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Feasibility Analysis of Drilling with Liquid Nitrogen in High Temperature Geothermal Wells

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Abstract: The main costs of developing geothermal processes are concentrated in the project of drilling, accounting for more than 70% of the total budget. Inspired by thermal stimulation technology，a new concept of drilling with liquid nitrogen was presented in this paper. The main objective of this paper is to investigate the effect of rapid cooling on bit-rock interaction and the feasibility of drilling with liquid nitrogen. Through the hardness test experiment results, it showed that the thermal stress caused by rapid cooling can reduce the resistance of indenter invades the rock. Then the micro-bit drilling experiment results indicated that liquid nitrogen can eliminate the thermal damage and enhance the wear resistance, which is the main factor affected the life and footage per bit in geothermal drilling. The negative effect is that liquid nitrogen increase the rock failure resistance slightly and need about 8% more mechanical specific energy compared with drilling with air, but the increase about 8% in mechanical specific energy is affordable to drilling engineers. All these results showed that drilling with liquid nitrogen is beneficial to improve the life and footage per bit, reduce non-production time and reduce drilling costs, it is a promising technology in geothermal engineering.

Keywords: Geothermal drilling, Liquid nitrogen, Thermal damage, Wear resistance.

1. Introduction

The increase in energy demands, decline in hydrocarbon energy resources and the link between energy utilization and environmental impact have prompted calls for sustainable approaches to the development and management of the Earth's energy resources [1]. As a green, pollution-free, renewable resources, many countries and institutions around the world have launched a great deal of study on the development and utilization of geothermal resources, such as the "Fenton Hill project" (USA) [2,3], "Iceland Deep Drilling Project" (Iceland) [4,5], "Kakinada geothermal field" (Japan) [6], "Olkaria geothermal project" (The Republic of Kenya) [7,8], and so on. Currently, the biggest problem in geothermal development is that the main costs of developing geothermal processes are concentrated in the project of drilling, accounting for 70% of the total budget, or even more[9]. It is mainly because of that geothermal drilling is distinct from traditional oil and gas drilling. Geothermal drilling is facing harsher downhole conditions than traditional drilling, include high temperature, hard rock, and total loss. These cause the high wear rates, so that the bit has to be replaced more often, leading to interruptions, long tripping times and high replacement costs of the bit. All these factors are causing extensive costs for drilling a deep well in geothermal drilling [10].Therefore, two key engineering problems need to be solved urgently in geothermal drilling. One is how to extend the life of the bit and increase drilling footage per bit in high temperature environment. The second is how to improve the rate of penetration and rock broken efficiency, reduce the drilling cost. In order to tackle the problem, a series new drilling technology has been proposed previously, such as spallation drilling [11, 12], new type bits [13] and aerated drilling [14]. Thermal spallation drilling uses a large, downhole burner, much like a jet engine, to apply a high heat flux to the rock face. It is a non-contact type of drilling and has been studied for more than 30 years, thermal spallation technology was first applied to drilling around the 1980s [15].It has shown its applicability and efficiency in laboratory environments [16, 17] and in shallow drilling applications in hard rock formations with depths up to 311m [18].A new concept of enhancing the drilling process for geothermal resources by combining conventional drilling and the spallation technology has been proposed by Kant[19]. But until now there is no literature published about the field application of this technology, it just stay in the experimental research and theoretical research level. Schlumberger Company invented an innovative Conical Diamond Element Bit to increase the performance of geothermal drilling. The CDE bit delivered more drilled interval at a higher ROP while providing a smooth, high-quality wellbore compared with the offset well that drilling with TCI bits in Philippines geothermal well construction [20].The new CDE bits also showed about 29% increase in footage than traditional PDC bits, but a slight ROP declined in in hard-rock geothermal applications, in California [21]. Due to the existence of reservoir fracture, massive losses including partial and total losses was the another challenge to drill the geothermal well[22].Usually, the targets of wells in geothermal drilling are faults, fractures or fissures that have high permeability and are connected with the geothermal reservoir. Loss of circulation in drilling operations causes poor cleaning of cuttings, low penetration rates, increasing the risk of drill-string stuck, increasing the consumption of drilling fluid materials, reducing the productivity of the well. Using aerated fluids for drilling of geothermal wells can solve these problems[23], but also generate some new issues need to be tackle. Disadvantages of using aerated fluids are non-productive time activities, potential dangers because of high pressures and high temperatures, and reduction in the drill bit life. These disadvantages are mainly caused by the bottom of the high temperature, due to the low heat transfer capability of aerated drilling fluid, the bits cannot be cooled in time, which lead to the high temperature of cutter and short bit life caused by thermal damage. Especially that the maximum temperature of the geothermal wells has reached 427℃ in the second IDDP (Iceland Deep Drilling Project) well, with the deep geothermal resources development, the highest bottomhole temperature will continue to rise[24]. The higher the formation temperature, the more severe the thermal damage of the bit.

