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Experiment on rock breaking with supercritical carbon dioxide jet

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ABSTRACT

Rock breaking with SC-CO_2 has the advantages of low threshold pressure and high rate of penetration, so it has attracted full attention. In order to clarify the law of rock breaking with SC-CO_2 jet, and enable it to serve SC-CO_2 drilling better, the SC-CO_2 jet system for rock breaking was used to carry out the experiments, which demonstrated that jet pressure, jet temperature, confining pressure, jet distance, rotary speed of core samples and jet time are the main factors to influence the rock-breaking performance and efficiency. The results showed the effects as follows. Jet pressure and confining pressure are the direct factors to affect rock-breaking performance. With the increase of jet pressure, the rock-breaking efficiency increases gradually, while as the confining pressure increases, it decreases with constant jet pressure or has the maximum around the critical jet pressure with constant pressure difference. With the increase of jet temperature, the efficiency increases at first and then decreases, and the relationship curve showed in parabolic function. Under the experimental conditions in this paper, the optimal jet distance is about 3–4 times of nozzle diameter. The rotary speed of core sample has no substantial influence on the erosion depth, but on the average width or diameter of eroded grooves. The average width and the size of the eroded cuttings are smaller when the rotary speed is higher. The erosion depth increases but the trend gradually decreases with the jet time being prolonged.

1. Introduction

Water jet technology is also called hydraulic jet technology. Water is used as a medium, and ejected at a high speed after being pressurized by high-pressure generator, forming a blast of water with highly concentrated energy in a special way of fluid motion through different shapes of nozzles. In the 1930s, people from North America firstly used high-pressure water jet to exploit unconsolidated deposits. In the 1950s, high-pressure water jet technology was applied in oil drilling (Ruihe et al., 2010). To further improve the cutting and breaking effect of water jet, human constantly tried new ways to improve the structure and property of water jet. In the 1980s, abrasive jet (Ruihe et al., 2010; Yiyu et al., 2009; Hongjian et al., 2008), cavitating jet (Gensheng and Zhongou, 2008), rotary jet (Ruihe et al., 1999; Yuhuan et al., 2002) and other new types of jet occurred and were applied in oil drilling, coal mining, cutting, cleaning and in other fields. In the middle and later periods of 1990s, water jet technology developed rapidly with the development of science and technology and the application fields had expanded in aviation, aerospace, construction, transportation, metallurgy, machinery, forestry, textile, environment protection, medicine and others.

New types of jet like cavitating jet (Gensheng and Zhongou, 2008), pulsed jet, rotary jet, non-circle jet, abrasive jet have gradually applied in oil drilling (Gensheng et al., 2001; Ruichang, 2010). With the rapid progress towards deep and ultra-deep wells, the demands of improving the ROP and reducing the cost of exploration and exploitation are more and more intense. So, to some extent, the water jet technology can't meet the demands of low cost and high efficiency drilling.

Supercritical carbon-dioxide (SC-CO_2) is a kind of non-gaseous, non-liquid, non-solid CO_2. When the temperature is above 304 K and the pressure is above 7.38 MPa, CO_2 will change into the supercritical state. Then the density of SC-CO_2 is high and close to liquid, meanwhile the viscosity is close to gas. So SC-CO_2 has many unique physical and chemical properties. In the 1990s, American drilling engineers Kollé (2002), Kolle and Marvin (2000) applied the SC-CO_2 technology into well drilling by successfully carried out the field experiment of the SC-CO_2 drilling. They found that the SC-CO_2 jet cutting rock needs much shorter time and much lower

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threshold pressure, the lowest pressure needed for eroding or breaking the rock, than water jet, to be specific, the threshold pressure for SC-CO_2 jet is just 2/3 for water jet when breaking the granite and even less than half for water jet when breaking the shale. In addition, SC-CO_2 will enhance (single-well) production and recovery after entering the reservoir. Thus SC-CO_2 achieved extensive attention in many countries.

However, researches on rock breaking with SC-CO_2 jet has rarely been carried on so far, yet only Kollé, Marvin, Al-Adwani and Gupta, etc in America, and Shen Zhonghou, Wang Ruihe and Ni Hongjian, etc. in China, have done a few exploratory studies (Al-Adwani, 2007; Gupta et al., 2005; Ruihe et al., 2012; Zhonghou and Haizhu, 2010; Zhonghou et al., 2010a,b), but the law of rock-breaking mechanism is still unclear. Hence, based on the detailed theoretical analysis of influencing factors, a large amount of rock-breaking experiments with SC-CO_2 jet were conducted to disclose the rock-breaking law with SC-CO_2, establish a better theoretical basis for better applying the SC-CO_2 in the well drilling industry, and enrich the jet theory.

2. Experimental materials and methods

2.1. Experimental materials

Industrial liquid CO_2 used in the experiment should be stored in high purity without too much water vapor, because carbonic acid and hydrate generated by H_2O and CO_2 can corrode and even dangerously plug the pipelines and other experiment apparatus. What's more, CO_2 is required to be of high purity to reduce the negative influences caused by other gas impurities on the rock-cutting efficiency.

