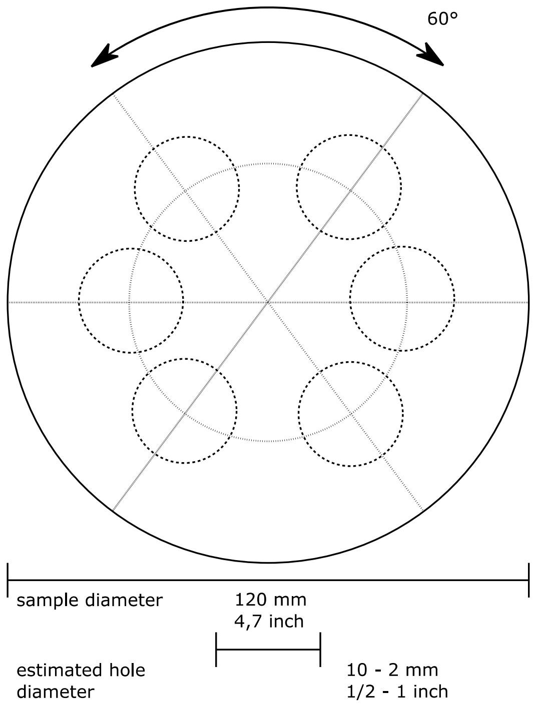

figure 14: rock specimen with dimensions

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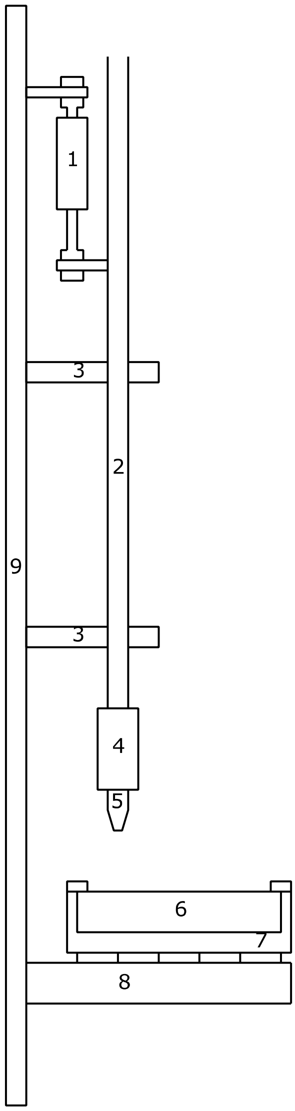

figure 15: technical sketch of test bench

figure 16: photo of manufactured test bench

The high pressure hose is guided through the steel tube (2) and is connected to the adapter (4) where various nozzles (5) can be screwed in. The sample (6) is clamped in a device (7) that can rotate about its central axis on the stator (8). The standoff distance is easily adjusted by a hydraulic cylinder (1) that is connected to the steel tube, whose axial sliding movement is controlled by the fixtures (3). The test bench is installed on a machine bed (9) in order to provide mobility.
The operating conditions cover a flow rate from 20 to 40 l/min with a possible pump pressure ranging up to 330 bar provided by a 40 KW triplex plunger pump. With the according nozzle outlet diameter the exit velocity of the high pressure water jet ranges from 80 to 180 m/s**Fehler! Verweisquelle konnte nicht gefunden werden.**. The fluid is pumped through a high pressure hose with a relatively high inner diameter to the

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nozzle in order to reduce any unnecessary pressure losses. Nozzles with an outlet diameter of 2.0 and 2.3 mm with a relatively low diffusion angle of 1°. The standoff distance is adjusted with a spacer, individually manufactured for each nozzle type and it is set in non-dimensional form in order to produce comparable results. The distance is adjusted in discrete steps of 1.5, 3.0, 5.0, 10.0 and 15.0 times the nozzle outlet diameter. Four different sandstone (sst) types of different age are tested from the following locations:

- Cretaceous Bad Bentheim sandstone, Gildehaus quarry location
- Triassic sandstone, Bad Dürkheim quarry location
- Carboniferous Ruhr Sandstone, Dortmund quarry location
- Triassic middle buntsandstone, Friedewald quarry location

The exposure time of the high pressure water jet is limited to maximum 2:00 minutes and the procedure of adjusting standoff distance and volume flow rate is the same for all four sandstone types (**Fehler! Verweisquelle konnte nicht gefunden werden.**). For each selected flow rate, the entire procedure is repeated three times in order to improve the statistical base for the data evaluation due to the inhomogeneity of the rock specimen. After the experiments the cavities in each specimen are measured concerning their depth and diameter. If the depth reaches the thickness of the slice, the experiment is not considered in the data evaluation as well as fractured or destroyed specimens.

Results and analysis

In order to quantify the measurement results and to compare them with the physical parameters of the rock, an index is defined. It includes the process parameters, in terms of hydraulic energy applied to the specimen, and the material answer, in terms of removed volume and it is defined as followed:

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

This index is called “Jetability Index” and it includes the applied volume flow rate, resulting pump pressure, nozzle exit speed, jet exposure time as well as standoff distance, measured depth and diameter of the produced cavity. Methods of robust statistics are used to gain this index by using three series of experiments, including many outliers distorting the database. Physical rock parameters are provided by the project partners regarding the sandstones from the quarries in Gildehaus, Bad Dürkheim and Dortmund. The test values for the jetability indices are listed in the following:

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- Bad Bentheim/Gildehaus: 2.9e-3 $\left(\frac{mm^3}{J}\right)$
- Bad Dürkheim: 2.3e-3 $\left(\frac{mm^3}{J}\right)$
- Dortmund: 7.1e-4 $\left(\frac{mm^3}{J}\right)$

The results clearly show that the Bad Bentheim sandstone from Gildehaus quarry location offers the best possibility to be eroded with a pure water jet. It has the highest value for the jetability index of 2.9e-3 (mm^3/J) ,followed by the sst located in Bad Dürkheim with a value of 2.3e-3 (mm^3/J) . Dortmund sst has the lowest value for the index with just 7.4e-4 (mm^3/J), which is appr. factor 10 less compared to the others. Considering the jetability 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, the Dortmund sst has the highest mechanical toughness, indicated by the highest values for uniaxial compressive (UCS) and tensile strength, as well as fracture toughness model I (KI) of all three tested sandstones. It also shows the lowest values for porosity, permeability and jetability. 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.
Despite of that dependency of several parameters affecting the jetability of the different sandstone types, a certain threshold velocity, or minimum amount of hydraulic energy, can be detected at which an erosion process starts. The experimental results reveal that the erosion process for the Dortmund sandstone does not start unless a nozzle outlet velocity of 180 m/s is reached. At lower speeds, referring to the data series for 100 m/s exit velocity, it can be stated that the sandstone from the quarry location in Gildehaus tends to be eroded slightly better than Bad Dürkheim sandstone. But above this threshold velocity both show almost the same characteristic. Furthermore, the standoff distance does not play a major role in the erosion process which can be explained by the relatively low diffusion angle of 1° of the used nozzles. The influence of the nozzle outlet diameter on the jetting performance is also not a predominant factor as it can be seen by comparing the jetability index values for certain velocities. The difference referring to the velocities is negligible as well as the differences in the diameters of the produced cavities in the specimens.

