Review of Thermal Surface Drilling Technologies

R. Ndeda, S. E. M. Sebusang, R. Marumo and E. O. Ogur

Abstract—Mechanical methods of drilling have been widely applied in drilling for water, petroleum, natural gas and geothermal energy. However, limitations such as rapid tool wear as well as downtime necessary for tool bit replacement and maintenance have facilitated the entry of non-contact drilling methods. Further, increased supply through discovery of new reserves, has been an added impetus towards the development of cheaper and more effective drilling alternatives.

Thermal drilling is a non-contact drilling method that was developed in the late 20th century. It involves the application of thermal energy to penetrate rock formations. This paper presents, through a review of literature, the state of the art of thermal drilling methods, analyzing previous and present approaches. Future research areas for each of the methods are also highlighted.

Keywords—Thermal spallation, Super Deep Fusion, Laser Drilling, Hydrothermal Spallation, Flame Jet Drilling, Electropulse Boring

I. INTRODUCTION

ROTARY drilling has been the most popular drilling method for petroleum and gas since 1900, when its implementation replaced cable drilling [1]. The method utilizes a rotary drill bit which is forced onto the rock, consequently crushing it. The method has been used for drilling for water, oil, gas and geothermal wells. Whereas the efficiency of the method has somewhat improved since its first introduction into the market, certain challenges have drawn research into other means of drilling.

Geological conditions of the location of the well has a large impact on the drilling cost. For example, research indicates that well costs in Germany are the highest worldwide, due to the geological conditions [2]. A study of the relationship between well costs and well depths indicated an exponential relationship, which is attributed to the hard crystalline rocks, prevalent in deep well drilling [3]. In an alternate scenario, where different rock types are arranged in layers, the drilling process would encounter several stops, which would involve changing of the drill bit to suit the specific rock [4]. This leads to reduction in overall drilling speed and hence increasing the cost.

Wear of the drill bit also contributes to inefficiency in the drilling process. Apart from machining hard rocks, high temperatures involved in deep underground drilling also affect the drill bit [5]. Maintenance of the drill bit and accessories involves taking the tool up to the surface and returning it to its original position, a process called ‘tripping’. An increase in tripping time leads to corresponding increase in drilling cost. Research posits that increase in bit life would reduce the total well cost by 5% [6].

Another common challenge encountered when using a drill string is the deviation from the vertical. Rotation of the drill string increases the frictional forces experienced which leads to a non-vertical hole. This may lead to differential stresses, leading to the instability of the hole [7]. In addition, other conditions which may further affect the drilling process are overpressure of the well, underbalanced well and swelling of the rock [8], stuck pipe and fishing for lost tools in the downhole environment [9].

Technical advances in the drilling tool and accessories have caused a slight reduction in the cost of well drilling. The advent of the tricone bit reduced the number of drilling runs, despite experiencing similar steering limitations as roller cone and drag bits [10]. Research and development focused on new methods of drilling seeks to reveal more efficient drilling methods, that will curb costs while increasing the rate of penetration into the rock.

Thermal drilling methods mainly employ the use of thermal energy to exert stress on the rock. Removal of the rock can be achieved either through melting and vaporization or through spallation. These methods have the advantage of lack of contact between the tool and the rock surface. Since the tool is not subject to wear like a conventional drill bit, using these methods is expected to reduce tripping time for maintenance and repair of drill bits, hence overall reduction in drilling time [11].

This paper provides an exploratory analysis of the most popular thermal methods, indicating the advantages and limitations, as well as providing a peak into the future.

II. ROCK MELTING

Application of thermal energy to the rock leads to melting of the rock. Further heating leads to vaporization. This section discusses drilling methods which use melting as a mode of rock removal.

