



Hard rock cutting with high pressure jets in various ambient pressure regimes

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ABSTRACT

An alternative drilling technology has been developed, in which ultra-high pressure jetting with in excess of 2500 bar jet pressure is combined with mechanical drilling techniques. In order to investigate the cutting performance of the fluid jets in hard rock formations, experiments under various ambient conditions were performed. Core samples from several drilling sites were tested under atmospheric conditions and enabled a solid basis for the comparison of the jettability of different hard rock formations. To simulate deep downhole conditions as realistically as possible, a pressure vessel capable of up to 450 bar internal pressure was designed and built. The experiments, performed under different ambient pressure regimes, show a completely different cutting performance than under atmospheric conditions. The main influencing parameters were determined and adapted to enable a sufficient performance for all tested conditions. Furthermore the usage of drilling fluids in place of water was investigated. The study shows that high pressure jetting is feasible in the challenging simulated downhole environment, including high ambient pressure, several jets with different pressures acting simultaneously, drilling mud as jetting resp. surrounding fluid and high traverse velocities.

1. Introduction

The utilisation of geothermal energy, especially in the form of EGS (Enhanced Geothermal Systems), is proposed to be one of the future cornerstones of Europe's renewable energy strategy. Because of the great depth of suitable geothermal reservoirs, drilling costs often represent more than half of the total costs of EGS. In order to increase the rate of penetration (ROP) and therefore reduce the drilling costs, an alternative drilling system is under development within the framework of the EU research project “ThermoDrill”. The core element of the project is a hybrid drilling system, consisting of conventional rotary drilling in combination with high pressure fluid jetting.

The concept of combining mechanical and hydraulic rock destruction methods for drilling purposes has existed already for decades. One of the first references can be found in the United States patent of Bobo¹ from 1963. The approach was to use an intensifier pump downhole to create the high pressure, which is finally transferred to the nozzles for impinging at high velocity on the bottom of the borehole and cutting an annular groove around the periphery of the well bore. The central portion of the bottom hole should then be easier to drill; a significant increase in the rate of penetration (ROP) is expected. Subsequent

concepts, for example Shi et al.,² Veenhuizen et al.³ and Kolle et al.,⁴ are all effectively based on this initial idea, although tool location and method of pressure generation, bit and nozzle configuration or the fluid used pursued different approaches. Laboratory tests, performed by Geier & Hood⁵ and Fenn,⁶ using PDC and disc cutter elements on pre-jetted rock samples confirm the favourable impact of jet kerfs on the mechanical rock removing process. A study on the physical effects of jet cutting on the mechanical rock destruction process and an estimation of the limiting constraints is given by Hlaváč.⁷

However, most of the experiments were conducted under atmospheric conditions, which do not represent the situation downhole. Only minimal literature relating to the application of high pressure jetting under significant back pressure is available. Back pressure denotes the pressure of the fluid layer between the nozzle outlet and the object to be cut. Hlaváč et al.^{8,9} conducted experimental studies about the cutting performance of submerged water jets and compared the results to the predicted depth of penetration from an equation, based on the theory presented i.a. in.^{10,11} Poláček and Janurová¹² performed tests with similar equipment in an extended pressure range (including vacuum), while using the same theory for comparison as Hlaváč.^{8,9} The maximum applied pressure in their chamber was 12 bar, respectively

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16 bar, therefore few conclusions can be drawn for the targeted back pressure range of 300–400 bar for deep drilling purposes. Nevertheless, it was observed that already with a small back pressure, the cutting performance decreases significantly.

Reichman summarized in his report¹³ jetting experiments on granite samples under back pressures up to 3000 psi (ca. 207 bar), with a maximum nozzle diameter of 0.45 mm and a jet pressure of 45000 psi (3100 bar). He observed ceasing of the cutting action at the maximum back pressure of 207 bar. Kolle¹⁴ noticed similar effects during his experiments on Sandstone, Limestone and Shale samples, using a pressure chamber capable of up to 1330 bar, with a maximum nozzle size of 0.36 mm and a varying stand-off distance.

Since all references report ceasing of the cutting action under high ambient pressure, there is no possibility to define the fundamental requirements of the high pressure system. However, the generation of at least one adequately deep kerf in the borehole bottom is considered as an indispensable requirement to significantly increase the ROP. Therefore, a comprehensive experimental study was conducted to identify appropriate jetting parameters, taking into account various ambient conditions. Especially the cutting performance of high pressure jets under back pressures of up to 450 bar was investigated in detail, using a newly developed pressure vessel. Contrary to the previous results for experiments under comparable (laboratory) conditions, the performance could be maintained satisfactorily. With the gathered data, the key requirements for the new high pressure system were defined. Additionally to water, two types of drilling fluid (mud) were used as jetting medium, in order to investigate whether mud can also be used as jetting fluid. The tests were conducted under similar ambient conditions in the pressure vessel as water.