Discussion of the results

The gained values for the jetability indices show a clear tendency towards higher nozzle outlet velocities to erode material from harder rock types. Next to this they proof

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partly the results of the jet drilling experiments at ambient conditions which stated that the sandstone from Dortmund quarry location is applicable to the technology at their current state. Considering the massive difference in the jet drilling performance at ambient conditions with almost the same jetability index values of the Gildehaus and Bad Dürkheim sandstone a discrepancy arises. As the repeatability of the jetability tests is given by controlling the operation parameters, mainly standoff distance and nozzle spray characteristic, one might come to the conclusion that the process with the radial water jet drilling technology is of such a high degree of complexity, that more fundamental work and investigations needs to be done in the understanding of the fluid structure interaction. This gained knowledge then can be transferred to understand, control and improve the technology. Another critical point that needs to be mentioned refers to the test procedure: as the erosion process is a highly transient process the time dependency is neglected by setting a fixed jet exposure time of 2:00 min. Experimental data from a small parallel test series indicate a time dependency between depth of cavity and initiation of the erosion process as well. At last the measurements are performed at atmospheric conditions. As a different conditions appear in real radial water jet drilling borehole, higher surrounding pressure, one step towards further in the experimental setup would be to repeat the measurements under partly simulated downhole conditions. As the approach of characterizing and quantifying different rock types by their ability to be eroded with pure high pressure water jets is rather unique and new, it is hard to find comparable results in literature. In (Wang, et al., 2015) and (Summers & McGroarty, 1982) similar experiments are performed with softer sandstones at atmospheric conditions and nozzle types referring to radial water jet drilling technology. Although it is not clearly defined in this paper what it meant by softer sandstone in terms of mechanical properties, it is stated that a threshold pressure of 90 bar is required to break the rock surface of the specimen and erode material.

4.2. Determination of minimum threshold velocity of harder rock types

Up to date the radial water jet drilling technology has mainly been applied in the oil and gas industry in softer sandstone type reservoir rocks, but so far not in harder rock types that typically may be found in geothermal reservoirs. In SURE WP6 the technology is applied to a wellsite in Iceland, where basaltic rocks are prevalent. In order to estimate the possible success of a jetting operation with the currently available technology, evaluating tests are performed in order determine the minimum threshold velocity for the high pressure water jet in order to possibly create a cavity.

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Test setup and equipment

Therefore, four different types of Icelandic basalt are investigated which represent possible layers from the test sites in Iceland where the radial water jet drilling technology is supposed to be applied within WP6 in 2018. The specimen differ in size to the jetability measurements before as they have a smaller diameter of just 40 mm. The process of sample preparation remains the same as before. With an adapter the specimen can be used in the same test bench. In contrast to the initial jetability experiments, the standoff distance now is being kept at a constant value of 1.5 times the nozzle diameter, based on literature research, suggesting the hard core region of the high pressure water jet is expected then to be fully developed. Based on the experiences with the harder Dortmund sandstone it is required to create higher nozzle exit speeds in order to successfully penetrate the Iceland basalt. Therefore, a more powerful triplex pump (250 kW) is used, capable of delivering pressures up to 1500 bar. Higher nozzle exit speeds are then realized by using a single nozzle with an outlet diameter of 1.1 mm. The high pressure water jet penetrates the rock surface for a maximum exposure time of 2:00min per sample.

Results and analysis

It can be clearly stated that the minimum nozzle velocity is 330 m/s to produce a cavity in VBA6-IC 03 specimen. Below that threshold velocity only material at the surface of the rock is ablated and no cavity is produced. In the following figure 17 the produced cavity in the Iceland Basalt specimen VBA6-IC-03 is shown.

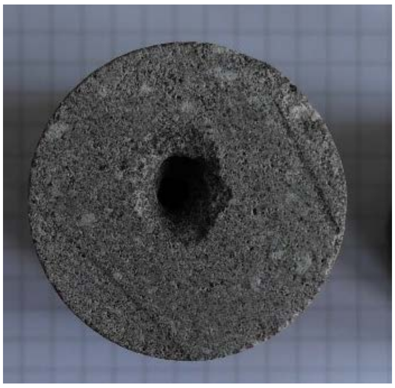

figure 17: Iceland Basalt specimen VBA6-IC-03 at 330 m/s nozzle exit speed

The produced cavity almost has a cylindrical shape, just on the top it shows an elliptical form. The average diameter is about three to four times the nozzle diameter of 1.1 mm.

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Regarding the measurement data of the other basalt types it is clear that they require even higher nozzle exit speeds, resulting in higher pump pressures, as no material is removed. VBA6-IC 02 and VBA6-IC 04 require exit speeds close to 400 m/s to extract material which leads mostly to fracturing of specimen next to creation of a cavitation. In the following figure 18 and figure 19 the fractured specimen are shown.

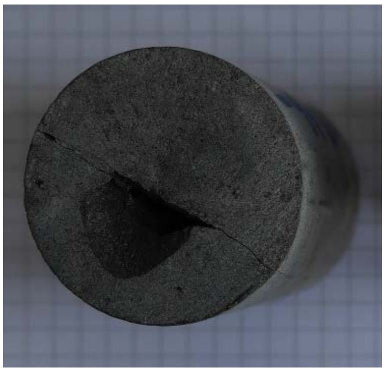

figure 18: Iceland Basalt specimen VBA6-IC-02 at 400 m/s nozzle exit speed

The specimen referred to VBA6-IC 02 is fractured which can be seen by the crack dividing the specimen in two halves that is initiated by the cavity in the middle of the rock cylinder. The fracture in this specimen does not lead to full destruction of the rock sample, the form of the cylinder almost remains and only a crack occurs. In contrast to that VBA6-IC 04 shows another response to an induced fracture which can be seen in the following figure 19.

figure 19: Iceland Basalt specimen VBA6-IC-04 at 400 m/s nozzle exit speed

The specimen referred to VBA6-IC 04 is also fractured and almost totally destroyed. It is not divided in almost two halves of same shape and geometry. The starting from the big fracture in the centre of the specimen, many cracks are induced in the sample and lots of smaller pieces of rock are extracted. Hence jetting through a formation type like VBA6-IC 04 might cause severe problems of plugging the annular cross section of

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jetting borehole due to large cuttings and debris. As already stated, below a nozzle exit speed of 400 m/s this formation type does not react to the high pressure water jet and no material is removed at all.

