Multiple radial fractures connecting horizontal boreholes – a lab study on the feasibility of the multifrac concept for geothermal heat extraction from deep reservoirs with low permeability

F Stoeckhert$^{1,2}$, C Solibida$^{1,4}$, L Witte$^1$ and M Alber$^{1,3}$

$^1$Ruhr-University Bochum, Bochum, Germany
$^2$Taberg Ingenieure GmbH, Luenen, Germany
$^3$Alber GeoMechanics, Dortmund, Germany
$^4$Geological Survey North Rhine-Westphalia, Krefeld, Germany

stoeckhert@taberg.de

Abstract. We conducted a number of experiments on cubic rock specimens with low matrix permeability to create and investigate multifrac systems for geothermal heat production on laboratory scale. Special focus was set on phenomena impeding the parallel propagation of multiple fractures like stress shadow and redistribution effects, rock heterogeneity and discontinuities. We subjected the specimens to a true-triaxial stress state using servo-controlled hydraulic pistons for external loading. High viscosity fluids were injected into parallel boreholes at controlled volume rates with metering pumps. Pressure transducers were connected to all boreholes to register injection pressure and pressure responses in neighboring boreholes. We also recorded acoustic emissions during the experiment for spatial and temporal monitoring of fracture growth processes and the interaction between propagating fractures. After the creation of the hydraulic fractures, the hydraulic connection between the boreholes was tested by fluid circulation. As inferred from acoustic monitoring, radial fractures were propagated stable and technically controllable. Hydraulic connection between the boreholes was established and verified by hydraulic circulation.

1. Introduction
The production of geothermal heat from deep reservoirs with low permeability often requires the creation of artificial conductivity for sufficient fluid circulation rates. The multifrac concept, which is well established in the hydrocarbon industry, involves hydraulic fracturing of at least two parallel wellbore with horizontal orientation in a reservoir. The horizontal sections of these wellbores are drilled in the direction of the minor principal horizontal stress to enforce a radial orientation of the hydraulic fractures. Size of the fractures and distance of the parallel wellbores are designed to create a hydraulic connection between the wellbores for fluid circulation. Using e.g. multi-stage fracturing with multi-packer tools, several of these fractures can be created in parallel orientations along the horizontal sections of the wellbore. The objective is to create a large surface area in the reservoir rock to produce geothermal heat using fluid circulation.
2. Material and Methods
To investigate the feasibility of the multifrac concept on lab-scale, we designed an experimental setup involving a true-triaxial compression frame for cubic rock samples and a high-pressure metering pump fluid injection system. Similar laboratory experiments have been conducted in previous studies, e.g. on the creating enhanced geothermal systems within crystalline rocks [1] or on the interaction of closely spaced fractures in the scope of applications for the mining and gas industry [2].

Cubic rock samples with an edge length of 15 cm were cut and ground square from lower carboniferous sandstones collected in a quarry in the Ruhr area in Germany. The sandstones are rather impermeable and exhibit high tensile and compressive strength. They represent a potential reservoir rock for deep geothermal projects throughout the Central European Basin. The properties of the Ruhrsandstone are summarized in table 1.

### Table 1. Mechanical properties of the rock sample material from [3].

| sample    | UCS  | tensile strength | mode I fracture toughness | Young’s modulus | compressional wave velocity | permeability |
|-----------|------|-----------------|--------------------------|-----------------|----------------------------|--------------|
| sandstone | 138 ±20 | 9.8 ±1.2       | 1.56 ±0.16                | 28 ±1           | 4.2 ±0.1                   | 10⁻¹⁸        |

Two coaxial parallel boreholes with a diameter of 6 mm were drilled into opposing faces leaving about 3 cm of intact rock between the holes (Figure 2). Two injection lines, made of 1/8” high pressure tubing fitted with an outside thread and sealed to the borehole wall by two nuts compressing an o-ring, are glued into the wellbores using dental PMMA/MMA cement. This yields an approx. 10 mm open hole section at the bottom of the borehole. This configuration is used to simulate two isolated hydraulic fracturing stages in a wellbore.

A third borehole is drilled parallel to the two coaxial boreholes and simulates a production well, to which the injection wells should be connected.