A. Super Deep Fusion Drilling

Deep geothermal drilling is the current market leader for drilling tools due to the world push towards clean energy sources. Hydrothermal geothermal systems, where steam at high pressure is obtained from rock formations that have adequate permeability and water, were widely used in the 20th century. However, the development of Enhanced Geothermal Systems (EGS) have enabled extraction of geothermal energy in rock formations that are devoid of water and permeability. This method relies on the circulation of water through fractures created during the drilling process in order to
generate sufficient steam for energy generation [12]. Whereas conventional holes for oil and gas reach a depth of 2kms, EGS requires wells of upto 5kms. At these depths, certain limiting conditions for conventional rotary drilling exist. The change in rock behavior from brittle to ductile makes it harder for conventional methods to drill. In addition, the stability of the well, which is enhanced by the presence of drilling mud, is compromised at high temperatures and pressures (greater than 373.95 °C and 220.64 bar respectively [13]) due to the reduction in the density of water, leading to a high likelihood of well collapse [14]. Another limitation of the conventional drilling process is the possibility of lost circulation when using drilling fluids, hence leading to leakage into the well which prevents well completion [15].

Super Deep Fusion Drilling uses a superheated molten metal to heat the rock face. Continuous heating through alternative magnetic fields in the drilling head causes the hole to deepen. The molten material solidifies into a casing for the well after being pressed by a compactor. After-cooling is then accomplished by the use of a heavy fluid which increases compressive forces on the casing as well as stabilization of the well [16]. This method is estimated to be able to drill 20km pit with diameter of 1m at a cost of €3300/m. This cost is inclusive of steel casing [17].

This method has the advantage of automatic casing as the drilling continues. In the case of oil and gas drilling, continuous casing of the rock ensures a closed environment, where there are no expected blow outs [18]. A further advantage is that it is unnecessary to have a means of disposal or transport of the rock cuttings to the surface. Once drilling of the well has been completed, the recyclable parts of the drilling head ensure that there is no need for waste disposal mechanism.

This method is, however, limited where karst regions which are characterized by holes, caves, and underground drainage systems exist. These areas would require the addition of conventional drilling as well due to the unexpected water outbursts [19].

Apart from EGS, this method is widely applicable for super deep well applications such as mining of minerals which dissolve at high pressures and recycling and extraction from oil and gas wells. The method is currently at the patent stage for most of the test equipment. However, further research should be engaged in analyzing dry rock characteristics and the applicability of this method on the same.

B. Microwave Drilling

Microwave energy has been widely applied in the industrial and scientific sectors. Application in rock drilling only came to the fore 50 years ago. The major challenge in development of the microwave drill for many applications has been the thermal runaway phenomenon, which indicates uneven heat dissipation and temperature distribution in material [20]. This has been attributed to resonance of electromagnetic waves within the object, in addition to heat loss characteristics of the material [21]. These losses would make the process extremely inefficient.

Research conducted by Jerby and Diktiar [22] developed a means of concentrating the microwave energy to a small spot in order to generate enough heat for rock removal. This was based on earlier research which indicated the dependence of microwave drilling on the power density delivered and the method of delivery to the rock [23]. Further, Whittles et al. [24] indicated that greater stresses were generated by increasing the power density instead of increasing the energy supply. The viability of microwave drilling for rock removal has been improved by these discoveries.

Microwave heating can be used for melting of the rock strata as well as spallation. In the case of melting, the method involves deposition of microwave energy to the intended spot around the microwave radiator. The underlying surface is at a higher temperature than the surface due to cooling effects of the machining environment. With continuous application of the microwave energy, the subsurface regions begin to melt. An electrode is then used to push the molten material to the boundaries of the hole. It is observed that the microwave drill is capable of making holes of 10^{-3} - 10^{-2}m [25]. Where spallation is the intention, differential absorption of the microwave energy by a heterogeneous rock sample leads to fracture of the rock [26]. Since absorption of microwave radiation by the rock is dependent on the dielectric properties of the individual constituents of the rock, differential expansion of these individual grains would lead to varied tensile and shear stresses [27]. Microwave spallation has been deemed to occur in quasi-homogeneous rocks such as basalt, gabbro and granite [28].

Laboratory experiments have been performed in microwave ovens [29] and through single mode application [30]. Research on the fracture and drilling of various rock types indicates that certain minerals easily absorb microwave energy (magnetite, chalcopyrite and water), hence, promoting the use of microwave energy in these environments. Those that do not absorb microwave energy include feldspar, quartz, marble and ice [31]. The presence of water in the pores of the rock has been noted to slightly aid the drilling process. Comparison between the operation of microwave energy between water saturated and dried samples indicated a considerable increase in heating rates for water-saturated granite and sandstone, with no change in basalt [32]. This research informed the fact that microwave drilling is dependent on both the type and the heterogeneity of rock. Consideration into the behavior of rocks with relation to period of exposure to microwave power indicates significant strength reduction in rocks with short exposure times. Further, there is a power limit above which there is no breakage induced in the rock [30].

The advantage of the microwave drilling process is that while rotation of the electrode is a requirement, the slow rotation involved does not cause mechanical friction, hence the possibility of directional holes is observed. Further, due to the use of the molten material, there is low wastage as well as a dust free environment [26]. Application of microwave spallation are in the treatment of minerals, where heating is directed and controlled for specific phases [33] and mining in space [34].

Limitations of this method are that the initial capital investment is very high, further aggravated by the dependence of operational costs on the life span of the magnetron. Further,
the inefficiency involved in conversion of electric energy to microwave energy (65%-90%) may be discouraging [35]. It is also mandatory to have adequate shielding to prevent microwave leakage.

III. THERMAL SPALLATION

The mechanism of thermal spallation has been present since the early 1900s [36, 37]. Thermal spallation involves the application of thermal stress to fracture the rock surface. The method is mainly dependent on flaws (micro-cracks) inherent in the rock formation. On application of heat, thermal stresses are generated due to the steep temperature gradient between the rock surface and the underlying layers, causing the extension of microcracks. When the thermal stresses exceed the compressive stress of the rock, a chip violently buckles off the surface [38]. Thermal energy can be supplied using a flame, super-heated water jet, microwave or laser beam. Thermal spallation has found wide application in drilling of boreholes, opening small orifices for installation of explosive charges and other mining applications.

To be considered, however, is the fact that spallation drilling hinges on the capability of rocks to spall. Experiments by Williams and Potter [39] indicated that certain soft and ductile rocks (limestone, soft sandstone, shale) did not spall under application of continuous heat. However, Xu et al [40] determined that spallation of soft and ductile rocks occurred on alternate heating and cooling of the rock.

Spallation is largely dependent on the energy applied to the rock. The spalling zone of rock occurs just below the melting temperature of the rock. Initial application of heat creates thermal stresses in the material due to the low diffusion rate into the rock. Continued application of heat would raise the temperature of the rock to melting point without spalling [41]. The delicate balance between supply of heat flux and surface temperature of the rock should be maintained within the brittle-plastic transition region.

Another aspect of thermal spallation that should be considered is the limitation of the area of application of the heat flux. Studies by Rauenzahn [42] indicated that application of heat flux should be limited to 10% of the rock surface, to ensure that the induced thermal stresses are not relieved, preventing spallation.

It is estimated that thermal spallation drilling could result in shorter downtimes and overall increase in drilling speed. Figure 1 shows expected linearization of cost versus depth index due to thermal spallation, also known as "linear drilling", as suggested by Potter and Tester [43].

The most popular methods of thermal spallation drilling are flame jet drilling, laser drilling, hydrothermal spallation and electropulse boring.

A. Flame Jet Drilling

The most popular method of thermal spallation is flame jet drilling, which owes its popularity to the high penetration rates that are achievable in hard rock types [11,44]. Flame jet drilling utilizes gas flow from the burner for removal of spalls from the drill site.

Initial commercial tests of flame jet technology were performed in 1940 in mining of taconite [45]. With the closure of the taconite industry, the technology lay dormant till the mid-70s where the method was applied to drilling of geothermal wells. Browning Engineering Company, in the mid-70s, indicated an average penetration rate of 52ft/hr when drilling granite using flame jet technology [46]. Comparison between flame jet drilling and conventional methods which achieve an average penetration rate of 16.2ft/hr, indicates a massive improvement. Another advantage of the method is its capability to drill very narrow holes as well as holes of upto 20 times the diameter of the flame jet nozzle [47]. This means that it can be used for both well drilling and completion.

Within the past 20 years, applications of flame jet drilling have, however, been limited to drilling of shallow holes (less than 0.5km) at ambient pressures [42,48]. This is due to several reasons. First, an air-filled environment is required for the purpose of maintenance of the flame as well as spall removal from the drill site. Due to the high pressures in deep drilling, the air-filled hole is largely unstable, aggravated by the water intrusion which may hamper the gas-enabled spall removal [49]. A further limitation in drilling large hole diameters is the reduction in lift velocity of the exhaust gas. Efficiency of spall removal is, therefore, impeded [50]. Second, deep drilling requires a high density drilling fluid, commonly known as drilling mud, which apart from carrying away particles, serves to balance the pressure in the well. This would mean ignition and maintenance of the flame in a liquid-filled environment.

Current research efforts are concentrated in studying the feasibility of using flame jet spallation for deep geothermal wells. Augustine et al [51] developed a flame capable of operating in a high pressure and density environment. The hydrothermal flame uses the principle of hydrothermal combustion where the oxidation process takes place at supercritical
conditions while in a dense aqueous environment [52]. Results demonstrated a generated heat flux of 0.5MW/m^2 compared to that of 1MW/m^2 for spallation in a low density environment at ambient pressure. Despite this variation, the generated heat flux was still within the range capable of inducing spallation. An added advantage of the hydrothermal flame is the potential for use at supercritical conditions. Rothenfluh [53] estimated that the hydrostatic pressure of the well exceeds the critical pressure of water at a depth of 2200m, which is the suitable condition for ignition and combustion of the hydrothermal flame.

Despite this progress, this method is limited significantly through the entrainment of the generated hydrothermal flame. Experiments conducted by Tester and Augustine [54] indicated that the supercritical jets were quenched by turbulent flow around the flame. This phenomenon is known as entrainment, which refers to the tendency of fluids to be drawn towards turbulent jets. Density and momentum differences between the flame and surrounding fluid initiates turbulent mixing, which then results in reduction of the temperature from supercritical to subcritical levels [11, 55]. This entrainment was found to grossly affect temperatures of the flame, such that spallation could not occur. Current research is concentrated on understanding and consequently elimination of these entrainment effects for efficient spallation in the deep drilling environment.

A further limitation of flame jet spallation is the safety threat posed by the possibility of combustion in oil and gas wells [56]. This situation, however, is not likely to be experienced in geothermal drilling, hence is a suitable application of this method. Application of flame jet spallation in extraction of close-to-the-surface minerals has been successful, where the spalls generated are processed for precious minerals.

It is evident that with growth of technology, many applications and yet more challenges are encountered. Whereas flame jet spallation is prospectively capable of replacing rotary drilling, current research efforts should in effect be concentrated on the reduction or eventual elimination of inefficiencies of the process.

B. Hydrothermal Spallation Drilling

Hydrothermal spallation drilling is the means of drilling which utilizes a high-temperature fluid jet to provide heat for the process. This method was designed as one of the solutions to the challenge of use of the flame jet in the downhole environment. The method utilizes hydrothermal flames enclosed within a combustion chamber in order to heat a stream of water, which is then ejected from the nozzle at high temperatures capable of causing spallation [57].

A comparison between mechanical drilling and hydrothermal spallation drilling of granite indicates a rate of penetration of 15ft/hr and 40ft/hr respectively [58]. Further, the process has been found to be effective at supercritical pressures prevalent in deep drilling. This, therefore, means an overall reduction in costs in deep drilling where there are hard, crystalline rocks. This method also has the advantage of improved trajectory control due to the lack of contact with the rock surface [49].

The largest hindrance to the efficiency of the hydrothermal spallation drilling method is entrainment of drilling fluid into the hot water jet region. This causes loss of heat in the jet before the energy can be transferred onto the rock. Investigations conducted by Rothenfluh [53] indicated that changing the operating conditions had no effect on reduction of entrainment. Current research in hydrothermal drilling is targeted at reduction of entrainment by drilling fluid. It is also necessary for future research to establish the effect of flow reversal of the jet fluid after impinging the rock [11].