In summary, these technologies solve partial issues in geothermal drilling, but it still has a long distance from widespread application and drastically reducing drilling costs. Inspired by the idea of reservoir stimulation with liquid nitrogen [25-27], a new concept of geothermal drilling with liquid nitrogen is proposed. As the high temperature of formation and heat accumulation during the cutting process, liquid nitrogen can carry the heat at the bit efficiently to eliminate the thermal damage, on the other hand the thermal stress caused by the huge temperature difference between drilling fluid and rock surface may be favorable for improvement of ROP. So that the main objective of this paper is to investigate the feasibility of drilling with liquid nitrogen and the applicability of PDC bit in liquid nitrogen assisted drilling in geothermal resource.

2. Experiment Study

The concept and application of well stimulation with cold fluid to create clouds in geothermal and petroleum industry that use rock failure phenomena induced by the thermal stress has been previously presented [28-33].Especially in geothermal reservoir, it is an attractive way to enhance and revitalize well performance capabilities through injection of cold water into the geothermal reservoir. In this research the authors extend the concept to put forward an innovation drilling method that use the thermal shock to help improve the rock broken efficiency. Unlike the well stimulation with cold water, the fluid medium used in the concept of thermal stress assisted drilling is liquid nitrogen. Compared to water and aerated drilling fluid, liquid nitrogen assisted drilling has many unparalleled advantages.

2.1. The advantages of drilling with liquid nitrogen

Liquid nitrogen is a colorless, odorless and transparent liquid with low viscosity In terms of chemical property, it is inert and free of synthetic substances. Because of its characteristics of low temperature and liquid character under normal temperature and pressure, it is often used as a highly efficient refrigerant. This kind of ultra-low temperature, non-toxic, environment friendly and low-cost liquid, therefore, could be potential and excellent drilling fluid in high temperature petroleum wells and geothermal reservoir wells.The main advantages of liquid nitrogen as drilling fluids are as follows.

Liquid nitrogen gasification occurred at the bottom of the hole, it is liquid when injected and is gaseous when it returns to the ground. A cubic meter of liquid nitrogen will be gasified to about 600 cubic meters of nitrogen. The use of liquid nitrogen not only will cause no damage to formation permeability, but also will gain higher annular velocities to achieve adequate hole cleaning because of the gasification expansion. Even though encounter with fractured formation, an adequate circulation rate of nitrogen can be maintained to achieve hole cleaning level.

Thermal stress will occurred at the bottom caused by the high temperature difference between liquid nitrogen(-196 ℃)and rock(the highest bottomhole temperature of geothermal wells has reached 427℃). Make full use of the thermal stress to improve the rate of penetration seemed to be very promising.

The high formation temperature and heat accumulation during cutting make the bits to stay in a high temperature working condition, which is the main cause of the short life of the drill bit. The ultra-low temperature of liquid nitrogen can reduce the temperature of bit significantly, which eliminate the thermal damage, extend the life, increase the footage per bit and reduce the frequency of drag bit out.

