Innovative Thermal Drilling Technologies based on mechanically assisted LaserJet Drilling (LJD) for hard rock (geothermal) applications

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ABSTRACT

Geothermal resources tend to be found in deeper and harder geologic formations than typical hydrocarbon reservoirs. Therefore, drilling technologies and processes from the oil & gas field have been improved constantly to make for more efficient and economic drilling. However, drilling speeds or rate of penetration (ROP) of classic drilling technologies, e.g. tricone bits, suffer greatly in deep and hard formations. Thus, there is a great need for tools with higher ROP and low wear to reduce drilling, trip time and cost. Today's tools still heavily rely on technologies based on tricone / PCD bits to mechanically break the rock and thus, having to mainly overcome its high compressive strength and, furthermore, requiring large amounts of energy and time. A new paradigm of drilling is needed for the future, as no fundamental, "paradigm" changing improvement or alternative to the mechanical breaking of hard rock have since been introduced to address the exponentially increasing challenges in deep drilling of hard, crystalline rock formations (like geothermal reservoirs). Problems mainly include very low rate of penetration (1 m / hr. or less), very high bit / tool wear and thus, low service live of e.g. under 50 hrs. This all makes for numerous, long and expensive round trips and thus, very high overall drilling cost.

Attempts to develop alternative means for delivering more / different energy to the bit and break the rock differently have been under way worldwide in the past 20 to 30 years. Thermal drilling or breaking of rock, e.g. Laser (supported) Jet Drilling (LJD), could potentially be such next fundamental change and thus, greatly improve drilling of hard rock. GZB in Bochum is investigating such innovative thermal drilling technologies, especially mechanically assisted LaserJet drilling. Hereby, Laser beams are being sent via water jet, protected by a gas shield, onto rock´s surface, where it concentrates locally causing the local temperature to increase instantaneously in order to weaken the rock structure through spallation and thermal stresses. The high power intensity laser beam in contrast to low rock thermal conductivity causes the local temperature to increase at once which results in a local induced thermal stress that spalls the rock. This weakening process in rock due to induced thermal stresses also results in fractures, mineral dehydration and thus, reduction in rock´s Young's and shear modulus. Subsequently, the now weakened rock will be drilled or "ground down" if needed using specially optimized mechanical bit technologies. This process continues on a new surface by removing the cuttings and fragments with help of drilling fluid as a flushing system.

This paper discusses the principle behind thermal drilling technologies, The LJD working principle and preliminary lab and field tests of Laser initiated thermal drilling, showing multiple advantages compared to conventional methods including: additional energy being sent to the bit, high ROP, longer bit life due to less wear, etc. Furthermore, a new LaserJet drill bit, required changes and modifications to be implemented in the present drill string equipment and economic and technical analyses of the possible advantages and disadvantages are being described.

Hence, a thermal drilling process conducted by using LaserJet technology delivering additional thermal energy for rock removal purposes followed by limited and decreased required mechanical work seems to be a breakthrough in the deep, hard rock drilling process of the future.

1. INTRODUCTION

Interest in geothermal energy resources has increased substantially over the recent years while it represents a large enough renewable resource that can be used to supply the high energy demand while having a minimal environmental impacts.

Geothermal resources tend to be found in deeper and harder geologic formations than typical hydrocarbon reservoirs and on the other hand drilling and completion processes and costs tends to be the key factor in making geothermal resources a technical and economic feasible option.

Various economic researches show that around 50-70 % of total investment needed to develop a geothermal resource comes from drilling costs alone (Mansure & Blankenship, 2010)(Lukawski et al., 2014). These costs are considerably higher than the conventional drilling processes for oil and gas while geothermal resources tend to be found in deeper and harder geologic formations, mainly granite rocks, than typical hydrocarbon reservoirs.