Hydrothermal spallation has been targeted for application in EGS. Due to the breadth of laboratory-based research, it will be imperative to conduct downhole testing of the method, along with the tool head design, in the future. It would be important to understand the behavior of the rock under applied stresses in a high pressure and temperature environment. Sensor development for the harsh downhole conditions is also a viable field of study. Sensors would be required for suitable heat detection of entrainment effects during spallation. This would assist in computation of spallation conditions at the drilling head and nozzle as the process progresses. Application areas related to EGS such as drilling of slim holes and directional drilling will also require investigation [49].

C. Laser Drilling

The use of laser technology in well drilling has previously been used for analysis. This includes oil film thickness measurement [59], detection of the crude oil properties [60] and permeability damage [61]. Investigations into the use of lasers for drilling were conducted in the late 60s and 70s. However, the inefficiency of the lasers caused the method to be rejected. Later, the development of high power lasers [62] and the use of fiber laser beam delivery technology [63] ensured the delivery of the beam to the downhole environment in addition to its ability to drill rock.

An outstanding advantage of the process is the obvious lack of contact between the tool and the rock face, which reduces tripping time due to the reduced wear. This foreseen cost reduction has been a driving force towards its adoption in the industry. A gas well of 3048m depth would cost $35,000 when using the laser as compared to mechanical methods which would attract investment of $350,000 [64]. Further, due to its faster rate of penetration into the rock, it is estimated that laser drilled wells will take 90% less time than conventional methods [65]. Faster drilling time means reduction in damage to the ecosystem. It is, also, envisaged that the environmental impact of the laser drilling would be lower than conventional means. In relation to power required, a 20kW fiber laser is powered by 1.5kW compared to a mechanical drill rig which requires 1.5MW of power to generate 2000HP [66].

The mechanism of rock destruction using lasers is through thermal spalling, melting and vaporization. Application of heat to the surface of the rock causes an instant increase in temperature which causes spallation. However, continued application of the localized heat flux results in dissipation of energy through various mechanisms. Melting of the rock occurs due to the absorbed flux. Other minerals such as clay
present in the pores of the rock are dehydrated, forming a glassy phase which also reflects the laser. Finally, this dehydration of the minerals cause formation of plume which decreases the energy transferred to the rock. This dissipated energy causes inefficiency in the laser, preventing it from reaching the exposed under-rock [67].

The lowest values of specific energy are attained during thermal spallation while the highest values occur when melting and vaporization of the specimen occurs. Spallation is, therefore, a juggling act to ensure that the energy input does not raise the temperature of the rock to melting. The use of pulsed lasers has been effective in this concern [68]. Research indicates an increase in rock removal when a pulsed laser with a high repetition rate is used in spallation. This has been attributed to the laser-driven shock wave that is generated by the increase in thermal cycling frequency [67]. Kobayashi et al [69] observed that spallation of adjacent rock surfaces occurred without laser irradiation being applied on the whole surface. Spallation, therefore, does not limit the size of the hole to the spot size of the laser. Optimization of the relaxation time is necessary in order to achieve optimum values of specific energy.

Spalls are removed from the borehole using purge gas. Nitrogen is the most common gas used for this application with co-axial purging found to enhance drilling [70]. However, the use of the laser with a mechanical scraper has been used in certain situations for spall removal [71].

Spallation in water filled environment has been investigated. It was determined that the rock melted instead of spalling. This occurred at certain laser wavelengths, depending on the water absorption coefficient. Further, the lower wavelength lasers were capable of functioning with a jet of water supplied in the drilling area. Despite these positive results, laser energy was dissipated through the following: absorption and reflection of the laser by water blockage by steam and clouded water and spattering of water [72]. This leads to diminished rate of penetration. In the case of water-saturated samples, it was noted that the specific energy required for water-saturated samples was high due to the high vaporization point of water and lower absorption rate of laser energy by water [73].