As the current state of the art jetting process is able to deliver respective nozzle pressures up to 300 bar, converted into the according nozzle exit speed depending on the cumulative are of the orifice outlet diameters, it can be stated that this technology at its current state is not able to create a wellbore in harder formation types.

Discussion

The measured values for the threshold velocity demonstrate that higher nozzle outlet velocities and hence, nozzle and pump pressures are needed, compared to sandstone rock types in order to successfully erode material. This occurs mainly due to the mechanical properties of the Icelandic basalt, referring to its high mechanical strength. But the comparison between these two rock types is so far only valid under atmospheric test conditions. In the reservoir, the rock is exposed to a three dimensional stress state as well as high temperatures and possible saturation of the rock. The combination of these three parameters influence the jetability of a rock and its minimum threshold velocity to initiate the erosion process. The interaction of these parameters will enhance the jetting performance of radial water jet drilling technology to some extend and might still lead to an applicability of the commonly used nozzle types in softer sandstone rock types. But a difference in threshold velocity between hard sandstone (Dortmund) and the tested Icelandic basalt of more than 100 m/s enforces the assumption that the currently available radial jet drilling technology is not capable of creating laterals in such hard formation types. Due to the multiple outlets of current radial jet drilling nozzles the exit velocity is limited to 100 to 150 m/s at field operating conditions. Doubling of the nozzle exit speed would result in an enormous effort in increasing the required pump pressure, which is not realizable at current state due to limitations of the equipment, like small diameter, thin walled pressure hoses and coiled tubing sections. Consequently, the erosion mechanism of the fluid jet acting on the rock surface itself needs to be improved.

4.3. Qualitative analysis of influence of saturation on jetting performance

As previously described one influence on the jetting performance, possibility of creating a cavity with a pure high pressure water jet into a rock, refers to the state of the rock, if its pores are filled with a fluid or gas. These states are called saturated and

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unsaturated conditions. Consequently, the basic assumption for the following experiments is that the pores in the rock under reservoir conditions are filled with a fluid. This reservoir fluid can be oil, in case of oil reservoirs, gas or water, more common found in geothermal reservoirs.

Test setup and equipment

In order to bring a specimen in a saturated state, small cores are taken and cut into cylinders of equal dimensions like in the previous experiments referring to the threshold velocities of harder rock types. After the unsaturated samples are cut they are placed in a desiccator cell, which creates a vacuum and thereby extracts the gases out of the pores in the sample. When this process is ended the specimen are submerged in degassed water and, due to the vacuum in the pores, this water is sucked inside the rock pores and thus, the rock becomes saturated. Again, the test bench of the previous jetability tests is used as well as the adapter for the clamping device enabling handling specimen of smaller diameter. The pressure is supplied by the smaller triplex type pump (45 kW), which is limited to maximum 330 bar. The hard sandstone from the Dortmund quarry location is selected to be investigated first. In order to evaluate the influence of pore fluid on the erosion process, the nozzle exit speed is adjusted to 140 m/s, which is 40 m/s below the minimum threshold velocity derived from the previous jetability measurements for this sandstone type at atmospheric and unsaturated conditions. All in all three samples are tested of which two are filled with pore fluid and one is left in unsaturated state in order to proof the influence as all specimens are made out of one and the same rock core. Hence, it is assumed that these three samples have the same mechanical and physical properties. For this test a single nozzle is used, having an outlet diameter of 2.0 mm. The standoff distance between nozzle outlet and rock surface is set to 1.5 times the nozzle diameter. The maximum jet exposure time on the specimen is 2 min.

Results and analysis

In the following figure 20 the result for a 2:00 min of jet exposure time on the unsaturated sample is shown.

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figure 20: Dortmund sandstone after 2:00 min jet exposure time, unsaturated

After 120 seconds of jetting with a nozzle exit velocity of 140 m/s no cavity is produced and hence no material removed as it can be seen in figure 20. This observation goes along with the results from the jetability tests where this behaviour of the Dortmund sandstone is documented by several test series at this velocity stage. In the following figure 21 a saturated sample is shown after 60 seconds of experiment.

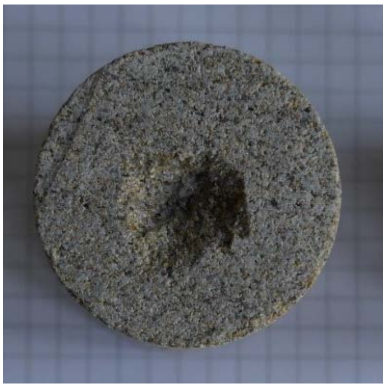

figure 21: Dortmund sandstone after 1:00 min jet exposure time, saturated

The specimen shown in figure 21 shows how the water jet successfully penetrates the rock sample under saturated conditions after only 1:00 min. It can be clearly seen that the erosion process is initiated and a shallow cavity is produced with lots of material removed from the surface. figure 22 shows a saturated samples after 2:00 min of jet exposure time.

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figure 22: Dortmund sandstone after 2:00 min jet exposure time, saturated

The specimen in figure 22 shows the effect of 2:00 min jet exposure time on a saturated rock sample. A deep cavity is produced in the centre of the specimen which leads to fracturing of sample and a big peace is broken off.

Discussion

This test series shows that the saturation of a rock has a big influence on the initiation of the erosion process. It reduces the minimum threshold velocity to produce a cavity and starting the erosion of the rock. The test against the unsaturated sample and the comparison with the measurement results for the Dortmund sandstone derived in the jetability experiments support this conclusion. In this test series, however, the reservoir parameters temperature and stress field within the rock are neglected. If a further decrease of threshold velocity may be expected in case they are considered in future tests, is not clear at current state of knowledge. Concerning the application of a stress field it is found in literature (Wang, et al., 2015) that the application of confining pressure might even increase the required nozzle exit speed to erode material.

4.4. Jetting experiments in water flooded environments

It is well known from literature that an exposed water jet behaves differently under atmospheric and submerged conditions. This refers to the velocity distribution inside the jet as well as to the aggregate state of the accelerated water. Due to the surrounding water a relatively high slip velocity occurs between the jet itself and the fluid which leads to two effects.
At first the velocity profile of a high pressure water jet exposed into water differs a lot compared that one at atmospheric conditions. Due to the ‘no slip condition’, resulting

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from the high shear forces acting at the outer regions of the jet and the surrounding fluid, the jet is deaccelerated at its outer regions to zero velocity and it loses a high amount of kinetic energy with increasing standoff distance (Miozzi, Lalli, & Romano, 2010). Resulting from the loss impulse in axial and radial direction the aggressiveness of the water jet is lower compared to atmospheric conditions. Based on an impulse balance the velocity distribution inside the jet can be derived analytically when a standard distribution for kinetic energy is assumed (Rajaratnam, 1976). With this the following figure 23 can be generated, showing the velocity distribution of a submerged water jet relative to the standoff distance. The specifications concerning nozzle outlet diameter (2.00 mm), averaged nozzle exit speed (160 m/s at 30 l/min flow rate) as well as standoff distance (divided into 6 steps) refer to the jetability experiments under atmospheric conditions for comparison reason. The first graphs refers to the jet directly at nozzle exit, the second to a standoff distance of 1.5 times the nozzle diameter, the second to 3.0 times the diameter, the third to 5.0 times and the fourth to 10.0 and respectively 15.0 times the nozzle outlet diameter.

It can be seen from figure 23 that the velocity distribution inside the jet, and hence the distribution of kinetic energy, is highly non-uniform in radial direction and massively depending on the standoff distance between nozzle outlet and target surface (Pope, 2000). Concerning a high pressure water exposed in free air, a much more homogenous velocity distribution can be assumed without zero velocity and thus particularly no loss of kinetic energy in axial direction of the jet. Consequently the impact load on the rock surface extracting particles differs a lot between atmospheric and submerged conditions.

The second effect of submerged conditions relates to the occurrence of cavitation regimes near the interface between high pressure water jet and surrounding fluid (Soyama & Mikamo, 2005). Due to the high velocity gradient between the core of the jet and the stagnating fluid in the surrounding near area, high pressure gradients result enhancing the growth of cavitation bubbles. These gas or liquid filled droplets are then transported at the target surface where they implode causing pressure peaks that are multiple times higher than the stagnation pressure of the fluid (Steller, Krella, Koronowicz, & Janicki, 2004).

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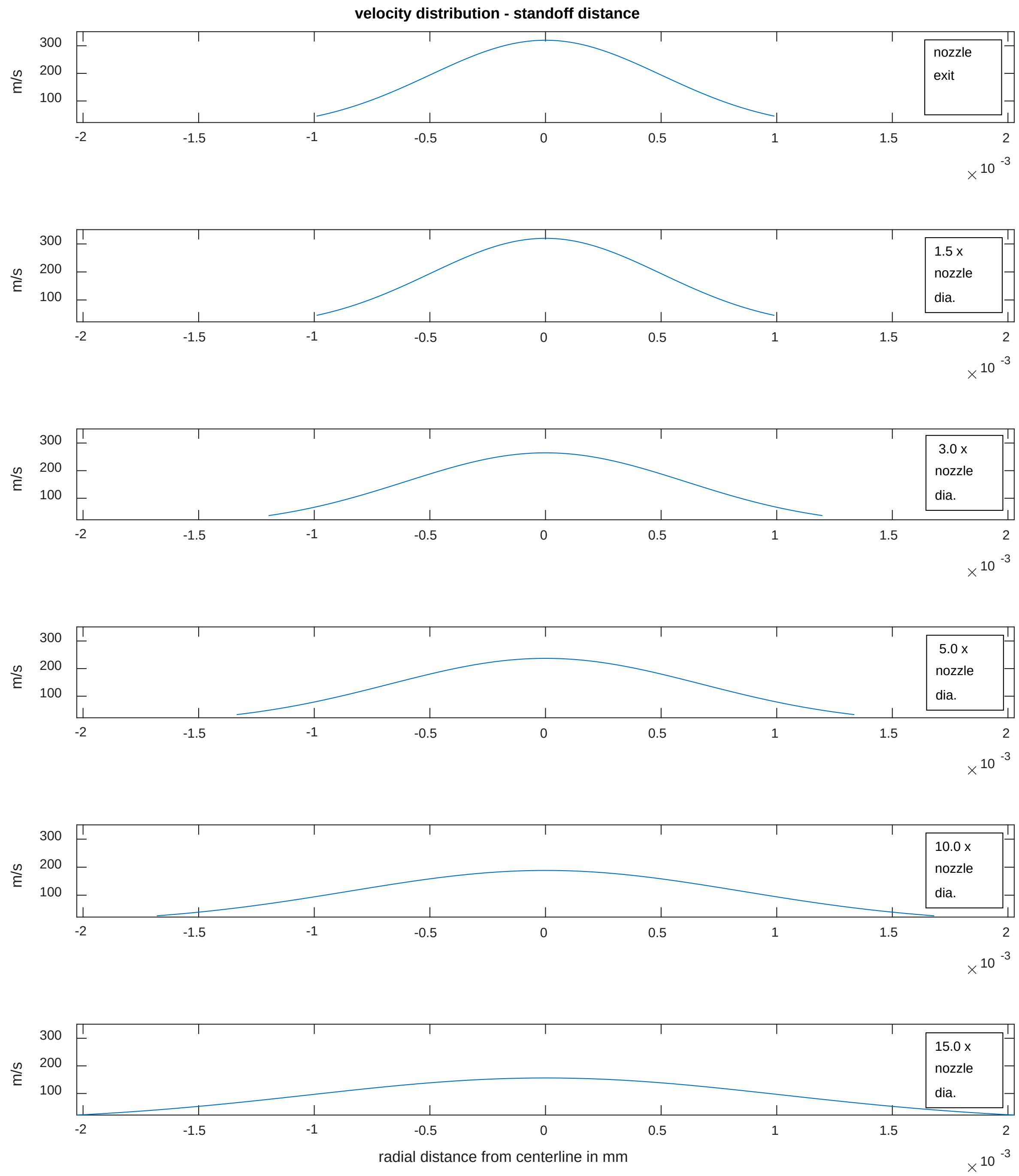

figure 23: velocity distribution high pressure water jet submerged conditions, calculated according to (Pope, 2000)

For the experiments in water flooded environments it is assumed that the main erosion mechanism relates to cavitation erosion which is greatly enhanced by these submerged conditions. Hence the objective of these experiments is to detect an increase in the mass or volume of removed material, although the high pressure water

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jet is faced with massive loss of impulse, and thus kinetic energy, due to the surrounding stagnating fluid. The identification and visualization of certain cavitation regimes in the high pressure water jet is done via high speed camera during the actual jetting process.

Test setup and equipment

In order to realize the submerged conditions a new test bench is designed mainly consisting of a transparent container filled with water which can be seen in the following figure 24. Its components are listed below:

1. High pressure hose: *behind the wall
2. Thread adapter for different nozzle designs
3. Nozzle
4. Rock sample in clamping adapter, applying pre-tension on the sample
5. Sample clamping with fixed position set by screw
6. Stator: keeps sample clamped in position
7. Jetting tube: optical access through three windows
8. Water tank: high enough water level to avoid entrainment of air
9. Camera
10. Backlight

The experimental setup is comparable to the setup of the jetability tests at atmospheric conditions. The nozzle outlet diameter is 2.0 mm and the standoff distance varies from 1.5 to 3.0 times the nozzle outlet diameter. Two flow rates are examined with three different sandstones. The exposure time varies from 10 seconds for the Bad Bentheim (Gildehaus) and Bad Dürkheim sandstone, to 60 seconds for the Ruhr sandstone of Dortmund quarry location.