Compared to water based and aerated drilling fluid, liquid nitrogen is easier to obtain. Establish liquid nitrogen machine unit on a rig location, then compress air to produce a steady stream of liquid nitrogen. Nitrogen back to the wellhead can be directly injected into the liquid nitrogen machine for cycle compression.

2.2. Effect of rapid cooling on rock surface properties

As the thermal stress only occur near the surface of the rock, while the interior of the rock is almost unaffected. The traditional rock mechanics test method cannot truly reflect the change of the surface properties of the rock, such as the uniaxial compression, triaxial compression and Brazilian split. In order to explore the effect of thermal stress caused by the cooling of liquid nitrogen on the properties of rock surface, the hardness test was carried out. The mechanism of the rock hardness test is to use the resistance of a small metal cylinder penetrate the rock surface to characterize the hardness of the rock, which is similar to the mechanism of the drill bit invading the rock. So that the penetration resistance can be used to represent the effect of rapid cooling on rock surface properties.

The experimental samples were purple sandstone, taken from Shandong Province, the hardness reached 12 grade, which indicating that the rock is as hard as the granite. The ston is sprayed with liquid nitrogen for 5 seconds then quickly use the rock hardness tester to determine the hardness of both sides of the rock.

Table 1. The test results of hardness

NO.	Hardness (MPa)	Maximum Load (KN)	Yield Limit (MPa)	Plasticity Coefficient	Hardness Grade
1	1432.67	5.19	1018.51	2	12
2	1458.52	5.25	1070.42	1.8	12
3	1405.64	5.10	1030.59	1.7	12
4	1135.32	4.12	733.58	2.9	12
5	1324.54	4.80	973.81	2.1	12
6	1270.48	4.60	921.21	1.9	12

The detailed experimental data are presented in Table1. The hardness, maximum load, yield limit reduction in hard sandstones under liquid nitrogen and dry conditions are determined by laboratory test. The results show average reduction in hardness, maximum load and yield limit are 13.18%, 13.00% and 15.74% respectively，the hardness grade and plasticity coefficient remains the same. Though the stress intensity factor didn't reach the fracture toughness , the thermal stress also reduce the mechanical force of indenter invades the rock. Full use of this advantage can reduce the resistance of rock fragmentation and improve the rate of penetration, which is significant for improving the efficiency of hard and high temperature rock drilling.

2.3. Micro PDC bit drilling with liquid nitrogen

The number of geothermal wells is on the rise, the types of drill bits used in the geothermal drilling are mainly the tricone bit and the PDC bit. Bit selection is the key point of the well design which will save time and money if the most appropriate bit is selected. Since the 1970s, PDC bits have been widely used around the world, they are designed to shear the rock rather than crush it, which is how the tricone bit functions. PDC bits have proven they are a viable means of accomplishing the goals that keeping the bit on bottom drilling by using a bit which lasts for more footage, and has a high ROP [34]. But it still has a long distance from widespread application and drastically reducing drilling costs. In order to study the feasibility and applicability of PDC bit in this new concept of liquid nitrogen assisted drilling, a series micro-PDC bit drilling experiment were carried out.

The specimen is iron basal cemented purple sandstone from Shandong Province. According to the triaxial compression experiment results, the cohesion strength is 19.82MPa, internal friction angle is 47.43 °, uniaxial compressive strength is 87.4MPa, and tensile strength is 5.7MPa. The bit is the core part, as showed in Figure3. The diameter of cutter is 12 mm, the diameter of bit is 28 mm, the diameter of water jet nozzle is 3mm, back angle of cutter is 15 °, the side angle is 0 °.