Another widely accepted application of lasers is perforation and completion of wellbores. Investigation into the laser perforation was done at high pressure by Gahan et al [74]. It was determined that the confining stress improved the thermal diffusivity of the rock due to the close contact of the grains. This led to an overall improvement of the perforation process.

Apart from the limitations already mentioned, other challenges require addressing before the method can be taken to market. Future research should be focused on equipment design for efficient performance for deep drilling and well perforation. Delivery of the laser to the downhole environment should be at the fore. The conventional drill string can be adapted for delivery of the laser. Since the laser has no Weight on Bit (WoB), studies suggest the use of a composite metal matrix instead of steel as there is no need for high tensile and compressive strength of the drill string [67].

It is also imperative to understand the mechanism of laser energy dissipation as well as drilling parameters which require control. Modeling of these processes will go a long way to explaining laser rock interactions. Additional investigation into the role of these parameters on both spallation and melting of rock in the drilling environment will be crucial. It is also important to analyze the laser-rock interaction when exposed to elevated supercritical pressures prevalent in downhole drilling.

D. Electropulse Boring (EPB)

Initial research into Electropulse Boring began in the 70s, with the notion of pulsing electrical voltage for generation of a shock wave [75]. In 2009, Bergen-Norway commissioned research into electropulse boring for drilling of geothermal wells [76]. The method employs transmission of electric pulses of between 100-1000kV through fluid-submerged electrodes in contact with the rock surface. On passing of the pulse through the rock, a volume of rock breaks away from the surface. Subsequent application of pulse causes further cracking of underlying rocks.

It is foreseen that this method should be able to drill large diameter, super-deep holes in hard formation with low costs. Rate of penetration of upto 35m/hr for a 50cm diameter borehole was achieved while drilling granite, which is comparable to the aforementioned methods. The extrapolated cost of drilling a 9km deep hole would be 1€M compared to the current rotary drilling costs of 100€M as shown in Figure 2 [76].

![Fig. 2. Cost comparison between Rotary Drilling and Electropulse Boring](Image)

This method can be applied in drilling large diameter wells, which are larger than the size of the EPB bit. The suggested method of delivery of the tool bit downhole has been through the use of the conventional drill string, with replacement of the drill bit with a boring tool. This method has, however, been constrained by the fact that the tripping time to replace the bit would subtract from the high rate of penetration benefits.
Whereas there is significant saving in the high rate of rock breakage, there is significant energy consumed in the use of annular fluid flow for transportation of cuttings when the diameter of the borehole is large. However, this can be significantly reduced by using a hose for this purpose [77].

Due to the vast differences in EPB technology and that currently in use for rotary drilling, adoption of this technology would require changing of all the equipment. Other risks associated with this method such as handling of high voltage on a continual basis would also require adherence to strict procedures during the drilling operation.

Focused research is therefore, required for development of a suitable drill rig, with suitable delivery of the tool to the downhole environment. In addition, it should be of paramount importance to analyze the operation of EPB in the downhole environment with increased temperature and supercritical pressure regime. Further, the effect on the drill rig would also be necessary to determine.

IV. COMPARATIVE ANALYSIS

Three parameters are commonly used for the determination of the efficiency of drilling methods. These are power used in the process, rate of penetration and specific energy. When mechanical drilling methods are used, the power input is expended in application of force which is greater than the strength of the rock, hence causing disintegration. Similarly, the use of thermal methods require enough energy to exceed the compression strength of the rock to cause fracture (spallation) or exceed the melting temperature of the rock [65].

Specific energy is a common unit in determining the efficiency of drilling method. Specific energy of thermal drilling processes is defined as energy required to disintegrate one cubic volume of rock and is defined by equation (1):

\[
S_e = \frac{\text{Energy Input}}{\text{Volume of rock removed}}
\]

For mechanical methods, specific energy can generally be defined as:

\[
S_e = \frac{\text{Mechanical Power Applied to the Rock}}{\text{Volumetric Rate of removal of the rock}}
\]

For rotary drilling, equation (3) is used to determine the specific energy.

\[
S_e = \frac{\text{WoB} + 120\pi \times T \times \text{RPM}}{A_{\text{Bit}} \times \text{RoP}}
\]

where \( T \) is the torque generated, \( A_{\text{Bit}} \) is the Bit Area, WoB is the Weight on Bit and RoP is the Rate of Penetration.