Drilling technologies and processes from oil & gas industry have been improved constantly to make more efficient and economic drilling processes. However, drilling speeds or rate of penetration (ROP) of classic drilling technologies, e.g. tricone bits, suffer greatly in deep and hard formations.(Tester et al., 2006) Thus, there is a great need for tools with higher ROP and low wear to reduce drilling, trip time and cost. Today's tools still heavily rely on technologies based on tricone / PCD bits to mechanically break the rock and thus, having to mainly overcome its high compressive strength and, furthermore, requiring large amounts of energy and time. A new paradigm of drilling is needed for the future, as no fundamental, "paradigm" changing improvement or alternative to the mechanical breaking of hard rock have since been introduced to address the exponentially increasing challenges in deep drilling of hard, crystalline rock formations (like geothermal reservoirs). Problems mainly include very low rate of penetration (1 m / hr. or less), very high bit / tool wear and thus, low service live of e.g. under 50 hrs.(Lukawski et al., 2014). This all makes for numerous, long and expensive round trips and thus, very high overall drilling cost. Attempts to develop alternative means for delivering more / different energy to the bit and break the rock differently have been under way worldwide in the past 20 to 30 years. Thermal drilling or breaking of rock, e.g. Laser (supported) Jet Drilling (LJD), could potentially be such next fundamental change and thus, greatly improve drilling of hard rock. GZB in Bochum is investigating such innovative thermal drilling technologies, especially mechanically assisted LaserJet drilling.

2. NOVEL NON-CONTACT THERMAL DRILLING METHODS

Thermal drilling methods mainly use thermal energy to apply exert stress on the rock. The rock removal can be achieved either by melting, spallation or vaporization. The use of thermal energy to apply stress on rock has the advantage that the need for direct contact between the tool and rock is omitted which reduces the tool wear significantly and consequently tripping time(Augustine, 2009). The following is a brief introduction and analysis of recent and state of the art in thermal drilling technologies.

2.1 Microwave drilling

This drilling method uses microwave waves to generate heat, spall and melt rock surface. Although spallation is a more favored solution but melting can be achieved in an easier fashion by concentration of microwave energy on the intended spot around the radiator. By continuous application of energy, the rock surface temperature increases and eventually begins to melt. An electrode is used to push the molten material from center to the wellbore edges.

The advantages of microwave drilling include low drill string rotation requirement which results in low wear and melting the material means a dust free environment during drilling process. The conversion of (drilling fluid hydraulic energy to) electric to microwave energy can be very inefficient (~65%) and at the same time the experiments show that there is a power limit above which, no further rock destruction occurs. It is also mandatory to prevent microwave leakage by shielding.(F Hassani, Nekoovaght, Radziszewski, & Waters, 2012; Ferri Hassani, Nekoovaght, & Gharib, 2015; Ferri Hassani, Radziszewski, & Ouellet, 2008)

2.2 Electrical Plasma for Hard Rock Drilling and Casing Milling

The Electrical Plasma system is a drilling mechanism which is not based on conventional drilling systems while the system uses electric arc with temperatures up to ten thousand of degrees Celsius and water steam as a plasma-creation gas (rather than conventional plasma-torch) which is applied on the rocks surface to generate heat and thermally induced stress, the process ends with pure condensed water. Three possible modes of disintegration are possible based on plasma temperature: spallation, melting and evaporation with the focus of current research being on achieving spallation.

The process is a non-contact method and with no need to transfer torque and weight on bit (no reaction forces on the drill bit and no radial forces in complex layered structures down the hole) with the focus of thermal characteristics of the rock rather than the mechanical ones(Gajdos et al., 2016; Gajdos, Kristofic, Jankovic, Horvath, & Kocis, 2015).

The application is mainly in areas of hard rock drilling, casing milling and Real Time Data Acquisition (RTDA) using spectroscopy(Kocis, Kristofic, Gajdos, Horvath, & Jankovic, 2015).

2.3 Hydrothermal Spallation Technology

Hydrothermal Spallation Technology is a spallation drilling system which utilizes a high temperature fluid-jet to provide heat for the process. This system creates rock chips or spalls by applying intense thermal stress on the rock's surface rather than relying on traditional drilling's physical contact to crush rock. A surface rig is coupled with a bottom hole assembly of a catalyst chamber, nozzle and dynamic seal. Water and fuel are pumped through drill pipe and BHA. hydrothermal flames heat a stream of water, which exits the nozzles at high temperatures(Augustine, 2009; Von Rohr, Rothenfluh, & Schuler, 2015;

Wideman, Sazdanoff, Unzelman-langsdorf, & Potter, 2011).

The issues mainly include: the inability to maintain a constant bore diameter, to prevent coolant ingress into the high temperature cutting region, oscillation in the bore diameter and system development has relied on an design optimization cycle with little possibilities to optimize or predict performance outside of test conditions.(EPRI, 2013; Potter, Potter, & Wideman, 2010).There has been an ongoing research at ETH Zurich, to apply supercritical conditions to the flame jet to overcome many of the previously mentioned problems(Meier, Brkic, Schuler, Kant, & Rohr, 2015).

2.3 Electro Impulse Technology (EIV) and Electro pulse boring (EPB)

Electro impulse technology uses electrical voltage impulse for drilling. The method employs electric impulses of between 100-1000kV through submerged electrodes near rock surface. Pulse travels through rock and a volume of rock breaks. continuous application of pulses causes further penetration into the rock. Although in this method there is significant saving considering relatively high ROP values, there is also significant energy consumed in use of drilling fluid for transportation of energy and cutting when the diameter of the borehole is large while this method can only be applied in drilling large diameter wells (0.5-1m for deep wells).

Focused research is therefore, required for development of a suitable drill rig due to the vast differences in this technology and conventional rotary drilling and downhole energy supply system. In addition, analysis of the process in the borehole condition and with Oil / water based muds is essential(Schiegg, Rødland, Zhu, & Yuen, 2015; Voigt & Anders, 2016).

3. LASER SPALLATION DRILLING PROCESS

In today geothermal, oil and gas industry all deep wells are being drilled by means of rotary drilling as conventional method. A conventional rotary drilling uses axial force and rotation to introduce shear and axial forces to penetrate through the rock formation. The rotary drilling functions efficiently in soft rock formations, however as soon as hard rock formations such as granite is reached many problems arises, the rate of penetration decreases significantly and the costs increase significantly with greater depths. The high costs are mainly the result of very low rate of penetration (1 m / hr. or less), very high bit / tool wear and thus, low service live of e.g. under 50 hrs. which as an example translated into an average of 140 m of drilling before each drill bit must have been changed. This all makes for numerous, long and expensive round trips and thus, very high overall drilling cost(Tester et al., 2006). Attempts to develop alternative means for delivering more / different energy to the bit and break the rock differently have been under way worldwide in the past 20 to 30 years. Thermal drilling or breaking of rock, e.g. Laser (supported) Jet Drilling (LJD), could potentially be such next fundamental change and thus, greatly improve drilling of hard rock. GZB in Bochum is investigating such innovative thermal drilling technologies, especially mechanically assisted LaserJet drilling via spallation process.

Thermal spallation is defined generally as applying excessive rapid thermal energy rather than mechanical grounding into a rock surface resulting in thermal stresses that initiate weakening and fragmentation of the solid into spalls which are disk-like flakes by expanding the existing flaws in the rock structure. The spalls which have an average size of 0.1 to 2 mm, will be disintegrated from the rock surface and will be washed away by means of cutting transport(Augustine, 2009; Rothenfluh, 2013). Hard rock formations such as granite are considered to be spallable, meaning spallation can occur to them in an easier fashion compared to softer rocks such as sandstone. This fact is an indication that thermal spallation technologies can have a great potential while most hard dry rock formations have to be drilled for geothermal applications.

Preston has provided the most extensive quantitative description of spallation process which is accepted as the most accurate description(Preston & White, 1934). Fig. 1 shows the spallation process with laser being the thermal energy delivery system. The following description is based on the fact that the spallation process can only occur if the intended material has existing flaws or weaknesses. The process begins by (a) the surface of the material starts to expand as heat is applied across its surface and causes the flaws and fissures in the material to grow (b) the induces thermal stresses start to grow and results in buckling of the upper surface. (c) the martial begins to be stressed compressively but it is the tensile stress applied at the edges of forming spall which leads to the final failure and ejection of the spall.

