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Advanced drilling technologies to improve the economics of deep geo-resource utilization

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Abstract— Access to deep energy resources (geothermal energy, hydrocarbons) from deep reservoirs will play a fundamental role over the next decades. However, drilling of deep wells to extract deep geo-resources is extremely expensive. As a fact, drilling deep wells into hard, crystalline rocks represents a major challenge for conventional rotary drilling systems, featuring high rates of drill bit wear and requiring frequent drill bit replacements, low penetration rates and poor process efficiency. Therefore, with the aim of improving the overall economics to access deep geo-resources in hard rocks, in this work, we focus on two novel drilling methods, namely: the Combined Thermo-Mechanical Drilling (CTMD) and the Plasma-Pulse Geo-Drilling (PPGD) technologies. The goal of this research and development project is the effective reduction of the costs of drilling in general and particularly regarding accessing and using deep geothermal energy, oil or gas resources. In this work, we present these two novel drilling technologies and focus on evaluating the process efficiency and the drilling performance of these methods, compared to conventional rotary drilling.

Keywords—Deep energy resources, Geothermal energy, Project costs, Novel technologies, Drilling performance

I. Introduction

The increasing worldwide energy demand, coupled with the need to reduce greenhouse gas (GHG) emissions into the atmosphere are two major challenges of our modern society. Countries are proposing energy transition strategies, with the aim of (i) converting our energy supply to renewable energy production and (ii) facilitating this energy transition employing lower-carbon-footprint energy sources [1,2]. To meet the increasing worldwide energy demand in an environmentally sustainable manner, access to geo-energy resources (heat, oil and gas) from deep reservoirs will play a fundamental role over the next decades.

The utilization of deep geo-resources is based on drilling boreholes and constructing wells, targeting the sought resource. However, installing wells to extract deep geothermal energy or hydrocarbons is extremely expensive, mainly due to the involved drilling operations, typically making up the majority of the overall project costs [3,4]. Indeed, drilling costs are found to increase exponentially with depth [3,5] and, furthermore, they occur in an early, high-risk phase of the project. A particularly crucial role of drilling is found in the economics of the so-called enhanced geothermal systems (EGS), where artificial reservoirs are generated in crystalline basement rocks through hydraulic stimulation [6,7] and deep geothermal heat is extracted to produce electricity (and/or heat) at the surface. Indeed, drilling operations in deep crystalline basement rocks typically account for more than half of the overall costs of a deep geothermal project [3,8]. This is due to the fact that, drilling crystalline rocks, using conventional rotary mechanical drilling methods is a very inefficient process, both regarding the technical and also the economical standpoints. Conventional drilling approaches in deep, hard rocks perform very poorly, being characterized by low rates of penetration (ROP) and require frequent replacement of the drilling tool, specifically due to their abrasion by the hard rocks, causing long non-productive times (NPT) and poor process efficiencies [9]. Therefore, with the aim of improving the drilling performance in challenging (deep crystalline rocks) formations, advanced drilling solutions, e.g., employing unconventional rock-breaking approaches, are proposed and investigated worldwide to remedy the problems of conventional, mechanical rotary drilling. Among these methods, including a broad range of alternative means to drill hard rocks, we mention, e.g., by thermal stressing [10-13], electric pulses [14], rock-hammering [15], lasers [16] and hydraulic jetting [17].

In order to improve the economics of deep geo-resource utilization by effectively decreasing the drilling costs, at ETH Zürich we are investigating, as part of a common effort with our industry partners, two drilling technologies, namely: 1) Combined Thermo-Mechanical Drilling (CTMD) and 2) Plasma-Pulse Geo-Drilling (PPGD). The CTMD technology is based on employing thermal assistance, e.g., a flame jet, to improve the drilling performance (increasing the rate of penetration (ROP) and drill bit lifetime) of conventional rotary drilling and thus improving the overall project economics of deep geo-resource utilization. The PPGD technology, in contrast, employs high voltage, nano-second-long electric pulses through the rock, generating a plasma inside the rock, that breaks the rock apart from within, i.e. against its low tensile strength without any mechanical abrasion of the drilling tool.

