Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

A New Method of Liquid Nitrogen Assisted PDC Bit Breaking Hot Dry Rocks in Geothermal Drilling

Chao Xiong, Zhongwei Huang, Ruiyue Yang, Xianwei Dai, Chengyu Hui, Guofeng Kui

China University of Petroleum-Beijing, Beijing, 102249, China

2811624454@qq.com

Keywords: Liquid nitrogen, PDC bit, Hot dry rock, Geothermal drilling

ABSTRACT

A hot dry rock (HDR) has a high potential for thermal energy. However, caused by its high temperature (150℃~650℃), high strength and abrasiveness, breaking HDR is difficult. The problem of low penetration rate, rapid abrasion of a drill bit, long well construction time and high drilling cost seriously restrict the economic exploitation of an HDR. Hence, a highly efficient rock breaking method is urgently needed to drill the HDR. In this paper, we propose an innovative cryogenic drilling method in which liquid nitrogen (-195.8 °C) is used as the drilling fluid to assist in PDC bit drilling. To determine the feasibility of this kind of drilling method and the effects of critical parameters such as rocks temperature, drilling speed and liquid nitrogen pressure on the rock-breaking efficiency, a series of laboratory experiments were carried out on the rock (granite sample at 25℃~400℃) breaking performances by water and liquid nitrogen assisted PDC bit. The experimental results show that liquid nitrogen assisted PDC bit can efficiently break HDR. The weight on bit (WOB) and drilling torque decrease with the temperature of the rocks increasing. The efficiency of drilling with water and liquid nitrogen is enhanced with the increase of rock temperature and drilling speed. Under this research conditions, the mechanical specific energy (MSE) of drilling with liquid nitrogen is higher than that of drilling with water, which means that the efficiency of drilling with liquid nitrogen is lower than water. It is mainly because that liquid nitrogen could not efficiently clean the bottom hole, leading to repeated cuttings broken, thereby the drilling efficiency is decreased. Besides, it also cannot be ignored that liquid nitrogen has a lower capability to lubricate the contact surface of the cutter and granite. Furthermore, it can be found that increasing the liquid nitrogen pressure can obviously improve the drilling efficiency because larger thermal stress could lead to serious damage rocks. Therefore, liquid nitrogen assisted PDC bit breaking HDR is expected to become an effective method for solving HDR drilling challenges if we improve the pressure of liquid nitrogen. The key findings of this study are valuable to provide theoretical guidance and laboratory basis for efficient HDR well drilling.

1. INTRODUCTION

A hot dry rock (HDR), which is usually buried at a depth of 3-10 km with the temperatures of 150℃~650℃ (Agemar et al., 2014; Liu, 2017), is a kind of geothermal resource having great capability to produce electricity (Johnston et al., 2011; Lund, 2008). HDR energy, as no CO_2 emission, wide distribution, sustainable and renewable natural resource, has more advantages over conventional fossil fuel (Lu, 2018; Zhu et al., 2015). The enhanced geothermal system (EGS), at present, is considered as the most feasible method to efficiently exploit the thermal energy stored at HDR (Majer et al., 2007; McClure and Horne, 2014). The EGS was first proposed by Los Alamos National Laboratory in the 1970s (Breede et al., 2013; Johnston et al., 2011). This includes three main processes: drilling into the HDR reservoir, using stimulation methods to form numerous interconnected fractures, and injecting cold water then heated by high temperature rocks and producing hot water to generate electricity. It can be noted that drilling well is the cornerstone of exploration and development of HDR resources (Zhang et al., 2018b).

The HDR formations usually have characteristics of high temperature, high pressure, and high compressive strength and abrasiveness, which poses huge challenges for drilling well (Liu, 2017; Lukawski et al., 2014). The drilling well for HDR is very difficult. Nowadays, the major geothermal drilling methods is the rotary drilling, which has been widely used in petroleum drilling (Teodoriu and Cheuffa, 2011). The roller cone bits are the most common drilling bits in geothermal drilling due to their great durability in hard and fractured rocks (Xu, 2014). But for HDR drilling, high temperatures make roller cone bits suffering from the problems of damaged seals, worn bearings and bit failure (Huang et al., 2013), which will reduce footage, increase tripping time, lower penetration of rate (ROP) and increase drilling costs. In recent years, polycrystalline diamond compact (PDC) bits are being used more often in HDR drilling due to no moving parts, bearings, seals and the improvement of manufacture technologies of PDC cutters (Vollmar et al., 2013). While the ROP of drilling HDR using PDC bits is still low and the heat damage and abrasive wear of PDC cutters limits the bits life (Bybee, 2005). Therefore, we proposed a new drilling method in which the liquid nitrogen is taken as drilling fluids to assist PDC bits breaking hot dry rocks.

Liquid nitrogen has been widely used in drilling and completion operations since its first application in the Gulf Coast of the United States in 1959 (McDaniel et al., 1997). It is a kind of cryogenic fluid, which boiling temperature is -195.8 ℃ at atmospheric pressure. Cryogenic liquid nitrogen can not only efficiently cool the PDC drilling bits reducing the heat damage of PDC cutters, but also deteriorate the mechanical properties of rocks due to the huge thermal stress (Wu et al., 2019b). These can significantly extend the bit life and increase ROP and lower drilling costs. Therefore, liquid nitrogen assisted PDC bits drilling method is expected to be more suitable for HDR drilling than other conventional drilling methods.

In order to study the damage of rocks submerged in liquid nitrogen, a large number of immersion experiments were conducted. McDaniel et al. (1997) observed that a coal sample could generate obvious shrinkage and be broken into small cubical units when it contacts with liquid nitrogen. Cai et al. (2014) used scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR) to investigate the pore structure changing of sandstone, marble, and shale samples after cooling by liquid nitrogen. The results showed that liquid nitrogen cooling could reduce the volume of pores and produce numerous micro-cracks inside the rocks, which can improve the rock-breaking efficiency. Cai et al. (2015) also investigated the damage of coal treated by liquid nitrogen. The permeability was increased by 48.89%~93.55% and the compressive strength was decreased by 16.18%~33.74% after the coal sample contacting with liquid nitrogen. In addition, Wu et al. (2019a) studied the damage characteristics of high-temperature granite cooled by liquid nitrogen. Liquid nitrogen could significantly reduce the strength of granite and large number of inter-granular cracks could be induced by thermal stress at the boundaries of quartz. As the temperatures of rock increase, the damage of granite become more obvious after treated by liquid nitrogen.

Some researchers investigate the liquid nitrogen jet breaking rocks. Wu et al. (2018) conducted liquid nitrogen jet breaking coal sample experiments and the rock-breaking efficiency of liquid nitrogen jet was compared with that of the water jet. Liquid nitrogen jet displays better performance than water jet on breaking coal, which can generate larger coal erosion volume and lower energy consumption than those of water jet. There is no doubt that liquid nitrogen jet can efficiently break low strength coal, but whether it can break high compressive strength rock, such as granite, Zhang et al. (2018a) carried out relative researches. They take the conjugate heat transfer method to simulate the thermal stress distribution when the liquid nitrogen jet impacts at the downhole rocks surface. And a series of liquid nitrogen jet impact high-temperature granite experiments have been carried out to investigate the thermal cracks. The simulation and experiment results show that the surface of granite can generate numerous visible fractures. But there is difficult to form erosion volume at the granite surface only depending on liquid nitrogen jet.

The above literature has proven that liquid nitrogen can significantly deteriorate the mechanical properties of rocks and make them easily be broken. But to our best knowledge, there is no experimental research on liquid nitrogen assisted PDC bits breaking high-temperature granite, and the rock-breaking efficiency of this new drilling method is still unclear. In order to validate the feasibility of liquid nitrogen assisted PDC bits breaking hot dry rocks and investigate the high-temperature granite breaking efficiency of this new drilling method, we carried out a series of laboratory drilling experiments using micro-PDC bits and the drilling fluid was liquid nitrogen and water respectively.

2. LABORATORY DRILLING EXPERIMENT

2.1 Experimental apparatus

In order to carry out the laboratory experiments of liquid nitrogen assisted PDC bits drilling hole, we designed and built a special apparatus. Figure 1 shows the configuration of this setup, which consists of three parts: drilling system, rock fixing device and data acquisition system. The drilling system contains a drilling motor, a rotary motor, a drilling pipe, and a micro-PDC bit. The drilling motor provides the power for a micro-PDC bit moving down. The rotary motor drives the micro-PDC bit to rotate. A stainless steel pipe makes the drill pipe. The outside diameter is 40 mm. The inside diameter is 7 mm. The length is 400 mm. The micro-PDC bit used in this experiment is shown in Figure. 2. Its diameter is 32 mm, and the nozzle diameter is 5 mm. The diameter and thickness of the PDC cutter are 13 mm and 4 mm respectively. The cutters back rake angle is 15° and its side angle is 0°. The sensors can measure the drilling displacement, WOB, drilling torque, and rotary speed in real-time and the data can be transmitted to the computer storage.