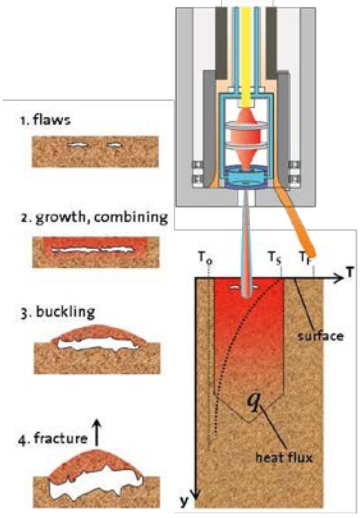

Figure 1: Laser spallation process principle. Modified after (Preston & White, 1934;Fraunhofer IPT)

4. LASER ENHANCED THERMAL SOFTENING

Temperature is one of the key factors that has a great impact on changing rock's geotechnical parameters. one of the first times that this phenomenon was recorded quantitatively was during firing of clay and kaolin. The rocks exposed to high temperatures had a reduction in plasticity as well as increase in resistance. since the 1970s, the extensive research in geosciences has resulted in a good knowledge on the effects of high temperatures on mechanical behavior of rocks(Sygała, Bukowska, & Janoszek, 2013).

Thermally induced high temperatures in rock influences the rock in a way that, thermal stresses start to grow inside which leads to propagation and expansion of micro cracks and fissure. As temperature increases, the expansion continues and eventually reaches a point that the rock structure starts to weaken and thermal softening occurs (Sygała et al., 2013).

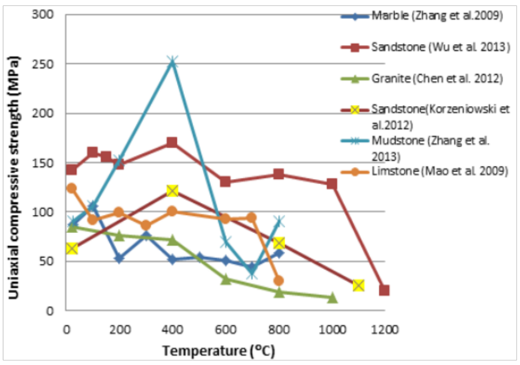

Figure 2: Change of the compressive strength of selected type of rocks subjected to high temperatures.(Chen, Ni, Shao, & Azzam, 2012; Keshavarz, Pellet, & Loret, 2010; Pinińska, 2007; Sygała et al., 2013)

It has been shown that granite softening process starts at 100°c and continues till temperatures around 800°c. the approximate reduction in uniaxial compressive strength is in range of 10, 15 and 80 % for temperatures of 100, 600 and 800 °c respectively(Ezzedine, Rubenchik, & Yamamoto, 2015). the possible effect of high temperature on rock's strength and rate of penetration has been shown in Fig. 2 and Fig. 3.(Chen et al., 2012; Keshavarz et al., 2010; Pinińska, 2007; Sygała et al., 2013)

The concept of LaserJet drilling is also based on laser induced thermal softening. as the laser beam hits the rock surface in a controlled manner, the induced temperature is intended to be kept at range of 550 to 600°c to stay in the spallation temperature spallation zone and soften the rock at the same time. As is shown in various studies there is a significant reduction in elastic modulus of granite at these temperatures range which can help the process to achieve a higher rate of penetration while using the mechanical assistance.

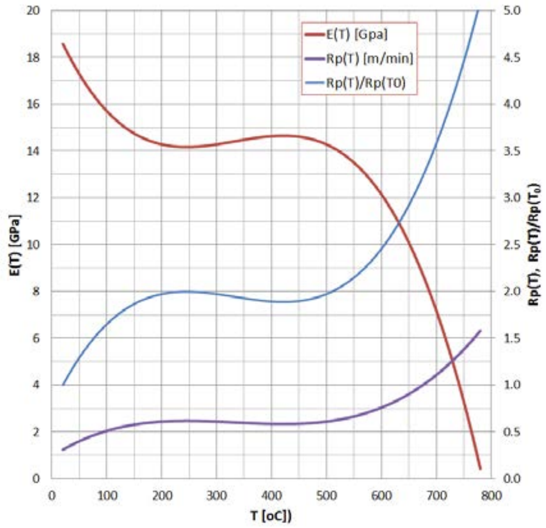

Figure 3: Elastic modulus reduction and Rate of penetration as a function of laser induced temperature.(Ezzedine et al., 2015)

5. SPECIFIC ENERGY

Specific energy is defined as energy required to remove a unit volume of rock which can be used as a base to compare different rock removal processes(Gahan et al., 2001).

As for focus of this research the specific energy values can be used to compare the intended novel laser spallation process to other conventional drilling methods.

lab tests show that laser rock removal process can be achieved either by vaporization, melting and spallation. As stated before, spallation process being the most favorable solution as it requires less energy to remove more volume of rock or just have smaller specific energy value(Adeniji, 2014; Bazargan, Engineering, Bahonar, & Jalalyfar, 2013; Kobayashi et al., 2009).

in Fig. 4, a comparison has been made between laser spallation and other conventional rock removal (drilling) processes. The numbers represent the following drilling methods in a chronological order from 1 to 7: percussive drills (small holes), rotary drills, drill-and-blast tunneling, Raise-and-tunnel-boring machines, flame jets, laser spallation and future optimized laser drilling. It is pointed out in Fig. 4 that by applying higher power intensities and having relatively low specific energy values, high ROP values ranging from 10 to 100 times more than conventional method can be achieved in an energy efficient manner(Xu, Reed, Parker, & Graves, 2004). The laser spallation process still needs to be optimized and understood better to reach its highest practical potential which is the reason that in the current research, the laser delivery system, a compatible mechanical assistance and a special drill head system has been designed to optimize the process.

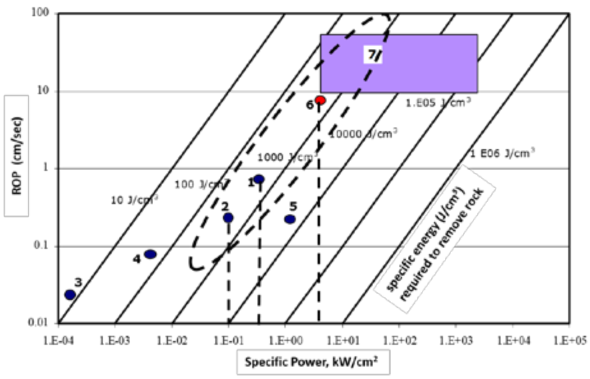

Figure 4: Comparison of Laser and conventional drilling methods. Modified after (Xu et al., 2004)

6. THE LASERJET CONCEPT

The LaserJet is a specific process which as the name suggests is based on a laser beam and a water jet. The LaserJet is formed by focusing a laser beam into a nozzle while it passes through a pressurized water in a chamber as is shown in Fig. 5. as the laser beam enters the water jet, fluid jet starts to act as an optical wave guide of variable length. In this process only the laser beam is used to effect the rock and the water jet ensures that laser beam is guided to the rock with stability and will have a constant beam spot diameter throughout the process. The diameter of water jet and consequently the beam spot may vary depending on the nozzle design while the water jet diameter is around 83% of the nozzle diameter. The working pressure of the water jet is around 500 to 1000 bars(Wagner et al., 2009).

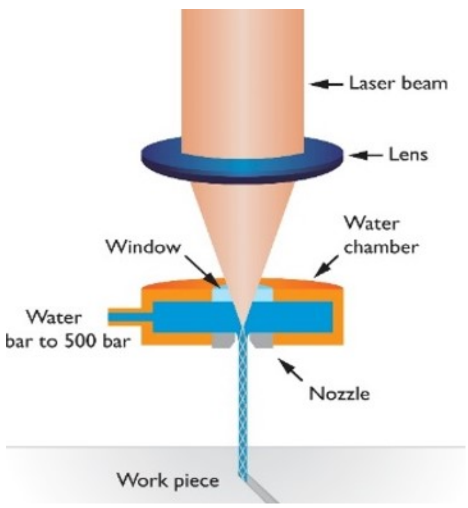

Figure 5: The water jet guider laser concept(Wagner et al., 2009)

As was shown in research on spallation(Preston & White, 1934), for achieving continuous spallation in an efficient manner only around 10% of the rock surface may be heated and the surroundings are preferred to be cooled down. The water guided LaserJet has the advantage that the laser is used for heating and the water jet is used to cool the edges around the beam spot.