In this work, we present these two drilling technologies (CTMD in Section II and PPGD in Section III), with the purpose of finding a drilling solution to improve the economics of deep geo-resource utilization projects. Firstly, we present the concepts behind these two novel drilling technologies. We also present experimental and field testing demonstration of the two methods. Process efficiency and drilling performance parameters for the two technologies are evaluated to illustrate the occurring advantages compared to conventional rotary drilling. Lastly, we discuss the developments needed towards the future implementation of the two technologies under deep drilling conditions.

II. Combined thermo-Mechanical Drilling (CTMD): A hybrid technology for deep drilling

An interesting approach to drill hard rocks, which is the basis of the combined thermo-mechanical drilling (CTMD) method is by thermal spallation [11-18]. In this case, the rock is removed not by means of mechanical action, rather by thermally loading the rock with thermal stresses caused by the sole action of flame jets [18]. In order for the thermal spallation process to occur, specific conditions have to be fulfilled, both for the heat source (regarding heat flux and temperature at the rock surface), and also specific rock material properties have to be found [19,20]. This translates to the fact that the thermal spallation process is applicable in hard rocks, however, the process is hindered in softer (as e.g. in some sandstone rocks) and fractured rock materials. Therefore, drilling the rock solely using thermal spallation appears to be limited to hard and un-fractured rocks and thereby not a feasible solution for deep wells, i.e., where different formations, including softer materials, as well as highly fractured crystalline rocks are typically encountered along the way down to great drilling depths.

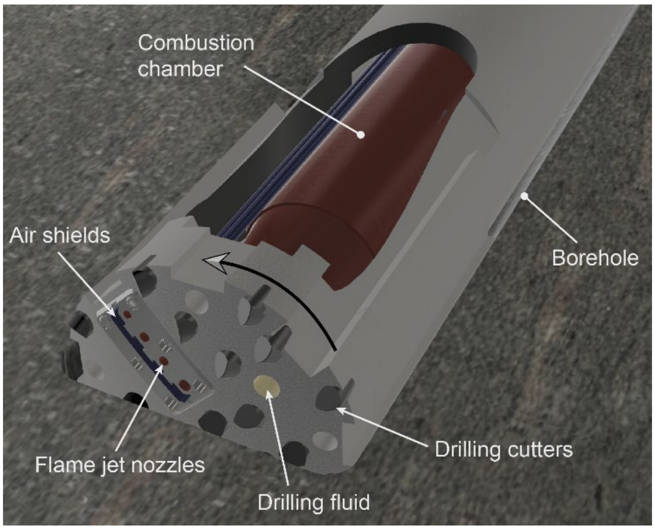

Fig. 1. The Combined Thermo-Mechanical Drilling (CTMD) technology as applied in the field (section showing inner part of drill head).

Hence, with the aim of improving the performances of drilling deep wells in hard rocks and ease the implementation of thermal-based drilling methods in the field, we propose a novel hybrid drilling technology called combined thermo-mechanical drilling (CTMD) [13]. This drilling technology is based on integrating a thermal assistance, e.g., by flame jets, into conventional rotary drilling [21,22]. A representation of the CTMD technology is given in Fig. 1, showing the integration solution for the technology into a 5.5-inch drill bit. Following this hybrid approach, the CTMD technology features three possible drilling modes. In case the rock material exhibits the required properties for a successful thermal spallation of the rock, (I) the flame jets can be operated, at any time during the drilling process, as a standalone mode to induce the spallation mechanism of the rock [23] – Mode I, thermal spallation drilling. Alternatively, (II) the flame jets can be used to provide assistance to the conventional mechanical drilling process, and thereby the flame jets, operated under rotation of the drilling tool, thermally weaken the rock material and facilitate the rock removal performed by drilling cutters [24] – Mode II, flame-assisted rotary drilling. As a third drilling mode, (III) conventional rotary drilling can be used without the thermal assistance, when formation and process conditions are best suited for standalone mechanical rotary drilling, as e.g., in soft rocks. Therefore, the prospect of using several drilling modes demonstrates the considerable flexibility of the CTMD technology to adapt to specific drilling conditions (rock material and process conditions) encountered during deep-well drilling, with the objective of maximizing overall drilling performance. The proposed drilling technology is expected to improve the drilling performance in deep wells, by enhancing drilling speed (rate of penetration, ROP) and reducing the occurring wear at the drilling tool, or equivalently, by increasing the drill bit lifetime. As mentioned previously, these two performance parameters are key factors responsible for the high costs of deep hard-rock drilling.