Results and analysis

The results are shown in figure 25. It can be seen that the Bad Bentheim sandstone from Gildehaus is penetrated till the maximum depth (height of the cylindrical specimen) every time, even with just a short exposure time of 10 seconds. In comparison to that the Bad Dürkheim sandstone is penetrated to its maximum depth twice. Only one hole is created with 25 liter per minute and a standoff distance of 3.0 times the nozzle outlet diameter. At a shorter standoff distance and same flow rate the rock is just ablated at the surface. Although the exposure time for the Dortmund sandstone is six times higher, only one hole is created. The other experiments show a small ablation at the rock surface.

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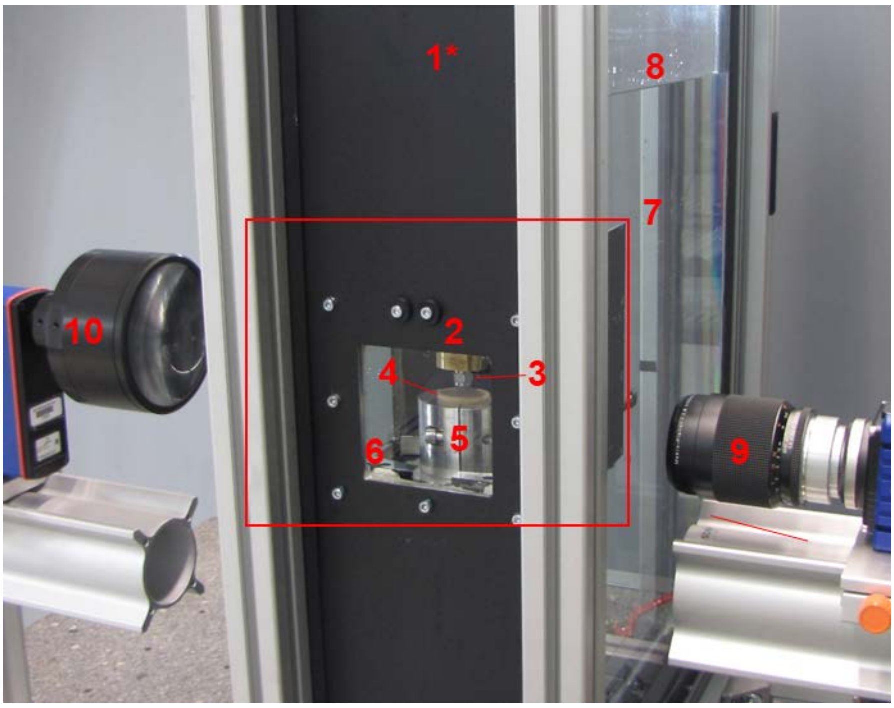

figure 24: test bench for water flooded environments

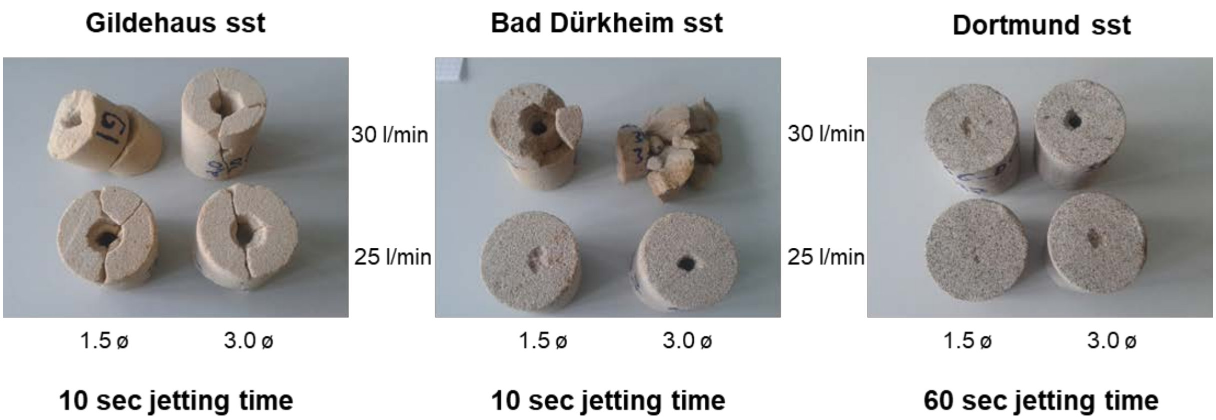

figure 25: results of experiments in water flooded environment

Discussion

Considering the results of the jet-ability experiments (**Fehler! Verweisquelle konnte nicht gefunden werden.**) it can be stated that the high pressure water jet behaves differently at submerged conditions. Comparing the experiments at atmospheric and water flooded conditions with the sandstone from Gildehaus quarry location at a nozzle

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exit speed of 133 m/s, respectively 25 l/min flow rate, it can be seen, that the material is removed much faster with the submerged jet. The enhancement of the erosion process might arise from the cavitation erosion that takes place at the surface of the specimen at the beginning of the jetting action. The surface is eroded faster and an entrance for the high pressure water jet inside the rock specimen is created in a shorter period of time. This process of introducing damage in the surface of a specimen before the water jet erodes material further has been reported in literature already (Steller J. , 1999). Concerning the experiments performed with a nozzle exit sped of 160 m/s, or 30 l/min flow rate, no difference and hence no advance can be determined, as in both cases, at atmospheric and submerged conditions, the samples is fractured due to the high stagnation pressure of the fluid inside the cavity (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The mentioned observations relate to the Bad Dürkheim sandstone specimens also.
For the harder sandstone type of Dortmund quarry location also an advance might be detected. Comparing the results of atmospheric and submerged conditions with standoff distance of 3.0 x nozzle diameter and 160 m/s nozzle exit velocity, respectively 30 l/min flow rate, it can be stated, that under water flooded conditions a cavity can be created. At ambient conditions no hole could be created with equivalent specifications. Again the additional load applied by the imploding cavitation bubbles might weak the surface before the high pressure water jet further removes the material out of the rock (Steller J. , 1999).

Although the number of test runs executed during the jetting experiments at water flooded experiments is quite low, a tendency towards higher material removal rates might be detected and needs to be investigated further.

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5. Documentation of jetting process

5.1. Acoustic measurements of jetting process

Test setup and equipment

As part of the pre quarry tests several sandstones are tested in relation to jetability with current state of the art radial water jet drilling technology. Next in order to determine the best combination of sandstone rock type and jetting technology, acoustic measurements are performed in collaboration with TNO. The main objectives of these initial, early experiments is to determine frequency ranges occurring and resulting from the jetting operations in large rock samples. These acoustic signals are then being recorded and evaluated in order to determine the sensors that would be needed to perform acoustic measurements in the quarry experiment. An exemplary setup including the used sensors and their positions on the rock specimen is shown in figure 26.