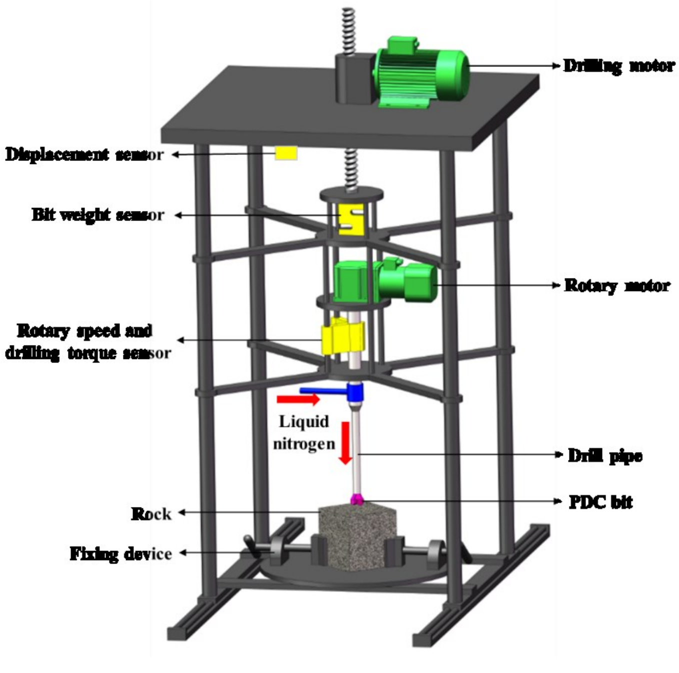


Figure 1: Schematic diagram of a laboratory drilling experiment setup.

Figure 2: Micro-PDC bit used in the experiment.

2.2 Rock samples

Granite is one of the major rock types of HDR formations. So we choose the granite as the experimental rock sample. In this experiment, the granite was collected from the Shandong province in China. The physical and mechanical properties of this type granite are shown as follows: its cohesive strength is 44.84 MPa, and its internal friction angle is 48.74°, and its tensile strength is 10.02 MPa, and its uniaxial compressive strength is 121.91 MPa.

2.3 Experimental procedures

In order to investigate the drilling efficiency of liquid nitrogen assisted PDC bit, we designed two groups drilling experiments using liquid nitrogen and water-assisted PDC bit respectively. The experimental procedures are shown as follows:

- The 200 ×200 ×200 mm granite cubes are put into a muffle furnace and heated to target temperature (100℃，200℃，300℃, and 400℃) respectively with a heating rate of 5 °C/min and then kept at the target temperature for 20 h.
- After taking the hot granite from the muffle furnace, it is wrapped by a layer of insulating material and then mounted on the drilling apparatus by the fixing device quickly.
- Taking the high rotary speed and low drilling speed drills a shallow pilot hole. Then changing the drilling parameters to the target value begins the drilling experiment. Table 1 shows the drilling parameters used in each temperature group.
- In each drilling experiment, the WOB and drilling torque are recorded in real-time.

Table 1 Drilling parameters.

Drilling fluid	Temperature (℃)	Drilling speed (mm/s)	Rotary speed (rpm)	Pressure (MPa)
Liquid nitrogen	25, 100, 200, 300, 400	0.1, 0.7	50	1, 2
Water	25, 100, 200, 300, 400	0.1, 0.7	50	1

3. EXPERIMENTAL RESULTS

3.1 Experimental data processing

Figure 3 shows the WOB and drilling torque vary with time during drilling. It is obvious that the WOB and drilling torque shows a similar trend. The WOB and drilling torque increase first and after that, it has an approximate constant with the increase of time. At the beginning of the experiment, the contact areas between the PDC cutter and rock are very small. It only needs a small force to penetrate rock and break it. As the experiment continues, the contact areas increase and reach the maximum at last. So the WOB and drilling torque increases gradually and then remains constant. In this paper, we extract the data at a stable stage to calculate the average value of the WOB and drilling torque. The average value is used to represent the WOB and drilling torque in this experiment conditions.

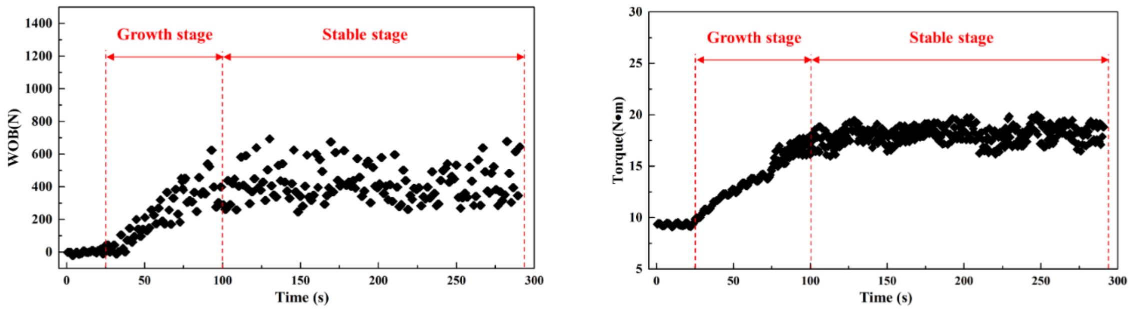


Figure 3: The typical WOB and drilling torque curves (50 r/min of rotary speed, 0.1 mm/s of drilling speed, drilling with water).

