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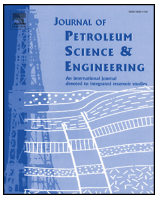

Experiment on coal breaking with cryogenic nitrogen jet

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ABSTRACT

Severe leakage of drilling fluid and reservoir damage due to water and solid invasion during well drilling are the key factors that restrict economic exploitation of coal bed methane (CBM) in China. To solve these issues, this paper presents a method of CBM well drilling with the assistance of cryogenic nitrogen jet, in which no aqueous phase and solid phase are contained. To determine the feasibility of coal breaking by cryogenic nitrogen jet and the effects of different parameters, such as nozzle diameter, dimensionless standoff distance, nozzle pressure difference and exposure time, we conducted corresponding rock breaking experiments on artificial and natural coals with the cryogenic nitrogen jet and the water jet. Rock breaking features and the energy consumption by the two jets were compared. The results indicate that the cryogenic nitrogen jet has better rock breaking performances and consumes less energy. Under the same conditions, the average rock erosion volume and the energy consumption with the cryogenic nitrogen jet were 18.34 times larger and 90.8% lower than those with water jet, respectively. Visible netted fractures could be created on the surface of coal samples blasted with the cryogenic nitrogen jet, and thus rock breaking could be facilitated effectively. The outstanding rock breaking performances of cryogenic nitrogen jet are attributed to three mechanisms: high-velocity jet impact, thermal shock and gasification cracking effect. In addition, under our experimental conditions, the erosion volume and depth were proportional to the pressure difference and inversely proportional to the dimensionless standoff distance. When the nozzle diameter changed from 1.5 mm to 3 mm, the increases of erosion volume were 3% at the pressure difference of 5 MPa and 41.7% at the pressure difference of 10 MPa respectively. This indicates that the effect of nozzle diameter is more significant at relatively higher pressure drops. With the increase of exposure time, both of the rock erosion depth and volume rose, while with a smoother trend. The results of this study are expected to promote the application of cryogenic nitrogen jet in CBM well drilling.

1. Introduction

Conventional well drilling with water-based fluid has the limitation of formation damages due to solid and water invasion in unconventional reservoirs (Freij-Ayoub, 2012). Because of the ultra-low porosity and permeability of such formations these damages could cause clay swelling and blockage of hydrocarbon seepage channels (Brino and Nearing, 2011; Ju and Wu, 2016; He et al., 2016). Generally, underbalanced well drilling is expected to deal with this issue. However, in coal bed methane (CBM) formation, this method will lead to serious wellbore collapse due to the relatively low strength of coal resulted from the development of cleats and poor cementations (Bennion et al., 1996; Salehi et al., 2010). Therefore, a new waterless drilling method, drilling with cryogenic nitrogen jet, is proposed to solve problems above in CBM well drilling. In this method, liquid nitrogen (LN_2) is used as a substitute for water-based fluid in CBM well drilling. No water and solid phase are contained in drilling fluid, thus no reservoir damage will occur. Besides, this waterless method can be applied in arid regions, because no water is consumed during well drilling. When liquid nitrogen contacts with the hot reservoir rocks, it will be gasified intensely (Li et al., 2016). Under the atmospheric pressure and the temperature of 20 °C, liquid nitrogen volume will expand by 694 times. The intense expansion can assist well drilling in two ways: (1) high-speed nitrogen flow can be formed in annulus to improve the cuttings carrying efficiency (Shen et al., 2011); (2) the dramatic volume expansion is able to inhibit severe leakage of drilling fluid resulted from huge amount of natural fractures in a coal formation (Bing et al., 2015).

LN_2 is a clean, inert and cryogenic fluid, which has extremely low boiling temperature (-195.8 °C at atmospheric pressure). After contact with cryogenic nitrogen, rock will be cooled down intensely. Owing to expansion coefficient differences of various particles and temperature gradient, thermal stresses will be induced in rock (Kim and Kemeny,

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2009). Thermal stresses can drastically enhance the rock breaking efficiency by generating new micro-cracks and by promoting propagation of originally existed cracks. Moreover, frost heave of pore fluid in saturated rocks may further intensify the rock damage by destroying the cementation of particles.

Cryogenic nitrogen fracturing has been successfully applied to stimulate the Devonian shale reservoir (Grundmann et al., 1998). It was believed to be a potential method to enhance stimulation reservoir volume (SRV) by generating many secondary fractures in formation. Recently, this waterless fracturing method has been paid increasing attentions due to the growing concerns about large water consumptions and contaminations caused by massive hydraulic fracturing. Many laboratory tests have been conducted to better understand the cracking effects of liquid nitrogen. McDaniel et al. (1997) found that the coal samples could be broken into smaller pieces when they were immersed into liquid nitrogen. Cai et al. (2015a) conducted permeability tests and uniaxial compression tests on rock samples with and without liquid nitrogen cooling. The increase of permeability by 48.89%–93.55% and decrease of compressible strength by 16.18%–33.74% reflected that liquid nitrogen could induce significant damage in coal samples. Besides, according to the investigation of rock pore structures using scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR) (Cai et al., 2014), the pore scale increased significantly, especially for the saturated rock samples, in which cracks were even observable. Cha et al. (2014) and Alqatahni et al. (2016) conducted cryogenic fracturing experiments on rock samples with and without triaxial confining stress. The crack assessment results based on X-ray CT and acoustic signatures indicated that cryogenic treatment by liquid nitrogen could generate large amounts of cracks and reduce rock breakdown pressure substantially.

