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Experimental study of water blocking damage on coal

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ABSTRACT

Water blocking damage, caused by the invasion of external fluids into the coal seams during hydraulic fracturing, is one of the reasons causing coalbed methane wells uneconomic in most areas of China. This paper presents an experimental study of water blocking damage on coal based on the measurements of surface tension, contact angle, gas-phase permeabilities and adsorption and desorption of nitrogen on synthetic coal samples. Distilled water, KCl, AN, and KCl+AN solutions were used as testing liquids in this study. Results show that the hydraulic fracturing fluid with surfactant AN causes the lowest damage to the reservoir permeability; the surfactant AN reduces the surface tension of the liquid and increases the wettability of liquid to coal reservoir; and the surfactant AN inhibits the occurrence of capillary and Jamin effects efficiently. It is concluded that the surfactant AN can reduce the water blocking damage rates of coal reservoirs; and the hydraulic fracturing fluid mixed with 1.5% KCl and 0.05% AN reduces the effect of water blocking damage on the coal permeability.

1. Introduction

It has been more than 30 years since China started to explore and produce coalbed methane, but commercialized large-scale developments have not been achieved by far (Tian et al., 2015; Yang, 2016). Besides the natural low permeabilities and the difficulties in stimulation of the coal reservoirs, hydraulic fracturing fluid damage to reservoirs may be one of the main reasons causing the low production of coalbed methane wells (Yuan et al., 2015; Fairhurst et al., 2007). It is known that if a hydraulic fracturing fluid is not compatible to a coal reservoir, damages from water, acid, and alkali sensitivities and water blocking may be incurred (Rahman et al., 1995; Civan, 2007; Kang et al., 2014; Huang et al., 2015; Fang et al., 2016; Xu et al., 2016). The sensitivities of acid, alkali, and salt caused by common active water-based fracturing fluids are negligible to coal reservoirs (Lin et al., 2011). In addition, due to the clay stabilization ability of KCl, water sensitivity is inhibited by adding KCl to the hydraulic fracturing fluid (Tian and Wu, 2014). However, no sufficient attention has been paid to the water blocking damage, which is probably one of the main reasons why the commercial development of coalbed methane in China is constrained.

After external fluids invaded a reservoir, due to the capillary pressure blocking effect, the driving force in the formation is not able to drain the external fluids out completely. Hence, the water saturation increases and gas-phase permeability decreases in the invaded zones. This decrease of gas-phase permeability is known as the water blocking damage (Bennion et al., 1994; Parekh and Sharma, 2004; Mirzaei-Paiaman et al., 2011; Holditch, 2013). Water blocking damage happened to coal reservoirs is inevitable but it can be reduced (Kamath and Laroche, 2003).

The capillary and Jamin effects are the main mechanisms of water blocking damage (Yang, 2013). Since the average pore size in coal reservoirs (Cai et al., 2013) is relatively small, a great capillary pressure may be incurred because of the invasion of external fluids (Mahadevan et al., 2007). The great capillary pressure may yield a large amount of liquid trapped in the pores; then causes an increase of irreducible water saturation and a decrease of gas-phase permeability. The coal reservoir development in Alberta, Canada, has proved that the capillary effect, albeit it is a potential in the reservoirs, is particularly serious when the initial water saturation is lower than the irreducible water saturation after the stimulation of the reservoir (Bennion and Thomas, 2005; Bennion et al., 1996; Amabeoku et al., 2008; Bahrami et al., 2012; You et al., 2004; Zeng et al., 2010). After the failure of using water-based fracturing fluid (Ye and Fan, 2005; PetroWiki, 2017) through “dry formation”, a multi-seam nitrogen fracturing completions approach yielded the commercialized development in the Alberta area (Gunter et al., 1997;

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Table 1
Proximate analysis and maximum vitrinite reflectance of the coal samples.

Sample name	M_{ad}, wt%	A_{ad}, wt%	V_{ad}, wt%	FC_{ad}, wt%	$R_{o,max}$, %
Shaqu	0.47	11.12	26.59	61.82	1.3
Dongqu	0.53	14.62	18.33	66.52	1.9
Jiaozuo	3.82	7.64	6.89	81.65	4.2

M – moisture content, A – ash content, V- volatile content, FC – fixed carbon content, $R_{o,max}$ - maximum vitrinite reflectance, subscript ad - air-dried basis.

Beaton et al., 2006). Additionally, during gas production, especially at the early unsaturated single-phase flow stage, the Jamin effect often occurs when bubbles occur. Capillary resistance is incurred as bubbles passing through the pores with various diameters. Jamin effect will inhibit the migration and production of gas from coalbeds (Li et al., 1999; Wang et al., 2008). Once the displacement pressure in the reservoir is not able to overcome the resistance brought by the capillary and Jamin effects, water blocking damage occurs.

Physical and chemical methods were used in controlling water blocking damage based on their mechanisms of actions. The main physical methods include the processes by increasing the pressure differences of production or heating the formation and hydraulic fracturing area (Liao et al., 2002; Yan et al., 2003; Denney, 2015); the widely used chemical methods include the processes by changing the wettability or reducing the surface tension of liquid (Standnes and Austad, 2000; Mahadevan et al., 2005; Xie et al., 2009; Bazin et al., 2010; Huang et al., 2012; Ganjdanesh et al., 2015).