A. *Technical implementation & design solution*

In this section, we present the technical solution followed to integrate a thermal assistance into a conventional drilling system and thereby implement the CTMD technology in the field [13].

A schematic of the drill head employing the CTMD concept is shown in Fig. 1. In order to provide thermal assistance to mechanical rotary drilling, a combustion system (see combustion chamber, shown in red in the section view in Fig. 1) generates a flame jet, which impinges the rock through several nozzles at the drill bit face (shown in red color in Fig. 1). As mentioned previously, the combustion system is employed during drilling modes I and II of the CTMD technology. During the flame-assisted rotary drilling mode the drill head rotates (see arrow in Fig. 1 for direction of rotation) and the flame jet nozzles direct the hot combustion products on the rock surface. The elevated temperatures and high heating rates experienced by the rock are therefore responsible for thermal weakening of the rock material [21]. The flame jet nozzles at the drill bit face are distributed along the drill bit radius to cover – and therefore thermally treating – during rotation a large portion of the borehole bottom-surface. Conventional drilling cutters are prescribed at the drill bit, similarly to mechanical rotary drilling, and they remove the weakened material to penetrate the rock [22,25]. Drilling fluid (drill mud or water) is used to provide cooling to the drilling system components and to transport the produced cuttings up-hole by exiting at the drill bit (see yellow nozzle in Fig. 1). Following this configuration, also air shielding is implemented at the drill bit by conveying compressed air to the drill bit face. This allows to shield the hot flame jets from the surrounding drilling fluid environment and therefore enhance the heat transfer of the flame jets to the rock surface.

Overall, this technical solution shows remarkable synergies with conventional rotary systems due to thermal assistance and rotary drilling systems' modularity, which in turns yield large potentials of integration of the CTMD approach into conventional drilling processes.

B. *Performance analysis of CTMD*

In order to investigate drilling performance parameters of the proposed CTMD technology and compare those to conventional rotary drilling, field testing has been carried out. The CTMD drill head has been integrated into a real-scale drilling rig (Bo.Rex, owned by the International Geothermal Centre Bochum, GZB, now Fraunhofer IEG). Specific rotating joints have been developed to allow the injection of additional fluids (combustion fluids and compressed air) into the drill string. Tests have been carried out in a granite (Grimsel granite from Switzerland) block, which is considered as a representative crystalline rock for deep drilling conditions.

Drilling tests have been carried out employing the CTMD technology (flame-assisted rotary drilling) and the results have been compared to mechanical rotary drilling (standalone mechanical drilling). To allow a consistent comparison of the results, the same process conditions (rotational speed and weight-on-bit) and identical drill cutters design solution have been adopted for CTMD and mechanical rotary drilling tests. Several drilling performance parameters have been monitored during and after the tests, including rate of penetration (ROP), wear state of the drill bits, size of the produced cuttings and drilling energy/force parameters [24]. In the following, we focus on two main key performance factors, namely, ROP and specific wear of the drill bits. The first parameter, as also mentioned above, is representative for the speed of the drilling process and is a major factor affecting the time spent to access deep geo-resources. The specific wear parameter is, on the other hand, a measure of the wear experienced by the drilling cutters at the bit face during rock penetration. The specific wear parameter is therefore inversely proportional to the lifetime of the drill bit. Hence, we show, in Fig. 2, these two drilling performance parameters, measured during our field test, and we compare CTMD technology to conventional, mechanical rotary drilling. Concerning the rate of penetration comparison, shown in Fig. 2.(a), we observe that CTMD technology can significantly intensify the drilling process, by increasing the drilling speed by a factor of almost three, compared to standalone mechanical rotary drilling. At the same time, the CTMD drill cutters experience a reduced wearing. Indeed, from Fig. 2.(b), we observe that the wear of the drill bit in hard granite can be more than halved, using the CTMD technology, compared to mechanical rotary drilling. Thus, these first evidence clearly show that the CTMD technology features remarkable advantages in terms of reducing the drilling efforts (time and thereby the drilling costs) to access deep geo-resources in hard rocks.