Dry drilling and liquid nitrogen assisted drilling were carried out respectively. Dry drilling experiment was performed as the control group in the atmosphere.The experiments was carried out according to the following steps

(i) Cut the rock samples into 20cm × 20cm × 15cm cuboids, then heat the rock samples to 100°C, 200°C and 300 °C respectively at the heating rate of 0.5°C/min in the heating furnace.

(ii) Remove the samples out of heating furnace, wrap a layer of thermal insulation around the samples and place cuboids in a core holder.

(iii) In order to protect the PDC cutters, set low rotation speed and ROP at the initial stage of drilling. After a shallow hole completed, adjust the forward speed and rotation speed to normal. The ROP was 2.9m/h and normal rotation speed were 54, 81,108rpm respectively.

(iv) Dry drilling and liquid nitrogen assisted drilling were performed respectively, record the drilling pressure and torque in real time.

By setting constant rate of penetration and different rotation speed, the corresponding torque and weight of bit (WOB) were directly measured. Then calculate the mechanical specific energy (MSE) to analyze the mechanical energy consumption. The concept of MSE to analyze the rock-drilling process from an energy point of view was first introduced by Simon[35] and Teale [36]. MSE is the amount of mechanical energy required to excavate a unit volume of rock, which has been widely used to evaluate the drilling efficiency. In this experiment, the rate of penetration is kept at 2.9 m/h and the rotation speed are set as 108 rpm, 81 rpm and 54 rpm.

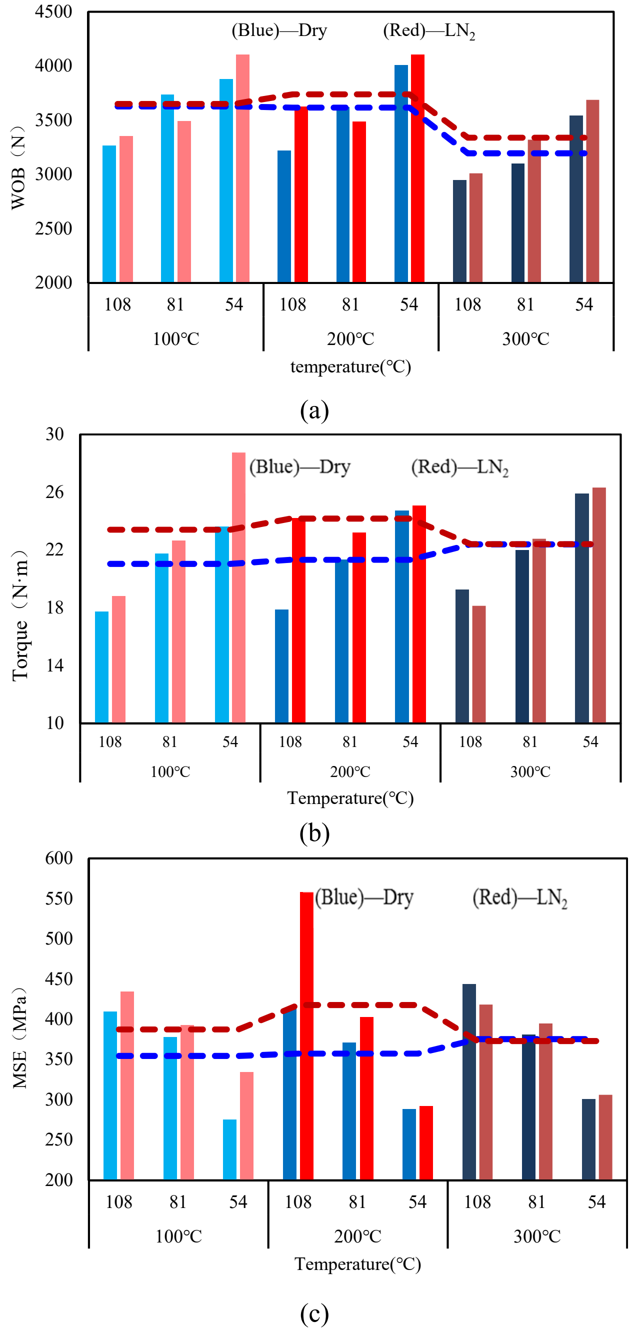

Figure 1. The parameters of varied with temperature and rotary speed,(a)WOB,(b)Torque,(c)MSE the dotted line represents the average of the three speeds at the same temperature.