Compared with the increasing permeability via hydraulic fracturing, water blocking damage caused by a hydraulic fracturing fluid has not received much attention. Because of the natural low permeability and low pressure of Chinese coalbed methane reservoirs (Zhang et al., 2001), it is difficult for coal reservoir to overcome the water blocking damage by itself. Water blocking damage is more serious for the coal reservoirs with low initial water saturation. Reducing the capillary pressure for hydraulic fracturing fluids to coal by adding a surfactant is one of the most effective and cheapest approaches (Liu et al., 2015, 2016; Ni et al., 2016). This paper presents an experimental study of water blocking damage based on the measurements of surface tension, contact angle, gas-phase permeabilities and adsorption and desorption of nitrogen on coal. Distilled water, KCl, AN, and KCl+AN solutions were used as testing liquids in this study.

2. Experiments and results

Previous experimental practices show that KCl is a clay stabilizer that can inhibit water sensitivity effectively. Note that the content of smectite, a swelling clay, is minor in Chinese coal seams (Guo et al., 2015; Huang et al., 2015). The application of the clay stabilizer in the industry is for the mitigation of swelling caused by the tonstein (Spears, 2012) from intervals. The aim of adding KCl in the experimental fluids of this study is to mimic the industrial used hydraulic fracturing fluids. The concentration of KCl used in the hydraulic fracturing fluid is usually about 1–2% (Ning, 1999). In this experiment, the 1.5% KCl solution is adopted as one of the base fluids.

Our previous studies indicated that the solution with 0.05%AN has the best effect on mitigating velocity sensitivity and the lowest capillary pressure (Song, 2016) which was considered as the critical micelle concentration; hence the 0.05% AN is adopted as the surfactant in this study.

2.1. Wettability experiment

The ability of the surfactant AN in reducing the surface tension of the liquids and improving the wettability of the coal reservoir is determined by testing the surface tension of distilled water, and solutions of 1.5% KCl, 0.05% AN, and 1.5% KCl+0.05% AN, as well as their contact angles to different coal samples.

2.1.1. Sample preparation

Coals collected from Shaqu, Dongqu and Jiaozuo areas were used for the experiments in this study. Table 1 lists the proximate analysis and maximum vitrinite reflectance for those coal samples. The coal samples are crushed to a size of about 200 mesh (0.074 mm) and then compressed into coal tablets of about 50 mm in diameter and 1 mm in thickness with a compressing pressure of 40 MPa (Song, 2016).

Note that using the crushed coal samples is to make the experimental results comparable because it's impossible to get coal plugs with same porous and quality. Kolak et al. (2015) compared the application of ground (crashed) and intact coal samples in the evaluation of hydrocarbon fate during supercritical CO_2 injection into coal seams. They underscored the need for using intact coal samples due to the differences in particle size and moisture content. Anggara et al. (2013) measured the swelling of a low-rank coal at the condition of supercritical CO_2 injection using crushed samples because of its advantages in sample preparation and experimental execution compared to the usage of block samples. Liu et al. (2016) also studied the water blocking effect in coal seams using the crushed samples. However, the effect of particle size and moisture content on water blocking damage mechanism is yet to be studied.

Although the crushed samples were eliminated all the natural fractures, this paper studies the water blocking damage which is caused by capillary and Jamin effects and happens in micropores. Except for the permeability, irreducible water saturation and residual gas in coal are also used to assess the water blocking damage. The permeability decrease in natural fractures is not the aim of this study.

2.1.2. Experiment results

JC2000D (the measurement range of surface tension is from 0.01 to 2000 mN/m, and the accuracy is 0.05 mN/m) uses the optical method (the droplet morphological analysis method) to measure the surface tension and the contact angle (Liu et al., 2015, 2016). Firstly, the surface tension of the distilled water and the solutions of the 1.5% KCl, 0.05% AN and 1.5% KCl+0.05% AN were measured respectively by using the pendant drop method at a constant temperature of 27 °C in this study. Then the coal tablets were put on the test plate to measure the contact angle of these four types of liquids to these coal tablets, respectively with goniometry. When the solution drops drip onto the coal tablets, an initial contact angle is formed and will become smaller with time. The final contact angle, used in this study, is the one when the shape of drip stabilized which arrives in about 10s.

Table 2 shows the measured surface tensions and contact angles. Results show that the surface tension decreases from the 1.5% KCl solution to the distilled water then to the 0.05% AN solution and the 1.5% KCl+0.05% AN solution; for Shaqu coal, the wettability (a greater contact angle means a lower wettability) decreases from the 0.05% AN solution to the 1.5% KCl+0.05% AN solution then to the 1.5% KCl solution and the distilled water; while for the coals from Dongqu and Jiaozuo, the

Table 2
Measured surface tensions and contact angles.

Type of liquids	Surface tension, mN/m	Contact angle, °		
		Shaqu	Dongqu	Jiaozuo
Distilled water	73.55	66.5	63.0	56.0
1.5% KCl solution	79.23	54.0	65.0	58.8
0.05% AN solution	29.08	9.5	14.3	9.0
1.5% KCl+0.05% AN solution	26.33	14.5	20.0	13.5