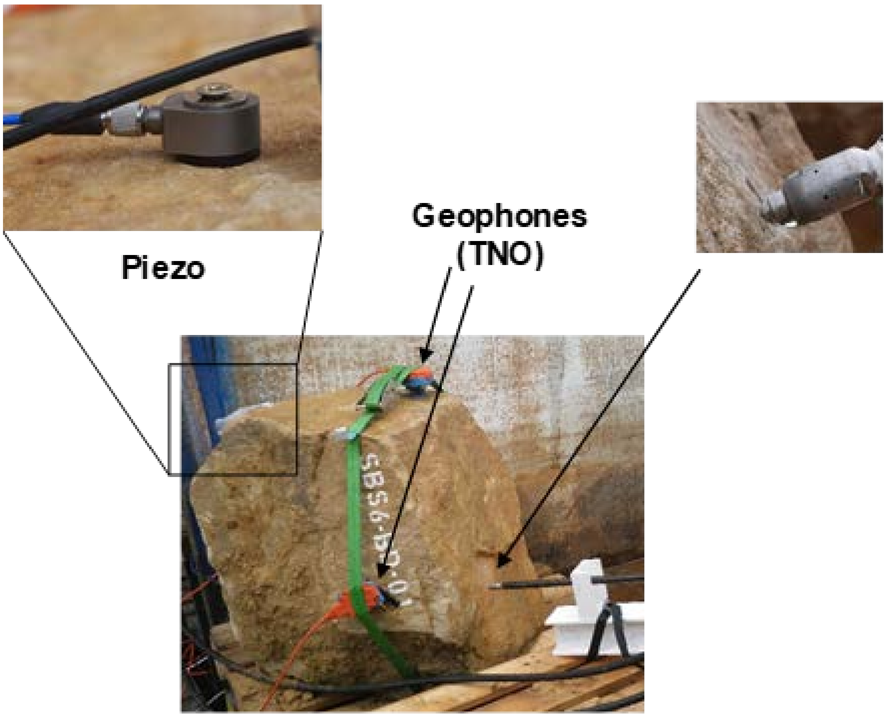

figure 26: initial jetting and acoustic measurements in 2016

To measure acoustic emission piezo sensors are set on the rock surface as well as geophones. After one experiment is recorded the nozzle is changed. During these experiments three different nozzles are tested. The boreholes created by the rotating, static and single nozzle are shown in figure 27.

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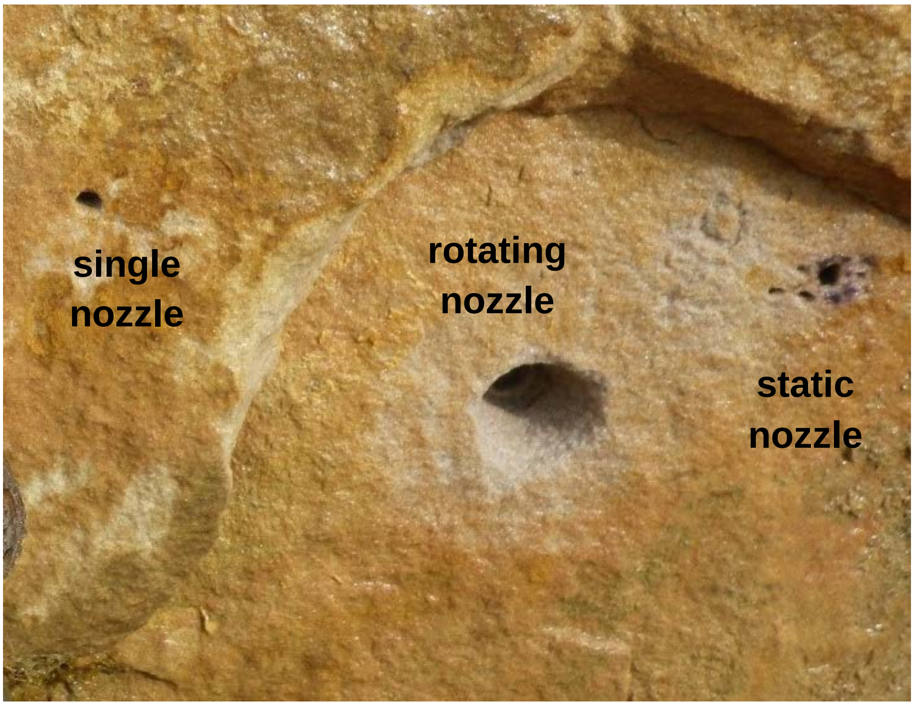

figure 27: created cavities and boreholes by different types of nozzles

Results and analysis

According to different nozzle design, borehole size and geometry the recorded acoustic emissions are different as well. The results are shown in figure 28 and it can be seen that the three nozzles produce different acoustic emissions. The single nozzle creates one very strong signal at 8-9 kHz compared to the static nozzle, although the frequency range is more or less the same. The rotating nozzle shows clearly a different signal compared to the other nozzles. Within a frequency range of 4-10 kHz very thin lines of strong signals can be seen. This seems to be typical for this type of nozzle.
Although the acoustic emission of the three nozzles are different it can be seen that the strongest signal for each nozzle is at frequencies between 8-10 kHz.

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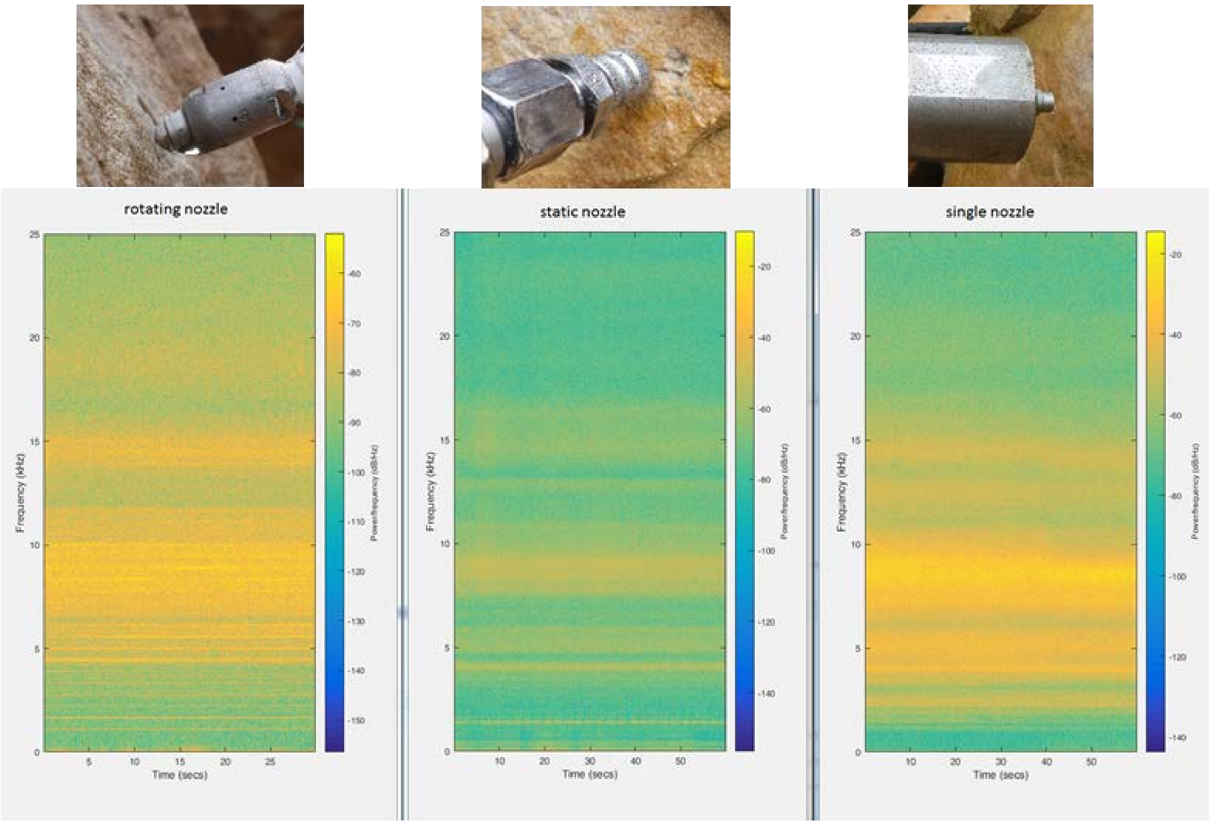