There are two kinds of experimental core samples. Man-made core samples, shown in Fig. 1a, are made of quartz sand and cement in the volume ratio of 2:1, and then mixed with water. Quartz sand particles (about 0.3–0.6 mm) are screened and sorted before casting the core samples to ensure high homogeneity of them. After the process of air drying for 30 days for hardening, the compressive strength could be measured of 30 MPa or so. Natural marble samples shown in Fig. 1b have the compressive strength of approximate 65 MPa. All of the samples have the outer diameter of 100 mm and the height of 160 mm.

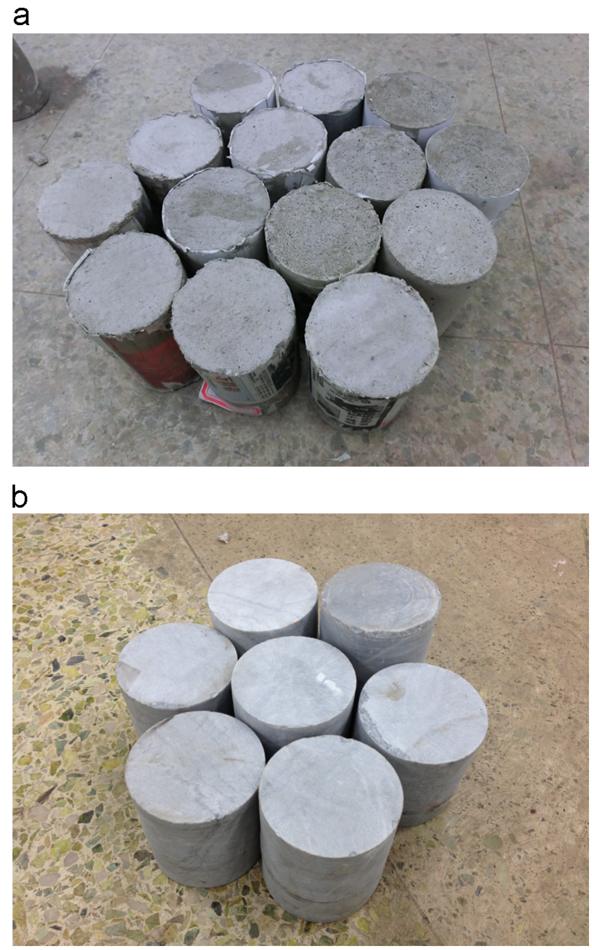

Fig. 1. Core Samples. (a) Man-made core samples. (b) Natural marble core samples.

2.2. Experimental process and apparatus

Fig. 2 shows the flow chart of the rock-breaking experiment system with SC-CO_2 jet. First of all, refrigerating equipment should be powered on before the experiment to cool the system into the range of 0–4 °C, meeting the conditions under which CO_2 can be liquefied from gas. Then, open the valves 1–4 on CO_2 cylinders and keep the valves 5–7 closed when temperature is low enough. The liquid CO_2 under the pressure of 4–5 MPa in the cylinders will flow into the refrigerating equipment automatically and the temperature will also be lowered to 0–4 °C after heat exchange. Then the CO_2 will be liquefied under the pressure of 4–5 MPa and stored into the storage cylinders. Shut off the valves 1–4.when the temperature and pressure have no change any more; power on the heater and set the experiment temperature on the control board; core sample is gripped by an specially-made tool and fixed on an holder in the bottom of the simulated wellbore; then make sure that the jet distance is precisely adjusted and all the joints are well sealed before starting the experiment. Open the valves 5–7, activate the high-pressure pump and adjust the flow rate and the pressure, as well as the confining pressure, bore hole temperature and other parameters to the experiment values and try to keep it stable for breaking the rock by jetting for a certain time period,

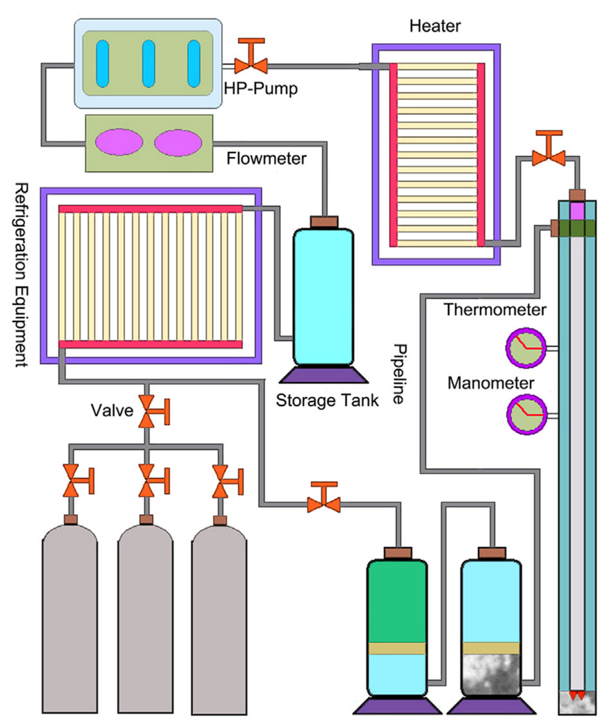

Fig. 2. Flow schematic of the experiment.