2. Theory

2.1. Pure water jetting

This paper aims not at establishing a new theory, but that adequate theoretical background is provided to obtain valid explanations for the observed behaviour during the experiments. Especially, the effect of back pressure on the jet cutting performance is of great importance. The erosion resistance, a term introduced by Reh binder,¹⁵ is defined as the ratio of average grain size to modified permeability. The modified permeability is determined with the procedure described in¹⁶ and is a measure of the cross sectional area of the pores. The bigger the modified permeability is, the lower is the erosion resistance. According to Reh binder,¹⁷ the jettability of a rock type depends on one hand on the erosion resistance and on the other, the threshold pressure, which can be seen as a measure of the “microscale” tensile strength. Common strength properties such as compressive and tensile strength are in some way covered in the threshold pressure. The theory is based on the idea that the water starts to penetrate the pores between the grains and subsequently causes the grains to be spalled individually; presuming the stagnation pressure of the water jet exceeds the threshold pressure. An important conclusion of the theory is that coarse grained specimens of a rock type are easier to cut than fine grained samples of the same rock type. Reh binder¹⁷ further notes that the cutting performance of a jet is mainly characterized by its hydraulic power and subsidiary by its stagnation pressure, providing a sufficiently high pressure.

The theory established by Crow¹⁸ also considers the permeability of the rock as a vital parameter for the cutting performance. According to the theory, a saturated zone exists in front of the cutting surface due to the finite permeability of the rock. The high pore pressure in this saturated zone, caused by the hydrodynamic surface pressure, leads to low effective normal stresses which are applied in the well-known Mohr-Coulomb failure criterion. The central thesis of the theory is that the rock in front of the cutting surface is in a constant state of incipient fracture. If the rock is saturated, Crow predicts a maximum cutting depth, independent of the traverse velocity. The phenomenon of

cavitation is included in a way that the cavitation bubbles prevent the rock surface from being exposed to the full jet pressure.

Both Reh binder and Crow distinguish between saturated and unsaturated rock, on the assumption that cutting performance is maximised for unsaturated rock due to excessive pore pressure. The influence of surrounding water on the jet itself is not discussed. By contrast, Cheung and Hurlburt¹⁹ attempt to explain observations made during submerged jet cutting experiments. They expected to see a difference between the cutting performance in air and under submerged conditions. Surprisingly, the same linear dependence of the kerf depth on the jet pressure and nozzle diameter reappeared. Also, the achieved kerf depth and the quality of the cut were equal for jets with the same parameters in air and under water, up to a certain stand-off distance. Their conclusion was that the jet was sheathed in cavitation bubbles up to a certain length. By using the principles of conservation of mass and conservation of momentum, they finally derived the following Eq. (1) to calculate the “protected” jet length x_c .¹⁹

$$x_c = \frac{v_0 D_0}{4v_E} \ln \left(0.113 \frac{v_0}{v_E} \right) \quad (1)$$

in which D_0 represents the nozzle diameter, v_0 the initial jet velocity, and v_E the entrainment velocity of the surrounding water. Eq. (1) is based on the assumption of a non-pressurized ambient pressure regime of the surrounding water. Basically the equation results in a threshold stand-off distance for efficient cutting under submerged conditions. In Kolle¹⁴ Eq. (1) is extended for a variable ambient pressure (back pressure) P_a and the differential jet pressure P_j to Eq. (2):

$$\frac{x_c}{D_0} = \sqrt{\frac{P_j}{P_a}} \ln \left(0.113 \frac{v_0}{v_E} \right) \frac{1}{4} \quad (2)$$

Consequently, even with high jet pressures, the cavitation shroud collapses within a very short distance. Kolle¹⁴ further derived Eq. (3), applying the findings of Schlichting²⁰ for the far field velocity of a turbulent axisymmetric jet:

$$v_m = \frac{6.57 D_0 v_0}{x} \quad (3)$$

where v_m is the jet velocity along the centreline of the jet. Eq. (3) states that the jet does not decay until the stand-off distance exceeds the nozzle diameter 6.57 times, with the limitation that all assumptions made in²⁰ are valid. Together with the fundamental idea that cutting occurs only if the dynamic jet pressure exceeds the threshold pressure of the rock, it is crucial to retain the jet pressure as effectively as possible by limiting the stand-off distance to 6.57 times the nozzle diameter. Beside the influence of the pressure regime on the jet, Kolle¹⁴ expands his considerations to the effect of confining pressure on the threshold pressure of the rock, which can be greatly influenced by varying confining pressures.

The hitherto presented theories already incorporated cavitation partly, although Crow¹⁸ considers the cavitation bubbles only as barrier for the contact between the jet and the rock surface. Cheung & Hurlburt¹⁹ derived the crucial correlation between the formation of cavitation bubbles and the stand-off distance for submerged jets. Kolle¹⁴ expanded these findings for higher ambient pressure regimes in his work. Nevertheless, cavitation has not been seen as a (main) contributing factor for the erosion mechanism. Lichtarowicz²¹ describes the erosion of, mainly metal, specimens due to a cavitating jet. Undoubtedly, the erosion is caused by the collapsing cavitation bubbles. Hence it appears that the cavitation bubbles not only protect the jet from being decayed, but also adding a substantial component to the cutting performance.

2.2. Abrasive water jetting

A consolidated review and description of the abrasive waterjet

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