figure 28: acoustic emission of different nozzle designs measured by piezo sensor

Discussion and future experiments

The gained knowledge of the initial experiments including acoustic monitoring of the radial water jet drilling process do serve as a start and preparation for further, more detailed tests at TU DELFT planned for October 2017. In these tests rock blocks will be clamped in a tri-axial cell while jet drilling is performed. During the jetting process acoustic signals emitted from the fluid-rock-interaction as well as the jetting equipment will be recorded by multiple sensors attached to the surface of the rock sample and the relating jetting apparatus. This setup in the tri-axial cell represents reservoir conditions more realistically due to its true tri-axial stress field applied to the rock sample. To compare and evaluate this effect a second experiment under surface conditions without tri-axial stress will be done as well. Via the acoustic measurement system the borehole path is monitored during the whole drilling process as well as the operation state and condition of the complete jetting process. After jetting is completed the data can provide enough detailed information of the jet drilling process including the direction of the jetted path.

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5.2. Optical investigations of RJD technology

Optical investigation of jet drilling experiments at ambient conditions

Test setup and procedure

During the jetting experiments with radial water jet water drilling technology a high speed camera is installed to get some visual impressions of the jetting process. The installation of the facilities is shown in figure 29 and figure 30. This visualization process is very fast and, due to the intensive spray of water, it is not possible to see the nozzle while jetting is happening. Although it is possible to analyze e.g. the rotation speed of the nozzle.

figure 29: high speed camera set up front

figure 30: high speed camera set up back

Results and analysis

The rotation speed is very much depending on the flow rate, but stays roughly at about 500 Hz during the experiments at atmospheric conditions. At submerged conditions the rotations frequency is supposed to be higher if the jetting bit has no contact with the surface of the borehole front. But if the contact between the rotating body and the rock surface occurs, the rotational frequency will be decreased due to surface friction between nozzle front and rock. To which extend must be investigated further by an according experimental setup. The high speed camera is recording with a frame rate

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of 20.000 frames per second. With that the two backward oriented nozzles are able to be observed while they pass through the water spray.
The frequency range is also measured by a piezo sensor as part of acoustic measurements shown in figure 31. The optical and acoustic investigations are carried out in parallel.

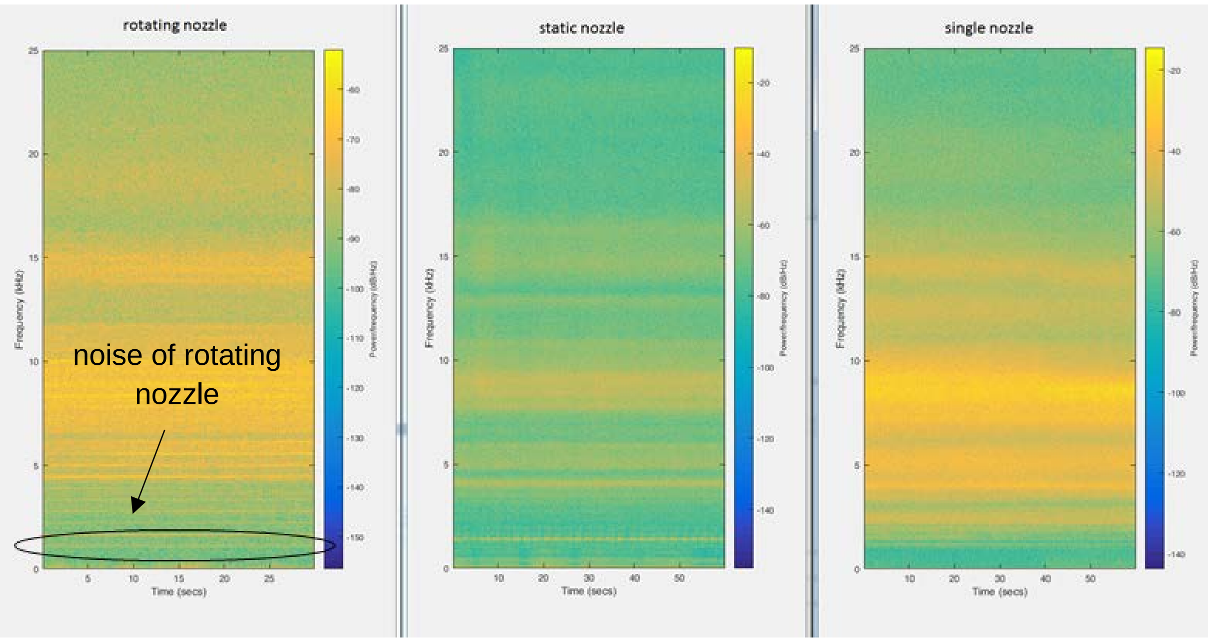

figure 31: noise recorded by piezo sensor - characteristic line in spectrum marks rotation frequency of nozzle

Optical investigation of operating conditions on jetting performance

Test setup

During the water flooded experiments cavitation and heavy degassing is observed. Even with a pump pressure of only 6 bar (tap water) cavitation occurs. To analyse this effect in more detail the backpressure is increased by using a pressure cell, producing slightly “confined conditions” like in a reservoir. The experimental setup is shown in figure 32 and figure 33. On the left photo the waterjet is not visible due to backpressure inside the cell. The maximum backpressure is 10 bar, therefore the experiments are limited by this factor.