7. LASERJET MECHANICAL ASSISTANCE DRILLING, PRELIMINARY LAB AND PROTOTYPE TEST SETUP

LASER in general stands for Light Amplification by Stimulated Emission of Radiation. it is a way to convert energy into radiation beam. The laser beam is a coherent high intensity energy light which can be used for rock destruction in form of vaporization, melting and spallation depending on the rock type and the intensity of the laser power applied on the rock surface.

The LaserJet mechanical assistance drilling system which is currently being developed at international geothermal centre Bochum, uses triple fluid delivery system, high power fiber optic cable to deliver the beam and a bottom hole assembly system.

Fluid delivery system consist basically of specially designed multi-fluid distribution swivel system and four concentric lasers compatible drill pipe system of which three is used to deliver required fluids for the process and one to protect and convey high power fiber optic cable and connectors.

There are three fluids simultaneously fed to the drill head: high pressure De-ionized water, Drill mud and air. The High pressure DI water is used for guiding the laser beam and the air to shield the LaserJet to increase its stable length from drill head to the rock surface. The drill mud has the same functionality as in conventional drilling process such as wellbore cleaning, cutting transport and enhance wellbore integrity during the drilling process.

The high power optical system uses a 30 KW laser to generate the power and high power fiber optic cable to transfer the beam from the laser generator to the drill bit. The laser parameters can be modified accordingly such as average power, power intensity, peak power, wavelength, etc.

The bottom hole assembly simply consist of two main parts: the laser cartridge and the mechanical drill bit. the mechanical drill bit acts as housing for the laser cartridge and also assists in the drilling process.

The laser beam exits through drill head nozzle and sweeps the rock surface. as the laser is traveling, it is shrouded and protected by the air. The beam hits the rock and induces the intended thermal stresses, increase the rock surface temperature to approximately 600 °c and consequently will result in spallation.

As mentioned before a lot of recent studies on thermomechanical behavior of rocks have shown that laser radiation can also reduce rocks mechanical strength significantly. As the spallation goes on, the hard rock softens at the same time and enables the mechanical drill bit to crush the rock efficiently and assists in the process.

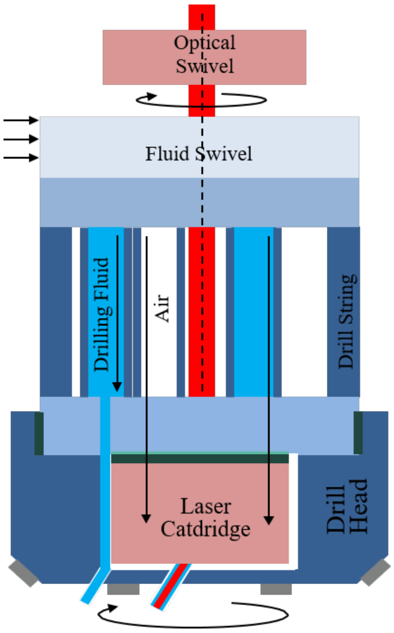

Figure 6: LJD schematical setup including mechanical assistance. (Fraunhofer IPT)

The initial lab test was conducted in order to understand the technical feasibility of laser spallation on granite by using a LaserJet rather than a conventional laser beam. As of writing this article the Conceptual design of the prototype has been finished which an overview of it is shown in Fig. 6.

8. FUTURE WORK

The initial test proved the technical feasibility of LaserJet spallation. However, in order to have continuous spallation and thermal softening, extensive tests have been designed to be conducted. a full scale working prototype is under construction which includes the laser compatible drill string, LaserJet Drill head including mechanical assistance.as the next step the prototype will be tested to understand, optimize and eventually reach a practical LaserJet drilling system.

9. ACKNOWLEDGMENT

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