Specific energy is dependent on several underlying factors. Different types of rock have a wide variation of properties and hence react differently to exposure to thermal energy. Rock formations with higher conductivity enable faster diffusion of heat into the rock, hence, lower specific energy is required. Further, heterogeneous rocks would behave differently, depending on the mineral composition and packing of the grains. For example, rocks containing a large percentage of quartz have a higher melting point [64]. Mineralogy of the rock could encourage formation of macro fractures which lead to energy loss and dissipation. Time of exposure of the rock to the thermal energy also affects the specific energy [65]. Table II makes a comparison of the specific energy used in drilling for the different thermal drilling methods. The table also indicates the rock formations in which drilling was performed. To achieve an adequate comparison, it would be pertinent for drilling to be performed on a similar rock type and in similar conditions.

### TABLE I

**SPECIFIC ENERGY FOR DIFFERENT DRILLING TECHNOLOGIES**

<table>
<thead>
<tr>
<th>Method</th>
<th>Specific Energy (kJ/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Water Jet</td>
<td>0.3 - 1.4</td>
</tr>
<tr>
<td>Rotary drill [78]</td>
<td></td>
</tr>
<tr>
<td>Surface set Diamond Bit (granite, quartzite)</td>
<td>1.4 - 2</td>
</tr>
<tr>
<td>Impregnated Diamond Bit (granite, quartzite)</td>
<td>10</td>
</tr>
<tr>
<td>Rotary drill (drag bit)</td>
<td>0.4</td>
</tr>
<tr>
<td>Laser drilling</td>
<td></td>
</tr>
<tr>
<td>CO laser</td>
<td>22.8</td>
</tr>
<tr>
<td>COIL laser</td>
<td>7.2</td>
</tr>
<tr>
<td>CO₂ laser</td>
<td>37.4</td>
</tr>
<tr>
<td>Nd:YAG Laser [79, 80]</td>
<td></td>
</tr>
<tr>
<td>Melting (Sandstone &amp; Shale)</td>
<td>2.2</td>
</tr>
<tr>
<td>Spallation (Sandstone &amp; Shale)</td>
<td>0.5</td>
</tr>
<tr>
<td>Pulsed (Limestone)</td>
<td>12.7</td>
</tr>
<tr>
<td>Super pulsed (Limestone)</td>
<td>5.1</td>
</tr>
<tr>
<td>Flame Jet (Barre Granite) [81]</td>
<td>8.7-18.2</td>
</tr>
</tbody>
</table>

Rate of penetration can be approximately be calculated using equation (4)[82].

\[
\text{Rate of Penetration} = \frac{\text{Power per unit area}}{\text{Specific Energy}}
\]

Potential increase in the rate of penetration would lead to a corresponding reduction in the cost of drilling.

Research indicates the inadequacy of the use of specific energy to compare thermal and mechanical methods. Studies conducted by Elahifar et al [83] attempted to compare laser drilling with rotary drilling, using specific energy and rate of penetration, with little success. This was attributed to the inequality of the experiments, such as the comparison of a 2-inch roller cone drill bit to an Nd-YAG laser of 9nm spot size. In addition, other ignored parameters such as the drilled diameter and size of the sample used enhanced the inadequacy of the comparison. These confirmed the results obtained by Graves [84], who challenged the comparison of specific energy, without accounting for the rock type, atmospheric conditions and size-power density relationship. The challenge for research, therefore, is to achieve a close-to-adequate comparison of these methods, as a step towards indicating their significance in the drilling market.

Table II shows comparative data available from various literature sources. Most of these thermal technologies have only been tested at laboratory scale, with simulation of the downhole environment being carried out by several researchers. It would be important for deep drilling experiments to be conducted, in order to be assured of the progress of the technology from laboratory to market.