The results are showed in Fig.1, when the ROP is kept constant, the WOB and torque decrease with the increase of rotation speed at same temperature. As the rate of penetration was set 2.9m/h in each group, so that the higher the rotation speed, the smaller the depth of penetration per round is, which means smaller rock breaking resistance thus the toque and

WOB decreased. In contrast, the MSE increased with rotation speed. The higher the rotation speed, more fine cuttings were generated, which results in an increase in the MSE. Fig. 1 also displays that the majority columns on behalf of liquid nitrogen assisted drilling(red color) is generally higher than that of dry (blue) .The dotted line represented the average parameters of the three speeds at the same temperature, it also showed that the red dotted line is always above the blue dotted line. The average WOB, torque and MSE increased first and then reduced in the range of 100 to 300℃, but the fluctuation rang was small.

The bit temperature and feature difference in the two drilling fluid environment also observed after the bit dragged out. As displayed in Fig.2, the left picture showed the bit after dry drilling, right is the bit after drilling with liquid nitrogen. Obviously, because of the low heat transfer coefficient of air and high temperature of the rock, the rate at which heat continues to accumulate on bit was greater than the speed at which air is taken away the heat, so that the temperature of bit (Fig.2 a) was extremely high after the bit dragged out from 300℃ rock. On contrast, the right bit is extremely cold due to the ultra-low temperature of liquid nitrogen. Fig.2 also displayed the change of cutter wear characteristics after the all experiment finished. The change of tooth surface coating represent the wear of the bit during drilling, after completed nine groups experiments respectively. The cutter surface coating of the bit used for dry drilling almost completely disappeared, showing black polycrystalline diamond layer. The right picture showed the feature of PDC bit used for liquid nitrogen assisted drilling, the wear of the bit is mainly at the edge of the cutter, where the bit contacts the rock.

(a) dry drilling (b) drilling with liquid nitrogen

Figure 2. The feature difference after dragged out. Left bit is after dry drilling ,right is drilling with liquid nitrogen

3. Discussion

Fig1. illustrated that the WOB, torque and MSE of drilling with liquid nitrogen were bigger than that of dry drilling from the micro-bit drilling experiment results. Which means that liquid nitrogen increased the rock failure resistance slightly compared with dry drilling by conventional PDC cutter. The results of the quantitative evaluation increase are shown in Table 2. Compared with dry drilling, the average of WOB increase about 2.85%, torque and MSE increase about 8% when drilling with liquid nitrogen at the same penetration rate of 2.9m/h. Maximum change of drilling parameters is at a temperature of 200℃and minimum at 300℃.

Table 2. The increment of drilling parameters

Item	100℃	200℃	300℃	Ave
WOB	0.65	3.38	4.50	2.85
Torque	11.27	13.38	0.07	8.24
MSE	9.27	16.90	-0.63	8.51

The contradiction lies in the difference between the two experimental results, the micro bit drilling experiment indicate that the liquid nitrogen increase the drilling resistance, which is contrary to the conclusion of rock hardness test that liquid nitrogen reduce the penetration resistance. The main reason is the difference between the two rocks broken environment. In hardness test experiment, two groups of experiments are conducted in the air. However, in the micro-bit drilling experiment, one group is in liquid nitrogen environment, another is in the air. Therefore, the experimental results of liquid nitrogen assisted drilling are mainly affected by thermal stress and liquid atmosphere. Though the thermal stress can reduce the resistance of bit invade into the rock, the MSE is still higher than dry drilling. It maybe can be attributed to the surface free energy difference caused by liquid nitrogen and air. According to the previous study by Perera[37,38] , N2 saturation causes the uniaxial compressive strength (UCS) of brown coal to increase by about 2%.Orowan [39]and Michalske[40] also explained the effect of fluid difference on the mechanics of silicate materials. They also point out that N2 increase the stress intensity factor compare with air and water, but the effect is slightly. So that the increase of WOB, torque and MSE is the result of thermal stress and surface free energy, thermal stress reduce the drilling resistance and liquid nitrogen increase the surface free energy compare with air. In general, about 8% increase in MSE is affordable to drilling engineers.