These field tests have demonstrated the readiness of the CTMD technology to drill hard granite under field conditions. Nevertheless, in order to enable the application and the future use of the CTMD concept under deep drilling conditions, additional research is needed. This effort will aim to understand the influence of high pressures and temperatures on the rock material, typically found under deep conditions, on the thermal cracking mechanism, and thereby study the resulting efficiency of CTMD. Additionally, to extend the use of CTMD technology, especially under deep geological conditions, we envision that further technical developments are required.

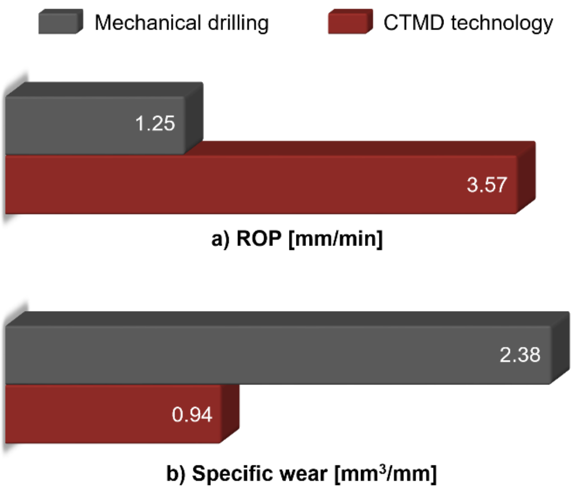

Fig. 2. Comparison of drilling performance parameters from field test: a) rate of penetration ROP; b) specific drill bit wear.

III. PLASMA-PULSE GEO-DRILLING (PPGD): AN INNOVATIVE TECHNOLOGY FOR ULTRA-DEEP DRILLING

As mentioned above, the wear of the drill bit and the drilling speed (ROP) are decisive factors for the high costs of deep boreholes (> 5km). At such depths in many regions

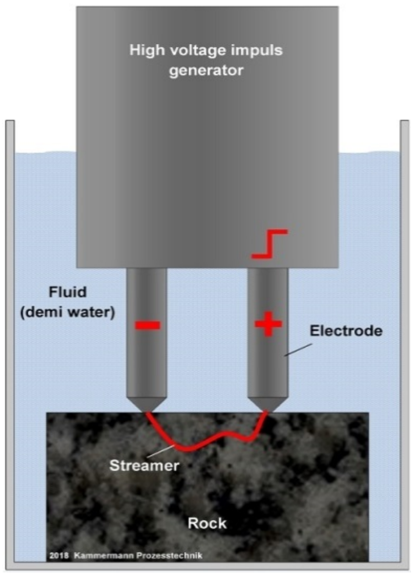

Fig. 3. Plasma-Pulse Geo-Drilling (PPGD) principle.

of the world, hard rock is encountered. Hard rock leads to both a pronounced wear and, thus, a substantially reduced ROP referring to the established rotary drilling method. The Plasma-Pulse Geo-Drilling (PPGD) technology shows great potential for improving these two factors [14]. PPGD does not remove the rock by mechanical action and, furthermore, it requires little energy per excavated rock volume. This yields two main advantages of PPGD, compared to conventional mechanical drilling: (i) a lower wear rate (or practically wear-free) during drilling reduces the number of round trips, and (ii) a lower volumetric energy input to drill the rock enables higher rates of penetration (ROP). These two aspects are responsible for considerably facilitating access to deep, hard rocks by improving the related drilling economics.

A. PPGD concept and operating principle

The mechanism of PPGD is fundamentally based on the electro discharge technology (EDT) originally developed in Russia [26].