Certain technologies appear to have higher specific energy despite the potential high rates of penetration in hard rock (Table I & II). It would be important to carry out cost-benefit analysis of these methods to determine their economic viability.
TABLE II
COMPARISON OF THERMAL DRILLING METHODS (PORTIONS ADAPTED FROM [85])

<table>
<thead>
<tr>
<th>S/No.</th>
<th>Item</th>
<th>Laser Drilling</th>
<th>Flame jet spallation drilling</th>
<th>Hydrothermal Spallation Drilling</th>
<th>SuperDeep-Fusion Drilling</th>
<th>Electro Pulse Boring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diameter of hole</td>
<td>Undisclosed</td>
<td>0.2-0.45m</td>
<td>20 - 25cm</td>
<td>50-200cm</td>
<td>Minimum of ≈ 200mm for shallow wells; 0.5-1m for deep wells</td>
</tr>
<tr>
<td>2</td>
<td>Volume of material removed</td>
<td>2-4 times the rate of mechanical drilling</td>
<td>undisclosed in literature</td>
<td>175cm/s (≈25cm diameter hole)</td>
<td>4000cm³/s (for 10000cm diameter hole)</td>
<td>380cm³/s (granite for 300-600 diameter hole); 125cm³/pulse</td>
</tr>
<tr>
<td>3</td>
<td>Velocity of Drilling (Rate of penetration)</td>
<td>90% faster than mechanical drilling</td>
<td>52ft/hr (for 330m hole)</td>
<td>15.8m/hr</td>
<td>5mm/s</td>
<td>3m/hr (for diameter of 50cm and excavation rate of 0.6m/hr)</td>
</tr>
<tr>
<td>4</td>
<td>Types of Drilled Rock</td>
<td>Ultra crystalline rocks (Granite, basalt, dolomite, quartzite)</td>
<td>Taconite, Granite</td>
<td>Hard rock, not suitable for sedimentary rocks</td>
<td>Granite</td>
<td>Granite</td>
</tr>
<tr>
<td>5</td>
<td>Depth of hole drilled</td>
<td>laboratory stage</td>
<td>should be capable of drilling upto 3km depth</td>
<td>laboratory stage(should be capable of drilling 10-20cm depth)</td>
<td>Tests conducted at a quarry(should be capable of drilling 6km)</td>
<td>200m(Initial field study)</td>
</tr>
<tr>
<td>6</td>
<td>Cost of Drilling</td>
<td>undisclosed in literature</td>
<td>undisclosed in literature</td>
<td>€3300/m (for 20km pit of 1m diameter; casing cost inclusive)</td>
<td>Estimated at €100/m (diameter of btwn 15-20 for a 6km deep hole)</td>
<td></td>
</tr>
</tbody>
</table>

V. CONCLUSION

A description of various thermal drilling technologies is presented in this paper. The mode of material removal has been discussed and the current status of the technology discussed. A comparison has been made between the conventional drilling methods and thermal methods, with the clear ability of thermal methods to compete being established.

There is limited data on the deep drilling tests of thermal drilling methods. There needs to be concerted efforts towards deep drilling in order to confirm the laboratory results. Comparative feasibility studies should be conducted on these methods, under similar conditions. It would also be necessary to weigh these methods against the current mechanical methods in use. For this purpose, an adequate comparison mechanism should be developed.

Cost-benefit analysis would also be important in determination of the viability of deep drilling conditions. Development of suitable testing rigs is required, due to the differences between thermal methods and mechanical methods. Knowledge of thermal damage both in the short term (during drilling) or in the long term (as drilling goes deeper) will be essential in prediction of the lifespan of the thermal spallation tools.

Research focus should be placed on the interaction between thermal energy source and the rock, in order to increase understanding of the environment and influences to the drilling process thereof. Entrainment has been noted as a major challenge affecting some thermal methods. Investigations into entrainment effects and methods of ensuring delivery of heat to the rock without dissipation would be of premier importance. The use of modeling and simulation techniques would be useful for this purpose.

Proper control of the process as well as real time data retrieval from the downhole environment would greatly enhance thermal spallation. Design of robust sensory equipment for accurate measurement at the high temperatures delivered by these methods as well as the harsh downhole environment is, therefore, requisite.

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