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Test procedure

During the experiments the pump is running at constant RPM and flow rate of 7 l/min, which corresponds to an appr. pressure of 30 bar. The backpressure is then increased from 0 – 10 bar in steps of 1 bar. Cavitation is visible and audible if it occurs. figure 34 shows the effect of backpressure in different stages.

figure 32: pressure cell with single nozzle

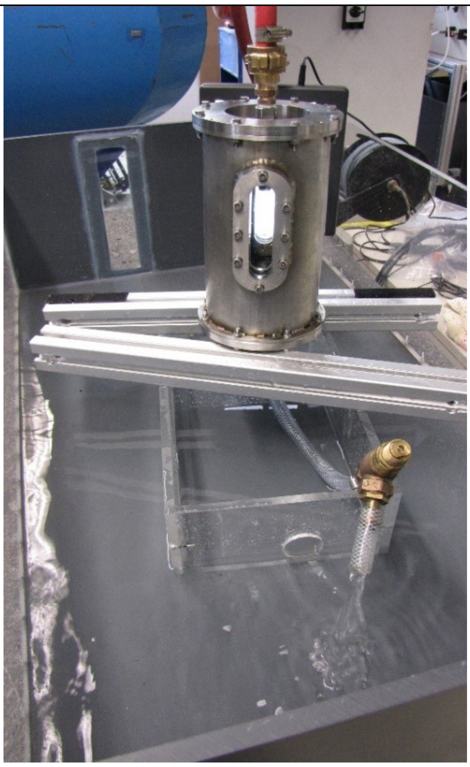

figure 33: experimental setup for pressure cell

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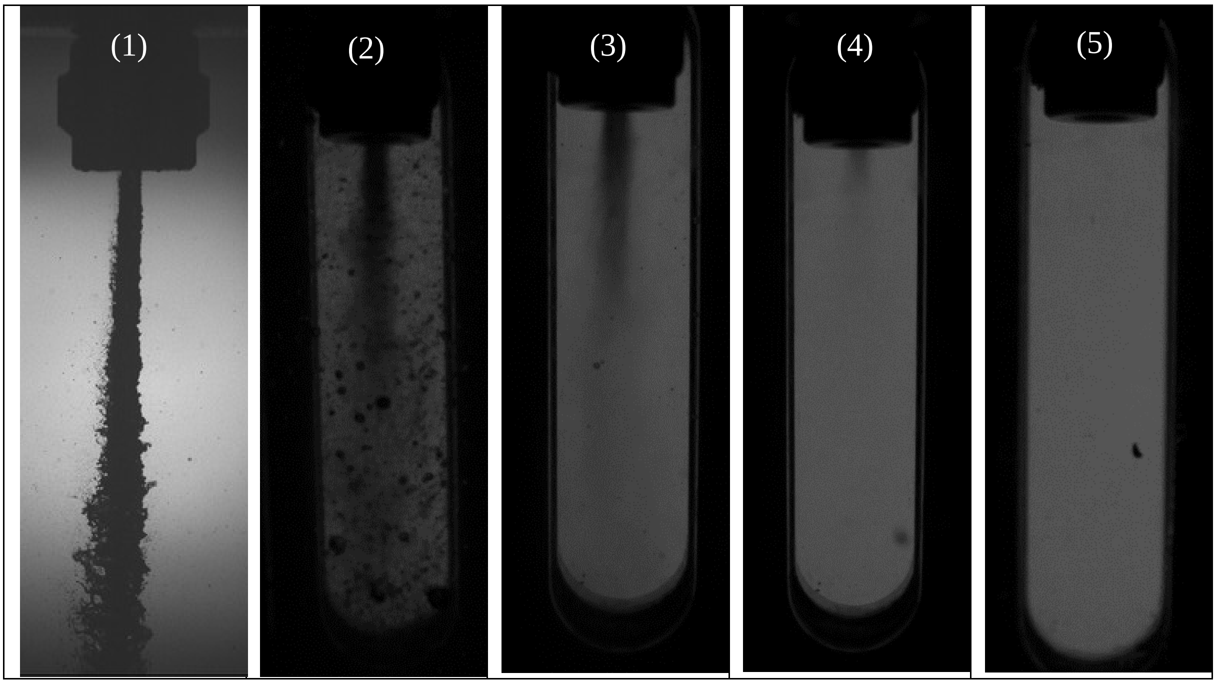

figure 34: photo of water jet at atmospheric condition (1), water flooded (2), 1 bar back pressure (3), 4 bar back pressure (4) and 8 bar back pressure (5) conditions

Results and analysis

It can be seen in figure 34 that cavitation occurs in water flooded environment (2). Despite increasing the backpressure from 1 bar (3) to 4 bar (4) cavitation is still visible and audible, but less strong. From 8 bar (5) to 10 bar cavitation is not any more visible nor audible.

The experiments do show that for a light waterjet at 30 bar nozzle pressure and appr. 7 l/min flow rate a minimum backpressure of 8 bar is needed to avoid cavitation. To be able to measure the exit velocity of the waterjet via particle imaging velocimetry (PIV) cavitation needs to be at all avoided. The measurements are not possible in a two phase flow regime, e.g. because of different refraction indexes.

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6. Conclusions and outlook

The experimental work and gained results in deliverable 5.1 lead to the conclusion that the currently available radial water jet drilling technology is not applicable to harder rock types as they are usually found in geothermal reservoirs under atmospheric conditions. Some experimental results indicate an improvement in the material removal performance towards reservoir conditions, but further detailed experiments and test series are required to quantify the improvement and evaluate the applicability of the currently available technology at these type of conditions. Furthermore, certain work and results of the deliverable reveals that the governing erosion process is not yet finally determined and completely understood. However, material removal due to cavitation erosion seems to be the main governing process, but its dependency on borehole conditions needs to be investigated further as well.

Due to the relatively poor experimental results of radial water jet drilling under atmospheric conditions it is therefore decided to investigate the addition of abrasives directly in combination with improving and designing a new jetting bit as planned under T5.4. The limitations of the current RJD equipment do allow only pressure drops at the nozzle of only 300 bar which is by far not enough to successfully penetrate hard rock formations. By use of abrasive particles carried inside an intensified high pressure water jet it is most likely to create boreholes even under those limited conditions (Momber & Kovacevic, 1997), (Kollé, 1999), (Wittig, Bracke, & et al., 2014).

Finally, further research will focus on developing and optimizing of the current nozzle design with regard to cavitation erosion. It is know from literature that optimum nozzle design specifications can cause an improvement in the material removal rate, possibly also at those limited field operating conditions (Soyama, 2011). How much this optimization of the current nozzle design will help in order to successfully create boreholes also in hard rock formation types will be shown by the experimental results of further test series in T5.2 and T5.4.

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