Following this approach, a suitable electrode arrangement is used to initiate a plasma channel (streamer), induced by a high voltage pulse, see Fig. 3. The streamer propagates through the rock and, thereby breaking the rock from within (Fig. 3). The electrodes are embedded into the drilling tool and the process is surrounded by a drilling fluid (e.g. oil or water). However, in order for this process to be effective in breaking the rock, the plasma channel must take place through the rock and not along the rock surface, i.e., through the fluid. This is primarily achieved by a rapid pulse rise, see Fig. 4. The rising time is an important factor, because of the remarkable dependency of the dielectric strength of materials with time of pulsed voltage application [26]. This is based on the observation that the rate of increase of dielectric strength in liquid is higher than that in solids for decreasing time of pulsed voltage application (see curve slopes for water and rock in Fig. 4). Consequently, the breakdown process depends essentially on the following parameters: (i) the properties of the involved materials, such as their internal structure, the contained minerals, their porosity, the free charge carriers and permittivity and (ii) the specific operating conditions, such as electrode geometry, pulse shape, pressure and temperature.

A more detailed explanation of the PPGD operating principle is explained below, using a simple 2-electrode arrangement (refer also to Fig. 3). Based on the conducted in-house testing, we have deduced the following 10-step process:

1) A high voltage pulse is generated by a pulse generator.
2) The generated electric field penetrates the water and the rock.
3) The different components of the rock have different permittivities, which leads to field displacement and polarization effects.
4) Field disturbances/field elevations occur at the grain boundaries/inhomogeneities.
5) Different field strengths/voltages occur over the individual rock pores.
6) Orientation polarization occurs in the fluid (water) during the electrical breakdown process in water.
7) The streamer starts to grow (Fig. 3). This is a dynamic process with a broad number of conditions affecting the streamer route, as also mentioned above: the distribution of the individual field strengths, the partial discharge paths, the relaxation rate of the water dipoles, etc. The streamer growth initiates earlier in the water than in the rock, however, the faster growth of the rock streamer allows the latter to overtake the water streamer.
8) The plasma channel (arc) forms within the rock and the pressure rises sharply due to the generated heat.
9) The pressure in the plasma channel exceeds the tensile strength of the rock, and the rock breaks. In addition, the acoustic shock wave, induced during the rock breakage, is reflected by the inhomogeneities, and thus intensifying the breaking process at the grain boundaries. The resulting pressure wave in the fluid helps removing loose rock fragments. Further, the latter mechanism promotes

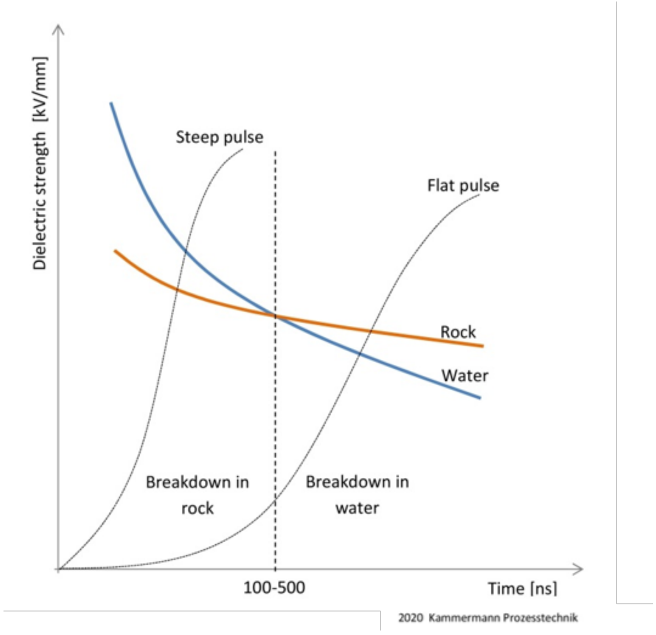

Fig. 4. Dielectric strength of water and rock versus time of pulsed voltage application [26].