On the other hand, the low temperature of liquid nitrogen reduce the wear of bit obviously. The main reason is that liquid nitrogen significantly reduce the thermal damage due to frictional heat generation. The liquid nitrogen maybe also increase the hardness of bit and enhance wear resistance, which is similar to the technology of cutting tools treated by deep cryogenic treatment(CT). The use of cryogenic treatment to improve mechanical properties of metallic material has been studied for several decades. Ultra-low temperature change the microstructural and properties of mental, such as dimension, cristallinity and tensile strength, wear resistance and hardness improvement have been widely confirmed by published papers [41].

From the hardness test and micro-bit drilling experiment results, it clearly showed that liquid nitrogen can reduce the penetration resistance of bit. On the other hand, it not only can eliminate thermal damage, but also can enhance the wear resistance of the bit by deep cryogenic treatment, which is the most important factor affected the bit life in geothermal drilling. These positive effects are very beneficial to improve the life and footage per bit, reduce non-production time and reduce drilling costs. Another important phenomenon is that liquid nitrogen increase the resistance of rock failure slightly compare with dry drilling. But in the geothermal drilling, the drilling speed is 2.9m / h, about 8%increase in mechanical specific energy is affordable to drilling engineers.

Above all, though liquid nitrogen increase the rock failure resistance slightly and need about 8% more mechanical specific energy compared with drilling with air, it can eliminate the thermal damage and enhance the wear resistance ,which is the main factor affected the bit life in geothermal drilling. So that drilling with liquid nitrogen is a promising technology.

4. Conclusion

According to the experiments and analysis results, several conclusions, which may be important for geothermal drilling engineering, can be drawn from this paper.

(1) Though the stress intensity factor didn't reach the critical value by rapid cooling of liquid nitrogen, the thermal stress also could reduce the mechanical force of indenter invades the rock.

(2)Liquid nitrogen increase the rock failure resistance slightly and need about 8% more mechanical specific energy compared with drilling with air, but it can eliminate the thermal damage and enhance the wear resistance ,which is the main factor affected the bit life in geothermal drilling. The increase about 8% in mechanical specific energy is affordable to drilling engineers.

(3) Drilling with liquid nitrogen is a promising technology in geothermal engineering. Make full use the advantages can significantly increase the footage and life per bit, improve the ROP and reduce the cost.

Liquid nitrogen assisted drilling still need to be further studied, such as the research on efficient drill bits, wellbore stability at low temperature, hydraulic parameters design and so on.

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References

[1] Rosen M A, Dincer I. Exergy as the confluence of energy, environment and sustainable development[J]. Exergy, 2001, 1(1): 3-13.

[2] Albright J N, Pearson C F. Acoustic emissions as a tool for hydraulic fracture location: Experience at the Fenton Hill Hot Dry Rock site[J]. Society of Petroleum Engineers Journal, 1982, 22(04): 523-530.

[3] FEHLER M C. Stress control of seismicity patterns observed during hydraulic fracturing experiments at the Fenton Hill hot dry rock geothermal energy site, New Mexico[J]. International journal of rock mechanics and mining sciences, 1989, 26(3-4): 211-219.

[4] Elders W A, Friðleifsson G Ó, Albertsson A. Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide[J]. Geothermics, 2014, 49(49):111-118.