Mechanical specific energy (MSE) is often used to describe the rock breaking efficiency (Pessier and Fear, 1992). The ratio of energy consumption to the volume of broken rock is defined as MSE. During the drilling process, the energy of drill bit breaking rock is supplied by a rotary motor and drilling motor, which can be calculated by

$$E_r = \frac{1000Mn}{9549}t \tag{1}$$

$$E_d = Fvt \tag{2}$$

Where E_r is the energy supplied by rotary motor, *J; M* is the drilling torque, *N·m*; *n* is the rotary speed, *r/min*; *t* is the drilling time, *s*; E_d is the energy supplied by drilling motor, *J*; *F* is the WOB, *N*; *v* is the drilling speed, *m/s*. The rock breaking volume can be calculated by

$$V = \pi r^2 vt \tag{3}$$

So the MSE can be calculated by

$$E_M = \frac{1000Mn}{9549\pi r^2 v} + \frac{F}{\pi r^2} \tag{4}$$

Where *r* is the radius of drilling hole, m; E_M is the mechanical specific energy, J/m^3.

3.2 Drilling with liquid nitrogen

Figure. 4 shows the experimental results of micro-PDC bit drilling assisted with liquid nitrogen in different temperature granite. It clearly shows that the WOB and drilling torque decrease with the increase of rocks temperature. The reduction in WOB and drilling torque may be attributed to the deterioration of the physical and mechanical properties of rocks, especially for the strength of the rocks (Karfakis, 1985; Wu et al., 2019a; Wu et al., 2019b). When the liquid nitrogen contacts with the hot granite rock, there will induce high thermal stress in rocks due to the huge temperature difference between the liquid nitrogen (-195.8 ℃) and the hot rock (25℃~400 ℃). The thermal stress can cause the microcracks and reduce the strength of the rocks, which is contributed to the PDC cutter biting into the rocks and breaking it.

At the same rotary speed (50 rpm), the WOB and drilling torque at different temperatures at 0.7 mm/s of drilling speed are larger than those at 0.1 mm/s of drilling speed. This phenomenon can be explained from the biting depth per revolution of PDC cutters. When the rotary speed is constant, the biting depth per revolution increases with the increase of drilling speed. The biting depth of the cutter is positively correlated with the WOB. So the higher the drilling speed is, the larger the WOB is required. In addition, the increase in biting depth means the increase of interaction area between the PDC cutter and the rock. And the more rocks are needed to be removed in each revolution, which can result in the increase of cutting force and drilling torque.

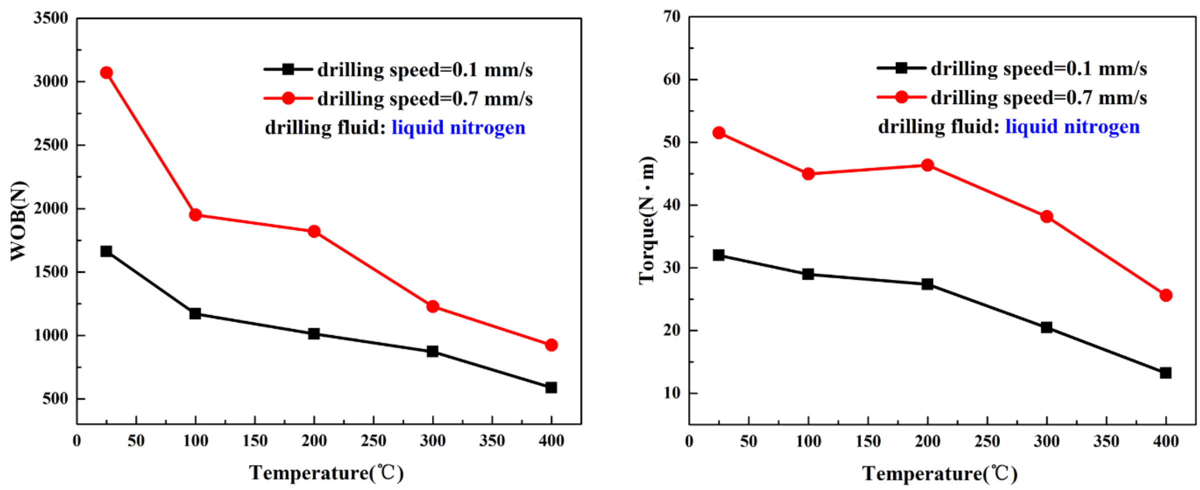


Figure 4: The WOB and torque of drilling with liquid nitrogen at different temperatures.

3.3 Drilling with water

The experimental results of drilling with water at different temperatures are shown in Figure 5. The variation trend of the WOB and the drilling torque of drilling with water is similar to those of drilling with liquid nitrogen. This variation trend may also result from thermal stress. Although the temperature of the water is distinctly lower than that of liquid nitrogen, there still exists a temperature difference between the water and hot granite and the thermal stress still can be formed in rocks. When the drilling speed is 0.7 mm/s and the temperature rises from 25℃ to 100℃, the WOB and the drilling torque drop sharply, with a decreased amplitude of 43.24% and 35.53% respectively. The WOB and drilling torque decreases more slowly in the temperature range from 100℃ to 400 ℃ compared to 25℃ to 100 ℃. There is no thermal stress produced in the rock when the temperature of the rocks is 25℃. The thermal stress begins to appear and gradually increases with the increase of rocks temperature.

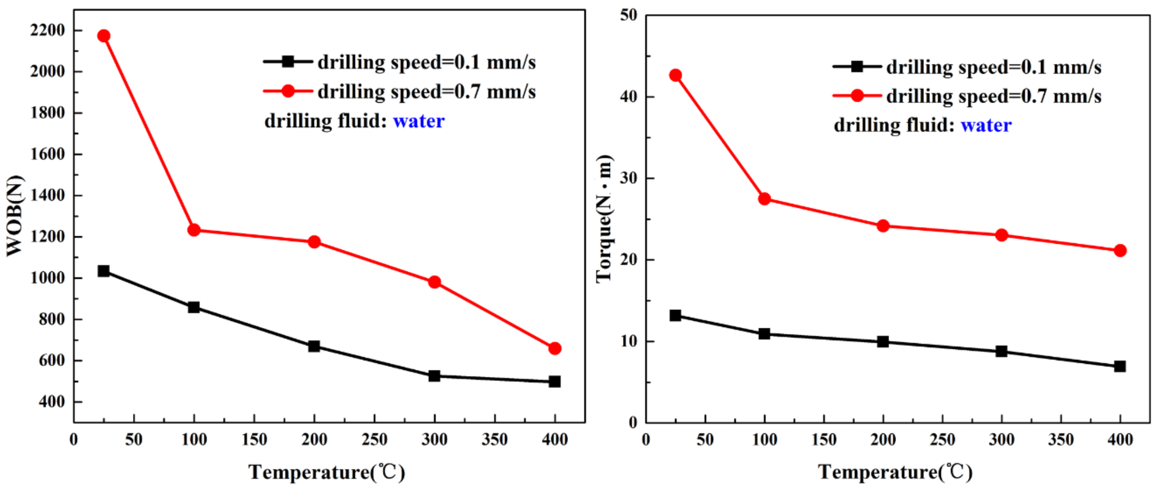


Figure 5: The WOB and torque of drilling with water at different temperatures.

4. DISCUSSION

4.1 The MSE of drilling with liquid nitrogen and water

In order to compare the rock-breaking efficiency of drilling with liquid nitrogen and water, The MSE was calculated according to the Eq. (4). The calculation results are shown in Figure. 6. It is clearly shown that the MSE decreases with the rise of granite temperature at all drilling parameters. These trends can be attributed to the increase of thermal stress as the rocks temperature increase, the damage of rocks becomes more serious, and the rocks are more easily to be broken. Figure. 7 shows the pictures of a granite sample after the drilling experiment with liquid nitrogen at the pressure of 1 MPa. The rotary speed is 50 r/min and the drilling speed is 0.7 mm/s. Since the hot crack will close when the sample is cooled to room temperature, we use red lines to outline the cracks in the figure, so that the hot crack can be more clearly shown. When the temperature of the rocks is 25℃， there are no macro-cracks on the rock surface. With the increase of granite temperature, more complex cracks are formed on the rock surface. The cracks induced by thermal stress can sharply decrease the strength of rocks and make them more vulnerable to fracture. This may explain why MSE decreases with the increase of rocks temperature.

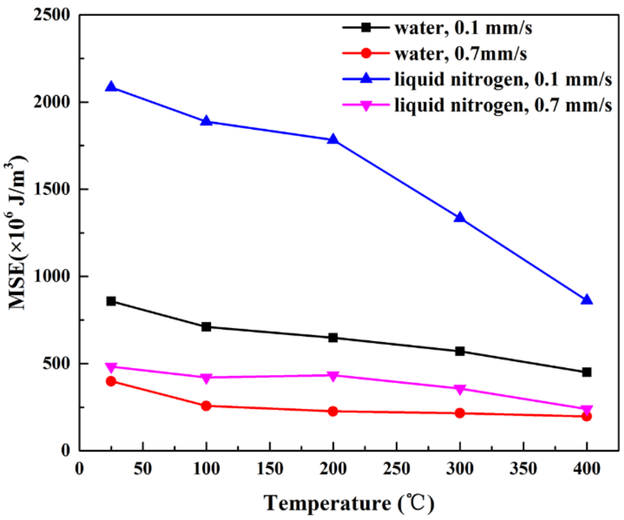


Figure 6: The MSE of different drilling parameters at different temperatures.

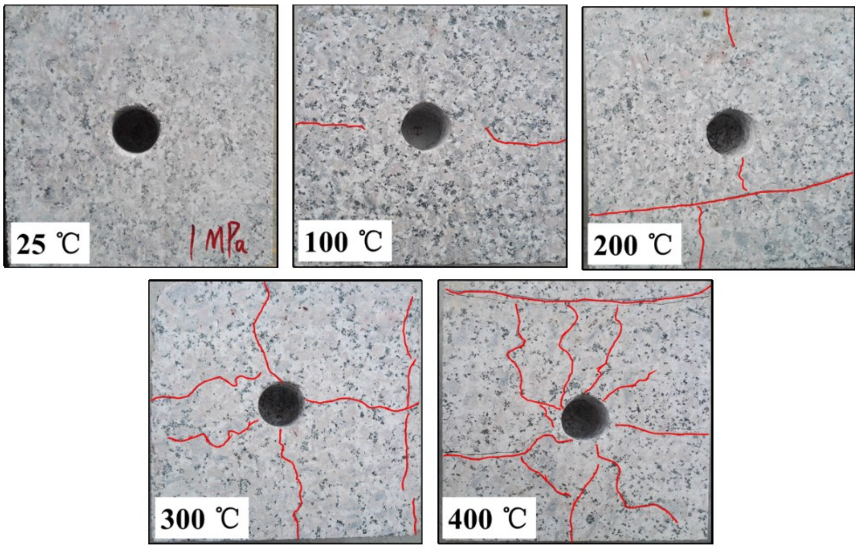
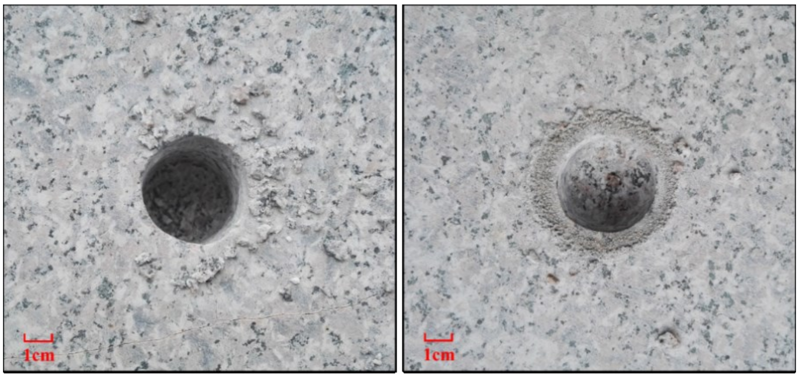


Figure 7: The cracks distribution on the granite sample after drilling with liquid nitrogen at different temperatures.

With the same drilling fluid and rotary speed, the MSE decreases with the increase of drilling speed at all temperatures. This is because the biting depth per revolution at high drilling speed (0.7 mm/s) is larger than that at low drilling speed (0.1 mm/s), which is conductive to form large cuttings and improve the rock-breaking efficiency. According to the theory of Rittinger (1867), it is well known that it takes more energy to break the rock into smaller pieces than larger pieces. Figure 8 shows the cuttings of granite at different drilling rates when the temperature is 200℃. As shown in Figure 8 (a), the wellbore is surrounded by a large number of cuttings of large size, with almost no powder cuttings. In contrast, there is a large number of fine or powder cuttings and little large size debris when the drilling feed is 0.1 mm/s, as shown in Figure. 8 (b). The rock breaking mode is a shear failure when the biting depth is large, which is considered as a more efficient rock failure mechanism than the scraping rock failure at small biting depth.



(a) Drilling speed: 0.7 mm/s (b) Drilling speed: 0.1 mm/s

Figure 8: The cuttings of drilling with liquid nitrogen (200℃ of rock temperature).

At the same drilling speed and rotary speed, it can be found that the MSE of drilling with liquid nitrogen is higher than that with water in Figure. 6. It means that the rock-breaking efficiency of drilling with liquid nitrogen is lower than that of drilling with water in our experiment. This result is opposite to the general knowledge that liquid nitrogen can induce huge thermal stress, lead to rock damage and improve the rock-breaking efficiency. It should be emphasized, however, that drilling is a complex process. The drilling efficiency is influenced not only by the physical and mechanical properties of the rocks but also by the type of drilling fluid and bottom-hole cleaning. Theoretically, liquid nitrogen can significantly reduce rock strength and improve drilling efficiency due to its extremely low temperature, which damages the rocks more seriously than water. However, at our experiment conditions, liquid nitrogen is easily vaporized and the viscosity of nitrogen gas is very low, which leads to the fact that cuttings at bottom-hole could not be carried away in time. The cuttings are repeatedly broken in the bottom hole, which can reduce drilling efficiency. In contrast, the water can efficiently clean the bottom hole and avoid repeated fragmentation of cuttings. In addition, water also has a certain lubrication effect on the contact surface of the cutter and granite, which can improve drilling efficiency.

4.2 Influence of liquid nitrogen pressure on rock breaking

The pressure of liquid nitrogen has a great influence on the thermal stress and the bottom hole cleaning, which can directly affect the drilling efficiency. In this section, the influence of liquid nitrogen pressure on drilling efficiency is investigated. The rotary speed is 50 r/min, the drilling speed is 0.1 mm/s and the temperature of the rock is 25 ℃. The experimental result is shown in Figure. 9. With the increase of liquid nitrogen pressure from 1 MPa to 2MPa, the WOB and drilling torque decreased by 20.3% and 21.9% respectively and the MSE also decrease by 21.8%. This means that increasing the pressure of liquid nitrogen can be conductive to the rock breaking and improve the drilling efficiency. On one hand, increasing the pressure of liquid nitrogen can increase the heat transfer rate on the rock surface, rapidly cool the rock, and generate greater thermal stress. On the other hand, the liquid nitrogen jet velocity increases with the increase of liquid nitrogen pressure, which can improve the bottom hole cleaning efficiency and reduce the repeated breaking of cuttings.

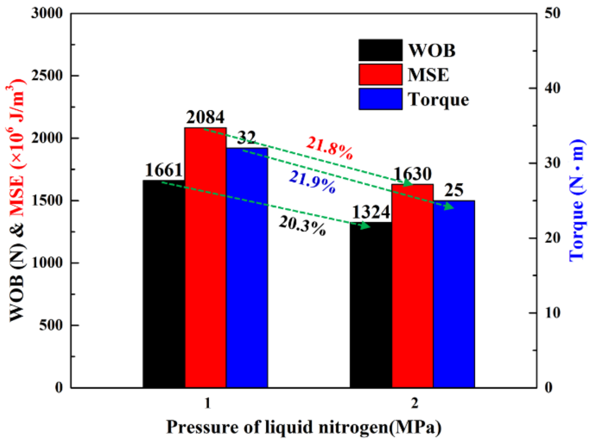


Figure 9: The parameters of drilling with liquid nitrogen at different pressure.

5. CONCLUSION

A novel laboratory apparatus of liquid nitrogen assisted PDC bits drilling hole was designed and built. A series of laboratory drilling experiments were carried out. The feasibility of liquid nitrogen assisted micro-PDC bits drilling hole was studied. The influence of rocks temperature, drilling fluid types, and the pressure of liquid nitrogen on drilling efficiency was researched. Key conclusions can be obtained:

(1) Liquid nitrogen assisted PDC bit is a feasible method to break the hot dry rock. Increasing the temperature of the rock can decrease the WOB and drilling torque and improve the rock-breaking efficiency.

(2) Under the conditions of this article, the efficiency of drilling with water is higher than that with liquid nitrogen. This is because the cuttings cannot be carried away in time due to the easy vaporization of liquid nitrogen and the low jet velocity. In addition, liquid nitrogen has a lower capability to lubricate the contact surface of the cutter and granite.

(3) Improving the pressure of liquid nitrogen can significantly decrease the WOB and drilling torque and improve drilling efficiency. This is because thermal stress and bottom hole cleaning efficiency are improved with the increase of liquid nitrogen pressure.

(4) This paper only investigates the low-pressure liquid nitrogen assisted micro-PDC bits breaking hot granite. The high-pressure liquid nitrogen assisted PDC bit drilling experiments need further research to prepare for the field application of this new drilling method.

ACKNOWLEDGEMENTS

This work was supported by the National Science Fund for Distinguished Young Scholars (Grant No. 51725404) and the '111'project of China (Grant No. 110000203920170063)

REFERENCES

Agemar, T., Weber, J., Schulz, R.: Deep geothermal energy production in Germany, *Energies*, 7, (2014), 4397-4416.

Breede, K., Dzebisashvili, K., Liu, X., Falcone, G.: A systematic review of enhanced (or engineered) geothermal systems: past, present and future, *Geothermal Energy*, 1, (2013), 4.

Bybee, K.: New bit design and cutter technology extend PDC applications to hard-rock drilling, *Journal of petroleum technology*, 57, (2005), 63-64.

Cai, C., Li, G., Huang, Z., Shen, Z., Tian, S., Wei, J.: Experimental study of the effect of liquid nitrogen cooling on rock pore structure, *Journal of Natural Gas Science and Engineering*, 21, (2014), 507-517.

Cai, C., Li, G., Huang, Z., Tian, S., Shen, Z., Fu, X.: Experiment of coal damage due to super-cooling with liquid nitrogen, *Journal of Natural Gas Science and Engineering*, 22, (2015), 42-48.

Huang, Z., Li, Q., Zhou, Y., Jing, S., Ma, Y., Hu, W., Fan, Y.: Experimental research on the surface strengthening technology of roller cone bit bearing based on the failure analysis, *Engineering failure analysis*, 29, (2013), 12-26.

Johnston, I., Narsilio, G., Colls, S.: Emerging geothermal energy technologies, *KSCE Journal of Civil Engineering*, 15, (2011), 643-653.

Karfakis, M.: Drilling mechanisms at elevated rock temperatures, *International Journal of Rock Mechanics and Mining Sciences*, (1985), 407-417.

Liu, W.: Drilling technical difficulties and solutions in development of hot dry rock geothermal energy, *Advances in Petroleum Exploration and Development*, 13, (2017), 63-69.

Lu, S.-M.: A global review of enhanced geothermal system (EGS), *Renewable and Sustainable Energy Reviews*, 81, (2018), 2902-2921.

Lukawski, M.Z., Anderson, B.J., Augustine, C., Capuano Jr, L.E., Beckers, K.F., Livesay, B., Tester, J.W.: Cost analysis of oil, gas, and geothermal well drilling, *Journal of Petroleum Science and Engineering*, 118, (2014), 1-14.

Lund, J.W.: Development and utilization of geothermal resources, *Proceedings of ISES World Congress* (2008), 87-95.

Majer, E.L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B., Asanuma, H.: Induced seismicity associated with enhanced geothermal systems, *Geothermics*, 36, (2007), 185-222.

McClure, M.W., Horne, R.N.: An investigation of stimulation mechanisms in Enhanced Geothermal Systems, *International Journal of Rock Mechanics and Mining Sciences*, 72, (2014), 242-260.

McDaniel, B., Grundmann, S.R., Kendrick, W.D., Wilson, D.R., Jordan, S.W.: Field applications of cryogenic nitrogen as a hydraulic fracturing fluid, *SPE annual technical conference and exhibition*, (1997).

Pessier, R., Fear, M.: Quantifying common drilling problems with mechanical specific energy and a bit-specific coefficient of sliding friction, *SPE Annual Technical Conference and Exhibition*, (1992).

Rittinger, P.R.V.: Lehrbuch der aufbereitungskunde in ihrer neuesten entwicklung und ausbildung systematisch dargestellt. Ernst & Korn, (1867).

Teodoriu, C., Cheuffa, C.: A comprehensive review of past and present drilling methods with application to deep geothermal environment, *Proceedings*, Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, (2011).

Vollmar, D., Wittig, V., Bracke, R.: Geothermal Drilling Best Practices: The Geothermal translation of conventional drilling recommendations-main potential challenges, *International Geothermal Association: Home*, (2013).

Wu, X., Huang, Z., Li, G., Li, R., Yan, P., Deng, X., Mu, K., Dai, X.: Experiment on coal breaking with cryogenic nitrogen jet, *Journal of Petroleum Science and Engineering*, 169, (2018), 405-415.

Wu, X., Huang, Z., Song, H., Zhang, S., Cheng, Z., Li, R., Wen, H., Huang, P., Dai, X.: Variations of physical and mechanical properties of heated granite after rapid cooling with liquid nitrogen, *Rock Mechanics and Rock Engineering*, 52, (2019a), 2123-2139.

Wu, X., Huang, Z., Zhang, S., Cheng, Z., Li, R., Song, H., Wen, H., Huang, P.: Damage analysis of high-temperature rocks subjected to LN 2 thermal shock, *Rock Mechanics and Rock Engineering*, (2019b), 1-19.

Xu, J.N.: Drilling and Completion Techniques for High-temperature Geothermal Wells, *Advanced Materials Research*, (2014), 688-691.

Zhang, S., Huang, Z., Huang, P., Wu, X., Xiong, C., Zhang, C.: Numerical and experimental analysis of hot dry rock fracturing stimulation with high-pressure abrasive liquid nitrogen jet, *Journal of Petroleum Science and Engineering*, 163, (2018a), 156-165.

Zhang, S., Huang, Z., Li, G., Wu, X., Peng, C., Zhang, W.: Numerical analysis of transient conjugate heat transfer and thermal stress distribution in geothermal drilling with high-pressure liquid nitrogen jet, *Applied Thermal Engineering*, 129, (2018b), 1348-1357.

Zhu, J., Hu, K., Lu, X., Huang, X., Liu, K., Wu, X.: A review of geothermal energy resources, development, and applications in China: Current status and prospects, *Energy*, 93, (2015), 466-483.