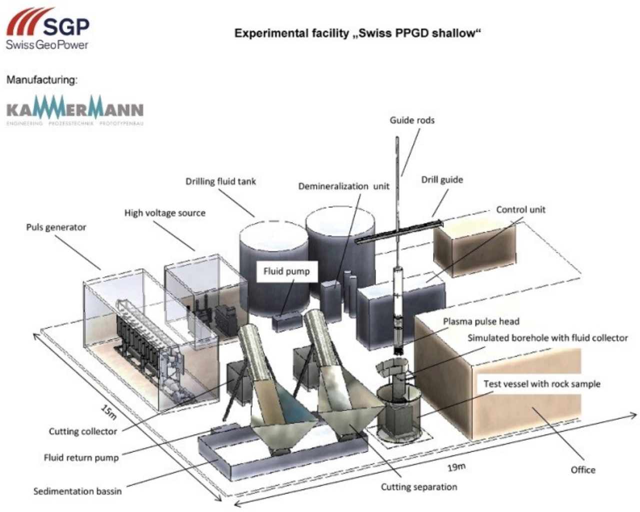

Fig. 5. Swiss PPGD experimental facility.

drilling in softer formations which are not subject to the laws described.

10) The pulse source controls both for how long the plasma channel is active and also the amount of energy input to the system.

Based on such a rock-breaking mechanism, the Plasma-Pulse Geo-Drilling process generates a plasma channel that breaks the rock against its low tensile strength, without any mechanical action on the rock material. The tensile strength of the rock is a much lower value, compared to the compressive strength of the material, which has to be overcome during conventional mechanical rotary drilling. For this reason, PPGD theoretically features greater rock-breaking efficiency prospects, compared to drilling hard rocks by conventional rotary drilling processes.

B. *Up-to-now PPGD test results and outlooks*

In order to investigate experimentally the PPGD technology, the Swiss PPGD experimental facility has been developed, see Fig. 5. This experimental facility allows to study a wide range of operating parameters and test conditions for the PPGD technology. Here below, we present the test results obtained by SwissGeoPower using the in-house Swiss PPGD experimental facility. Until now, the best results have been achieved with a borehole diameter of 20 cm using demineralized water as drilling fluid. The tests are carried out in granite rock, in samples with a height of 12 cm, see Fig. 6. The corresponding ROP resulted in 7.2 m/h and a specific energy (SE) input (input drilling energy per unit of removed rock volume) of 477 J/cm^3. These are promising values, compared to the low rates of penetration, commonly found in hard granite rocks using conventional rotary drilling [27]. Currently, tests are being carried out using various electrode arrangements.

One challenge for the PPGD experimental set-up is to withstand the particular conditions found during the tests. Indeed, the test set-up must accommodate very high stresses by high voltage impulses, high pressures and high temperatures for many hundreds of hours.

Future work on PPGD technology includes to study the effects of deep in-situ conditions (pressure and temperature) on the efficiency of the drilling process. This will be investigated via specific laboratory experiments and also using numerical models [28,29] developed in our group.

Fig. 6. Drilling results in granite using demineralized water as drilling fluid.

IV. Conclusions

In order to improve the drilling economics and facilitate deep geo-resource utilization, in this work, we present two advanced drilling technologies, namely, CTMD and PPGD. Employing the CTMD approach, we show a significant increase of the resulting drilling performance parameters, e.g., faster penetration and improved drill bit lifetime. A peculiarity of this hybrid drilling technology is the high degree of integration into conventional drilling system. Furthermore, we envision that CTMD can profit from the know-how and expertise established in the conventional rotary drilling industry to further develop and ease its implementation under deep drilling conditions. Concerning the PPGD technology, laboratory tests provide evidence for increased ROP in hard granite rock and an inherently (tensile fracturing) more efficient rock-breaking mechanism, compared to conventional drilling methods. Additionally, PPGD is a contact-less drilling process, thereby enabling to drill hard granite rocks with practically no wear of the drilling tools, a crucial factor in deep drilling projects.

All in all, we conclude that the two technologies both show remarkable advances in improving drilling speed and reducing or even completely avoiding wear of the drilling tools, especially for hard-rock drilling. Further research and development is required to extend and facilitate the application of the two methods under deep borehole conditions.

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