[5] Fridleifsson G O, Elders W A. The Iceland Deep Drilling Project: a search for deep unconventional geothermal resources[J]. Geothermics, 2005, 34(3): 269-285.

[6] Kato O, Doi N, Sakagawa Y. Characteristics of fractures based on FMI logs and cores in well WD-1 in the Kakkonda geothermal field, Japan[R]. Geothermal Resources Council, Davis, CA (United States), 1995.

[7] Bodvarsson G S, Pruess K, Stefansson V, et al. East Olkaria geothermal field, Kenya: 1. History match with production and pressure decline data[J]. Journal of Geophysical Research: Solid Earth, 1987, 92(B1): 521-539.

[8] Bertani R. World geothermal power generation in the period 2001–2005[J]. Geothermics, 2005, 34(6): 651-690.

[9] Baer F, Overmeyer L. A Cost-efficient Well Construction for Deep Geothermal Resources[C]//EGU General Assembly Conference. 2012, 14: 1180.

[10] Kant M A, Rossi E, Höser D, et al. Thermal Spallation Drilling, an Alternative Drilling Technology for Deep Heat Mining-Performance Analysis, Cost Assessment and Design Aspects[C]// 42nd Workshop on Geothermal Reservoir Engineering. 2017,1-8

[11] Augustine C R. Hydrothermal spallation drilling and advanced energy conversion technologies for engineered geothermal systems[D]. Massachusetts Institute of Technology, 2009.

[12] Song X, Lv Z, Li G, et al. Numerical analysis on the impact of the flow field of hydrothermal jet drilling for geothermal wells in a confined cooling environment[J]. Geothermics, 2017, 66: 39-49.

[13] Azar M, White A, Segal S, et al. Pointing towards improved PDC bit performance: Innovative conical shaped polycrystalline diamond element achieves higher ROP and total footage[C]//SPE/IADC Drilling Conference. Society of Petroleum Engineers, 2013.

[14] Rizo Jr T M, Cuenca A P. Aerated fluid drilling observations in geothermal operation in Luzon, Philippines[C]//Southeast Asia Show. Society of Petroleum Engineers, 1984.

[15] Heard, H., 1980. Thermal expansion and inferred permeability of climax quartz monzonite to 300°C and 27.6MPa. Int. J. Rock Mech. Min. Sci Geomech. Abstr.1980, 289-296.

[16] Hoeser, D., Flame-jet assisted drilling technology. 2016, PhD Thesis No. 23896, ETH Zürich.

[17] Stathopoulos, P., Hydrothermal spallation drilling experiments in a novel high pressure pilot plant. 2013, PhD Thesis, ETH Zurich.

[18] Augustine, C.R., et al., Feasibility of Spallation Drilling in a High Pressure, High-Density, Aqueous Environment: Characterization of Heat Transfer from an H2-O2 Flame Jet. Geothermal Resources Council Transactions, 2007. 31: p. 241-245.

[19] Kant M A, Rossi E, Becker D, et al. Enhancing the Drilling Process for Geothermal Resources by Combining Conventional Drilling and the Spallation Technology[C]. // 42nd Workshop on Geothermal Reservoir Engineering.2017,1-8

[20] Iskandar F F, Fanti D, Liang T T. Innovative Conical Diamond Element Bits Deliver Superior Performance Drilling a Geothermal Well in the Philippines[C]//Offshore Technology Conference Asia. Offshore Technology Conference, 2016.

[21] Graham P, Krough B, Nelson T, et al.Innovative Conical Diamond Element Bit in Conjunction With Novel Drilling Practices Increases Performance in Hard-Rock Geothermal Applications, California[C]. // 42nd Workshop on Geothermal Reservoir Engineering.2017,223-227

[22] Dwinanto A, Rachmat S. Aerated Underbalance Drilling Screening Assessment at "X" Geothermal Field[J]. KnE Energy, 2015, 1(1): 22-46.

[23] Wolke R M, Jardiolin R A, Suter R L, et al. Aerated drilling fluids can lower drilling costs and minimize formation damage[J]. Geothermal Resources Council Transactions, 1990, 14: 457-463.

[24] Elders W A, Fridleifsson G O. The Science Program of the Iceland Deep Drilling Project (IDDP): a study of supercritical geothermal resources[C]//Proceedings World geothermal congress. 2010.

[25] Curtis J B. Fractured shale-gas systems[J]. AAPG bulletin, 2002, 86(11): 1921-1938.

[26] Grundmann S R, Rodvelt G D, Dials G A, et al. Cryogenic nitrogen as a hydraulic fracturing fluid in the devonian shale[C]//SPE Eastern Regional Meeting. Society of Petroleum Engineers, 1998.

[27] Cai C, Li G, Huang Z, et al. Experimental study of the effect of liquid nitrogen cooling on rock pore structure[J]. Journal of Natural Gas Science and Engineering, 2014, 21: 507-517.

[28] Siratovich P A, Sass I, Homuth S, et al. Thermal stimulation of geothermal reservoirs and laboratory investigation of thermally-induced fractures[C]//Proc., Geothermal Resources Council Annual Meeting. 2011: 1529-1535.

[29] Correia H, Sigurdsson O, Sanjuan B, et al. Stimulation test of a high-enthalpy geothermal well by cold water injection[C]//Geothermal Resources Council, 2000. 2000, 24: 129-136.

[30] Kitao K, Ariki K, Watanabe H, et al. Cold-water well stimulation experiments in the Sumikawa geothermal field, Japan[J]. Bulletin of the Geothermal Resources Council, 1995, 24(2): 53-61.

[31] Kitao K, Ariki K, Watanabe H, et al. Cold-water well stimulation experiments in the Sumikawa geothermal field, Japan[J]. Bulletin of the Geothermal Resources Council, 1995, 24(2): 53-61.

[32] Grundmann S R, Rodvelt G D, Dials G A, et al. Cryogenic nitrogen as a hydraulic fracturing fluid in the devonian shale[C]//SPE Eastern Regional Meeting. Society of Petroleum Engineers, 1998.

[33] Cha M, Yin X, Kneafsey T, et al. Cryogenic fracturing for reservoir stimulation–Laboratory studies[J]. Journal of Petroleum Science and Engineering, 2014, 124: 436-450.

[34] Letvin A, Stroud P, Scagliarini S. Performance evaluation of polycrystalline diamond cutter (PDC) bits used in the production interval of Well AW-01 in the Akiira Ranch Field, East African Rift Valley, Central Kenya[C] // 42nd Workshop on Geothermal Reservoir Engineering.2017,229-234.

[35] Simon R. Energy balance in rock drilling[J]. Society of Petroleum Engineers Journal, 1963, 3(04): 298-306.

[36] Teale R. The concept of specific energy in rock drilling[C]//International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Pergamon, 1965, 2(1): 57-73.

[37] Perera M S A, Ranjith P G, Peter M. Effects of saturation medium and pressure on strength parameters of Latrobe Valley brown coal: Carbon dioxide, water and nitrogen saturations[J]. Energy, 2011, 36(12):6941-6947.

[38] Perera M S A, Ranjith P G, Viete D R. Effects of gaseous and super-critical carbon dioxide saturation on the mechanical properties of bituminous coal from the Southern Sydney Basin[J]. Applied Energy, 2013, 110(1):73-81.

[39] Orowan E. The Fatigue of Glass Under Stress[J]. Nature, 1944, 154:341-343.

[40] Michalske T A , Freiman S W. A Molecular Interpretation of Stress Corrosion in Silica[J]. Nature, 1982, 295(5849):511-512.

[41] Baldissera P, Delprete C. Deep Cryogenic Treatment: A Bibliographic Review[J]. Open Mechanical Engineering Journal, 2008, 2(1).