Researches above are mainly about the rock cracking under the condition of static contact with liquid nitrogen. In the aspect of dynamical liquid nitrogen jet study, Cai et al. (2015b; 2016) modeled and analyzed the flow field of abrasive liquid nitrogen jet, and the simulation results showed that velocities of abrasive particles in liquid nitrogen jet were higher than that in water jet. This means that better rock breaking performance can be obtained by using the abrasive liquid nitrogen jet. Laribou et al. (2012) carried out laboratory tests on the metallic surfaces treatment by high pressure cryogenic nitrogen jet, and 200 μm thick alloy fragments were removed from the surface at the time period of 2 min. Grosdidier et al. (2015) analyzed the interaction mechanisms between nitrogen jet and metallic surface, and concluded that the most prevailing interaction mode during jet impact was the brittle mode owing to the effect of thermal shock.

Metallic surface treatments by cryogenic nitrogen jet have already been investigated for several years. However, to our best knowledge the aspect of rock breaking by cryogenic nitrogen jet has not been explored yet. Rock breaking features and the feasibility of well drilling with this jet are still unclear. Thus, in order to figure out the feasibility of CBM well drilling with cryogenic nitrogen jet, we developed the experimental setup and procedures to test the rock breaking performances on artificial and natural coal samples. By comparing rock breaking results by cryogenic nitrogen jet with that by water jet, we obtained rock breaking characteristics, mechanisms and parameter influences of this new jet, which will be the theoretical basis for further applications in CBM well drilling.

2. Experimental setup and materials

2.1. Experimental apparatus

Rock-breaking experiments with the cryogenic nitrogen jet were conducted in the State Key Laboratory of Petroleum Resources and Prospecting in China University of Petroleum, Beijing. The cryogenic nitrogen jet system, as shown in Fig. 1, consists of a liquid nitrogen tanker, a cryogenic fluid plunger pump, a track trolley, nozzles, electronic control system and low-temperature resistant pipelines. The cryogenic nitrogen pump is shown in Fig. 2. Maximum flow rate and output pressure are 4000 L/h and 35 MPa, respectively. In our experiments, the pipeline and pump head in the system were circumferentially winded with insulation materials to limit the heat transfer between liquid nitrogen and warmer pipes. Because the heat transfer can cause intense evaporation of liquid nitrogen, the pressure in pipelines will rise sharply. Once the rising pressure exceeds the upper pressure limit of system, the system will burst. Thus to ensure the safety of the system and operators a pressure interlock system was set up. It was designed to cut off electric and stop the pump once pressure in the system exceeded the upper pressure limit. Besides, before starting the pump, V-1, V-3 and V-4 need to be turned on. Then with the assistance of the LN_2 truck, liquid nitrogen is injected into the pump and pipelines at a low flow rate in order to pre-cool the whole system, until the temperature recorded by the temperature transducer T at the end of pipelines is low enough to guarantee that the fluid flowing out from nozzle is liquid nitrogen rather than nitrogen gas. After the whole system is fully cooled down, we can turn on the pump and started experiments. When the experiments are finished, V-5 should be turned on to release pressure in the system.

Fig. 3 shows the structure of the nozzles. The acceleration length L is two times the nozzle diameter D, and the convergent angle of nozzles is set to 13.24°, which can help to form high velocity concentrated jet. The nozzles are made of brass and need to be placed in the stainless steel body, which can connect pipeline by a thread. The track trolley with five core containers is shown in Fig. 4. It can move along the rail and five coal samples can be placed in it. So these samples can be eroded one by one without turning off the pump, which means that pre-cooling the system repeatedly is not required. Therefore, experiment time and consumption of liquid nitrogen can be saved by using track trolley.

2.2. Coal samples

In our work, we used two types of coal samples: artificial coal samples and natural coal samples, as shown in Fig. 5. The artificial coal samples were made of coal fines (less than 10 meshes) and cement in the mass ratio of 1.5:1. They were homogeneous and mainly used to test the effects of different parameters on rock erosion. The natural coal samples were made into cubes (150 × 150 × 150 mm). Mechanical properties of them were tested, as shown in Table 1.

2.3. Experimental program

Table 2 shows the experiment scheme in this work. In order to obtain the differences of rock breaking characteristics between cryogenic nitrogen jet and water jet, and to determine the influences of different parameters on rock breaking performance, including nozzle pressure difference, dimensionless standoff distance, exposure time and nozzle diameter, totally 31 coal samples were tested.

2.4. Uncertainties

The following analyses are performed to estimate the uncertainties of the erosion volume and erosion depth measurements. Formula of erosion volume V is:

$$V = \frac{m_1 - m_2}{m_1} \times \frac{\pi d^2 h}{4} \tag{1}$$

where m_1, m_2, d and h are mass of the intact coal sample, mass of the eroded coal sample, diameter and height of intact coal sample, respectively. The uncertainties of erosion volume result from two aspects: variations in repeated measurement of d and h and indication error of measuring instruments (Guide to the Expression of Uncertainty in Measurement, 1995). The erosion volume uncertainties induced by repeated measurements of d and h are: