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Experimental study of changes in fractures and permeability during nitrogen injection and sealing of low-rank coal

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ABSTRACT

To investigate the influence of nitrogen injection and sealing (N_2–I–S) on the fracture and permeability of coal reservoirs, two low-rank coal samples from the Fukang (FK) and Wudong (WD) mining areas in the southern margin of the Junggar Basin, China, were collected and used for N_2–I–S experiments. A Chandler Model 6100 Formation Response Tester (FRT) from the Chandler Company was used for N_2–I–S experiments with sealing times of 6, 18 and 36 h and a sealing pressure of 584 psi for the samples, and the real-time permeability changes were monitored during the N_2–I–S process. An NDP-605 NanoDarcy Permeameter was used to test the permeability with different effective stresses before and after N_2–I–S, and the difference in pore distribution before and after N_2–I–S was determined by low-field nuclear magnetic resonance (NMR) for the samples. X-ray CT (μCT) was used to observe the changes in the distribution of fractures before and after N_2–I–S. The results showed that the permeability of FK increased by 43.75%, 91.67% and 162.99% and that of WD increased by 13.96%, 49.92% and 73.68% after 6, 18 and 36 h of sealing time, respectively. For each N_2–I–S period, the permeability increased with increasing sealing time, while the change rate gradually decreased, as demonstrated by a curve similar to the "Langmuir isotherm adsorption" curve. The stress sensitivity of permeability increased after N_2–I–S, and the decrease in permeability with increasing effective stress was greater than that of non-N_2–I–S-treated samples. Low-field NMR showed that the amplitude of 100% water saturation had no obviously changes after N_2–I–S, which means that no new fracture formed after that. Meanwhile, X-ray CT images also showed that no new fracture formed after N_2–I–S, but the connectivity is enhanced. Further analysis showed that N_2–I–S dispersed fracture fillers and opened up the fractures of the coal reservoir, resulting in an enhancement in permeability, but also increased the degree of fracture closure, which caused an increase in the stress sensitivity of the permeability.

1. Introduction

The permeability of coal reservoirs in China is generally low (typically lower than 1 mD), and gas injection is an effective way to improve permeability (Zhu et al., 2003; Sayyafzadeh et al., 2015). Because of the large amount of adsorption swelling caused by CO_2 injection in coal reservoirs, the reservoir permeability is reduced, and injection is difficult to maintain (Harpalani and Schraufnagel, 1990; Zarębska and Ceglarska, 2008; Zhou et al., 2013). Therefore, CO_2 injection is mostly used in coal reservoirs with higher permeability. The first CO_2 injection test was conducted in the Fruitland formation, Allison Unit, San Juan Basin, USA, with an initial permeability of the coal reservoir ranging between 100 and 130 mD (Reeves and Oudinot, 2005). While N_2 injection is more suitable for coal reservoirs with very low permeability (Reeves and Oudinot, 2004). The adsorption amount of N_2 is only approximately one-fourth that of CO_2, and N_2 scarcely reacts with coal reservoirs and formation fluids (Shi et al., 2014); thus, the adsorption swelling degree of coal reservoirs under N_2 injection is smaller than that under CO_2 injection and is reversible (Bustin et al., 2008; Perera et al., 2015; Zhang et al., 2015a,b). N_2 injection for stimulating productivity was first developed for the hydrous low-rank coal reservoir of the Cretaceous Horseshoe Canyon Formation in Alberta, Canada (Hoch, 2005). The American ARI company carried out N_2 injection for 34 low-rank coalbed methane (CBM) wells in the Fruitland formation, San Juan

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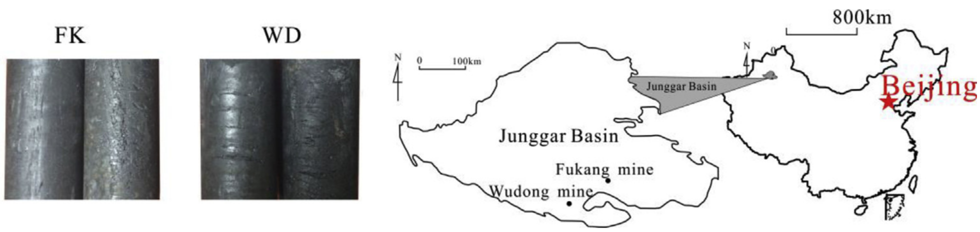

Fig. 1. Sampling sites and sample forms.

Basin, USA, which caused a fivefold increase in the total productivity, and the recovery factor increased by 10–20% (Reeves and Oudinot, 2004). The production of a single well in the Ishikari coalfield has been increased fourfold by N_2 injection (Shi et al., 2008). N_2 injection was also carried out on high-rank coal reservoirs in the Yangquan, Luan and Jincheng mining areas in the Qinshui Basin, China, but the effect on productivity was not obvious (Ye et al., 2007; Nin et al., 2012; Li et al., 2016).

A large number of experiments and numerical simulations of N_2 injection for improvement of gas production have been carried out (Zhu et al., 2002, 2003; Jessen et al., 2008; Shi et al., 2008; Mazumder and Wolf, 2008; Zarebska and Ceglarska, 2008; Harpalani and Mitra, 2010; Kiyama et al., 2011; Zhou et al., 2013; Wang et al., 2015). The experimental results of Zhou's injection of N_2 into a saturated CH_4 coal reservoir showed that N_2 injection can accelerate methane output by up to 71% (Zhou et al., 2013). A numerical simulation by Wang showed that N_2 injection can effectively promote CH_4 production. For high-permeability reservoirs, the N_2 content required to produce gas, but for low-permeability reservoirs, it is lower (Wang et al., 2015). Most studies have focused on N_2 injection, resulting in partial methane pressure reduction and methane desorption, thus increased CBM productivity (Zhu et al., 2002, 2003). However, few studies have reported the pattern of variation of reservoir permeability caused by N_2 injection, and the reasons for those variations in permeability have rarely been discussed. In an engineering practice analysis, Ye et al. (2007) showed that enhanced CBM recovery by N_2 injection is caused by partial methane pressure and permeability enhancement. It is not a good explanation for the mechanism of N_2 injection to increase productivity by only partial methane pressure reduction and methane desorption. When high pressure gas enters the reservoir, it not only has the effect of promoting desorption of methane to the reservoir, but also the impact force brought by high pressure gas will also destroy the fracture structure of reservoir, and affect the permeability of reservoir. Hou et al. (2016) research by inject air into coal reservoir shows that the compressive strength and Poisson's ratio decrease by 16% and 8% after injection, and by mathematical calculation, the permeability increases by 70%. The results of Wang et al. (2015) shows that the total pore volume markedly increases during N_2 injection with increases in transition pores, mesopores and macropores of 8.0%, 50.0% and 138.3%, respectively. Luo (2014) conducted laboratory experiments to shows that the permeability of high-rank coal reservoirs is improved after N_2 injection.

Previous studies have shown that N_2 injection can improve reservoir permeability, but it is not clear about the dynamic change of permeability and mechanism of increasing permeability during the process, and there is a lack of research on permeability change under different effective stress. Therefore, this paper selected two low-rank coal samples using a Chandler Model 6100 Formation Response Tester (FRT) to simulate the process of N_2 injection and then sealed the inlet and outlet of samples under the N_2 atmosphere to simulate the closed environment of the underground coal reservoir after N_2 injection. The variation in permeability during N_2—I—S was monitored in real-time with FRT, the pattern of variation of permeability sensitivity under different effective stresses were tested by an NDP-605 NanoDarcy Permeameter, and pore distribution was tested by low-field NMR in each N_2—I—S period. The changes in the distribution of fractures and minerals before and after N_2—I—S were observed by X-ray CT. The results were summarized, and the characteristics and the mechanism of permeability change were explored to further explain the reasons for the productivity enhancement after N_2—I—S.

2. Experiments and methods

2.1. Sample preparation

Two low-rank coal samples from the Fukang (FK) and Wudong (WD) mining areas, southern margin of Junggar basin, China, were sampled for this experiment (Fig. 1). Proximate analysis and macerals were tested according to GB/T 212–2008 and GB/T 15588-2013 standards, respectively. The volatile matter (V_{daf}) and moisture content (M_{ad}) of the two samples were similar, but the differences of macerals between these two coals obviously showed that the FK coal was higher in vitrinite content, while the WD coal was higher in content of inertinite and minerals (Table 1). Uniaxial mechanical parameters were tested in accordance with DZ/T 0276.19–2015 (DZ/T 0276.19–2015). The uniaxial compressive strength and residual strength of WD were greater than those of FK, while the Young's modulus and Poisson's ratio were lower (Table 2).

The coal samples were drilled into a cylinder with a diameter of 25 mm and height of 50 mm (the error was less than 1 mm) along the direction paralleled to the bedding plane (Fig. 1). The coal pillar bottom and top surface was polished by laser cutting machine to reduce the error of the permeability testing experiments. After processing, the coal samples were sealed in polythene bags and stored at low temperature, approximately 4 °C, to prevent oxidation and moisture loss.

2.2. Test methods and experimental instruments

2.2.1. N_2—I—S experiment

N_2—I—S experiments were carried out in Fracturing acidification Laboratory of Langfang Branch of PetroChina Exploration and Development Research Institute using a Chandler Model 6100 FRT produced by the American Chandler Corporation, which was used to evaluate the effects of different fluids like gas, water and drilling fluid

Table 1
The test results of proximate analysis and macerals of WD and FK sample.

No.	R_{max}/%	M_{ad}/%	A_d/%	V_{daf}/%	V/%	I/%	L/%	M/%	TRD/cm^3/g	ARD/cm^3/g
FK	0.64	2.77	2.74	39.64	79.80	18.7	0.6	1.1	1.32	1.30
WD	0.72	2.53	4.12	32.24	34.20	62.20	3.60	2.5	1.37	1.28

R_{max}- Maximum vitrinite reflectance; M_{ad}- Moisture, air-dried basis; A_d- Ash, dried basis; V— Vitrinite; I— Inertinite; L-exinite; TRD- True relative density; ARD- Apparent relative density.