![Figure 1. Experimental setup (left), cubic rock sample (upper right) and rock sample fitted with loading plates and injection lines (lower right).](image)

To induce fracture propagation radial to the boreholes, we applied a true triaxial stress field to the cubic sample using three servo-controlled hydraulic rams (cf. experimental setup in [3]). When using 15 cm cubes, two of these hydraulic rams have a maximum capacity of 25 MPa and the third, which is
placed in a 4.5 MN testing frame, has a maximum capacity of around 80 MPa. In the experiments presented here, the external load on the sample was either 10 MPa, 10 MPa and 1 MPa or 15 MPa, 15 MPa and 1 MPa, to enforce radial fracture propagation. The orientation of the injection holes was parallel to the minor external loading magnitude in all experiments. The sample faces, to which the external load was applied to, as well as the interfaces were machined to be plane and parallel. Teflon sheets between the sample and the loading plates reduced frictional shear stresses.

Figure 2. Isometric view of specimen geometry with injection (indicated by yellow and orange circles) and production (purple circle) boreholes and position of the AE-sensors on the cube surfaces (grey circles).

Throughout the experiment, we monitored, recorded and located acoustic emissions in the frequency range of around 100 kHz to 1 MHz. Analysis of acoustic emissions yield spatiotemporal information about fracture initiation, fracture propagation and fracture orientation. A more extensive description of the experimental methods used to record, locate and analyze the acoustic emissions is given in [3, 4].

The injection system incorporates two piston metering pumps, which provide constant flow rates in the range from $10^{-5}$ ml/min to 10 ml/min with an accuracy of $\pm 0.1\%$. The pumps use water to drive a 220 ml and a 50 ml piston fluid separator, which transfer the water pressure to the injection fluid. Each of the two injection systems is connected to one of the coaxial boreholes. All boreholes are equipped with pressure sensors. We used sugar beet syrup with a fluid viscosity of around 20 Pa·s and an approximately Newtonian fluid rheology at experimental flow rates [5]. Scaling laws for hydraulic fracture mechanics [6, 7] indicate that using high viscosity fluids in hydraulic fracturing laboratory experiments yields benefits in terms of translating results to field scale.

The experimental protocol starts with the application of the external load in two stages. After the first load level is established, the injection boreholes as well as the production borehole are pressurized with syrup to around 1 MPa to check for any leakages. After this, the fluid is shut in in the boreholes and the external load is increased to the final level. Then fluid injection is performed into one of the injection wellbores at constant flow rates between 0.01 ml/min and 5 ml/min until acoustic emissions indicate
fracture initiation and propagation. At this point, injection was stopped and resumed at lower injection rates in most experiments to maintain stable fracture propagation conditions and to control the fracture extent. After the first fracture was hydraulically connected to the production borehole, as indicated by the observation of a pressure increase in the production borehole, injection into the first injection borehole was stopped and the aforementioned procedure was repeated in the second borehole.

3. Results and discussion
We present a detailed description of the results of two experiments below. In experiment SW-C-2, the rock cube was subjected to $\sigma_1 = \sigma_2 = 10$ MPa perpendicular to the injection and production holes and $\sigma_3 = 1$ MPa along the holes. The fluid pressures vs. time are shown in Figure 3. Clearly, the production hole was connected to the injection holes via fractures. After circulation, from $t = 1500$ s on, the effective hydraulic aperture $e_h$ of the fracs was calculated using the cubic law with the measured fracture length as well as the known fluid properties. After the experiment the rock cube was cut parallel to the boreholes to visually observe the induced fracs and compare them with the distribution of located acoustic events.

![Figure 3. Multifract experiment SW-C-2. Fluid pressure development (left) and fracs in the rock block (right). The purple circles denote located acoustic emissions.](image)

In another experiment (“SK4-C-3”) the external loading was increased to $\sigma_1 = \sigma_2 = 15$ MPa with $\sigma_3 = 1$ MPa. Figure 4 shows external stress, injection pressures and injection rates. The external loading is applied in two stages, each of which is accompanied by significant acoustic emission due to sample compression. Then, fluid is injected in one of the two injection boreholes until a significant increase of acoustic events attributed to fracture propagation was observed. After releasing the injection pressure, to prevent unstable fracture propagation, a second injection cycle was started. Injection was again stopped as soon as significant acoustic amplitudes were observed. This already occurred at much lower injection pressures than in the first injection cycle, indicating a lower refrac pressure. After injection was stopped, the injection borehole was shut in and the pressure decay was recorded. Acoustic events were recorded during an around 500 s period of gradual pressure decrease and stopped as the pressure was released. After this, a similar procedure was applied to the second injection borehole.
Figure 4. Experimental recordings from experiment SK4-C-3 with external stress perpendicular to the borehole (“MaxStress”) and injection pressures (upper diagram) as well as injection rates (lower diagram) for the two injection boreholes (“P5” and “P6”) as well as the production borehole (“P4”). Grey circles in the upper diagram show the amplitudes of acoustic events recorded during the experiment. The prominent clusters of acoustic events exhibiting similar vertical line shapes in the upper plot result from active ultrasonic transmission measurements during the experiment.

Figure 5 gives the coordinates of located acoustic events during the first peak pressure in this experiment. It can be observed that over time the cloud of events extends in the y- and z-directions, which are perpendicular to the borehole axis. We interpret this to be the effect of radial propagation of a “penny-shaped” fracture. During this period, fracture propagation seems to be stable and controllable and stops as soon as the injection pressure is released.

The locations of all acoustic events recorded during the experiments form two discrete parallel circular clusters (Figure 6) that are oriented perpendicular to the injection boreholes around each open hole section of the two injection boreholes. They extent to the production borehole but are rather contained inside the specimen.
Figure 5. Location of acoustic events recorded in experiment SK4-C-3 with respect to the center of the cube in x-, y- and z-direction at peak injection pressure. Axes are oriented as shown in Figure 2. Color of the dot symbols indicate the amplitude of the event (blue=low, pink=high).

Figure 6. Locations of all acoustic events recorded during injection cycles in experiment SK4-C-3 shown in four orthogonal perspectives.

4. Conclusion
In the laboratory experiments we were able propagate hydraulic fractures in stable and controlled conditions such that the fractures were oriented radial to the boreholes and were contained inside the rock specimens. Acoustic emission monitoring revealed symmetric radial propagation of parallel penny-shaped fractures in most experiments. We did not find evidence for significant restraints of fracture propagation by stress shadowing. In some experiments rock and/or stress heterogeneity led to complex fracture geometries with inclined fractures or fractures crossing discontinuities. However, we were able to establish hydraulically conductive connections between two boreholes in these experiments as well.
The hydraulic conductivity between the boreholes was increased by several orders of magnitude in all experiments. Based on these results, we conclude the feasibility of the multifrac concept, at least on laboratory scale.

References

[1] Frash L P, Gutierrez M, Hampton J and Hood J 2015 Laboratory simulation of binary and triple well EGS in large granite blocks using AE events for drilling guidance Geothermics 55 pp 1–15

[2] Bunger A P, Jeffrey R G, Kear J, Zhang X and Morgan M 2011 Experimental Investigation of the Interaction Among Closely Spaced Hydraulic Fractures 45th U.S. Rock Mechanics/Geomechanics Symposium (San Francisco, CA, June 26 - 29)

[3] Stoeckhert F, Solibida C and Alber M 2020 Hydraulic Fractures in Discontinuous, Anisotropic and Heterogeneous Rock - A Lab Study ISRM International Symposium - EUROCK 2020 (June 2020)

[4] Molenda M, Stöckhert F, Brenne S and Alber M 2015 Acoustic Emission Monitoring of Laboratory Scale Hydraulic Fracturing Experiments 49th U.S. Rock Mechanics/Geomechanics Symposium (San Francisco, California, USA, 2015/06/28-2015/07/01) (American Rock Mechanics Association)

[5] Schellart W P 2011 Rheology and density of glucose syrup and honey: Determining their suitability for usage in analogue and fluid dynamic models of geological processes Journal of Structural Geology 33 pp 1079–88

[6] de Pater C J, Cleary M P, Quinn T S, Barr D T, Johnson D E and Weijers L 1994 Experimental Verification of Dimensional Analysis for Hydraulic Fracturing SPEPO 9 230–8 (en)

[7] Detournay E 2016 Mechanics of Hydraulic Fractures Annu. Rev. Fluid Mech. 48 pp 311–39