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Experimental study on the petrophysical variation of different rank coals with microwave treatment

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ABSTRACT

To maximize coalbed methane recovery, the reservoir is often stimulated because of its low permeability. An exploratory study on improving coal porosity and permeability by microwave treatment was proposed. Pore size distribution of four unconstrained coals (lignite, subbituminous, bituminous, and anthracite), before and after microwave treatment, were evaluated using the nuclear magnetic resonance. With continuous exposure to microwaves, the pore size distribution of coals (especially the lignite coal) extends, and the pore volume and connectivity increase. In addition, coal porosity and permeability evaluated based on the Schlumberger Doll Research model increase by 33–72% and 73–181%, respectively. The mechanism was revealed by combining P-wave tests, thermal imaging and X-ray computed tomography scanner. The moisture and minerals bounded in pores are selectively heated and then detached, and, as a result, the pore structure is opened. Continued exposure to microwaves rapidly converts the mobilized moisture into super-heated steam. Under the steam pressure, pores and fractures generally expand. Borrowing from microwave-assist oil recovery, we presented a conceptual design of a CBM extraction borehole with microwave irradiation.

1. Introduction

During the past 20 years, coal bed methane (CBM) has become an important energy resource (Moore, 2012). It is expected that CBM will remain an eco-friendly component in the energy portfolio over the next decades (Beaton et al., 2006). CBM recovery before coal extraction is important from greenhouse gas emission, productivity development, and safety and economic of mining point of view (Li et al., 2015; Lin et al., 2014; Szlązak et al., 2014).

Unlike sandstones and shales, coal reservoir is a network of pores and fractures, and the vast majority of gas is stored in the microporosity system (Karacan and Okandan, 2000). CBM recovery involves desorption at the grain scale (<nm), diffusion at the micropore scale (nm), and seepage at the mesopore (μm) and cleat (mm) scales (Clarkson and Bustin, 1996; Gurdal and Yalcin, 2001). Hydro-fracturing, hydro-slotting, and blasting have been widely applied to enhance coal permeability (Hao et al., 2014; Javadpour et al., 2015; Shen et al., 2012). However, the coverage and persistence are limited. Recent studies proposed innovative ideas such as electrochemical modification, supercritical CO_2 injection, tetrahydrofuran extraction, and liquid nitrogen cooling (Al-Abri et al., 2012; Cai et al., 2015; Guo et al., 2014; Ji et al., 2014). These methods can significantly improve gas absorptivity or diffusivity but cannot solve the key problem: low permeability. Thermal methods such as cyclic electrical heating, steam injection, and in situ combustion have also been employed. However, the economical profitability or even the technological feasibility of these methods can be greatly reduced in low permeability reservoirs (Bientinesi et al., 2013). Microwave irradiation can be an alternative because it is less affected by formation geology and is capable to distribute heat over a large volume.

Microwave energy is commonly used in a variety of industrial, scientific, and medical applications for processing, drying, and heating (Jerby et al., 2002). Microwave irradiation in enhancing coal grindability (Lester et al., 2005) is often conducted at normal temperatures. However, in coal coking (Lester et al., 2006), an 8 kW microwave was used to reach a temperature over 1000 °C. Coal was desulfurated for cleaning (Uslu and Atalay, 2004) in a microwave oven at a temperature of 193 °C. Compared to conventional heating, which is transferred by conduction, microwave heating is realized by the conversion of electromagnetic energy to thermal energy, where the microwave-material interaction is controlled by the dielectric properties (Folorunso et al., 2012). Coal is transparent to microwave, while polar molecules (e.g. moisture and pyrite) absorb microwave energy and thus will be heated more rapidly (Kingman, 2006; Sahoo et al., 2011).

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The differential heating between the heated and host phases causes evaporation and ejection of moisture and thermally stresses, which will in turn affect the petrophysical property of coal (Whittles et al., 2003).

Only a few articles have been published on the microwave modification or fracturing of coal to date. Kumar et al. (2011) used a Sairem GMP15 kW microwave cavity to irradiate confined and unconfined bituminous coal cores. They evaluated the internal fractures via microfocused X-ray computed tomography and concluded that the exposure of microwaves to a coal core generates new fractures and increases the apertures of the existing fractures. Liu et al. (2015) investigated the pore structure of Ximeng lignite under microwave irradiation and found that the specific surface area of the microwave-treated coal differently decreased, whereas its average pore diameter and total pore volume differently increased. However, still little attention has been devoted to the effect of microwave on the petrophysical properties of different rank coals. In this paper, coal samples of various ranks were investigated and the petrophysical variation before and after microwave treatment was quantitatively evaluated.

2. NMR principles and theory

Petrophysical properties of coal include the size, connectivity, and distribution of pores and fractures (Yao and Liu, 2012). Petrophysical characterization methods include SEM, CT, mercury intrusion, and N_2/CO_2 adsorption. The drawbacks of these methods are slow data acquisition, inefficient testing, limited aperture range, and damage to samples (Fu et al., 2015). Nuclear magnetic resonance (NMR) is a nondestructive, easy and less time-consuming technology (Yao et al., 2010), which covers the widest aperture range (see Fig. 1). NMR uses a magnetic field to create a dipole moment, the amplitude of which is proportional to the number of hydrogen atoms within the fluid and thus is a measure of the pore volume (Cutmore et al., 1986). The dipole moment can be expressed as a spectrum of transverse (T_2) relaxation time (Li et al., 2013), which can be given as:

$$\frac{1}{T_2} = \rho \times \frac{S}{V} \quad (1)$$

where S is the pore surface area, m^2; V is the pore volume, m^3; and ρ is the transverse surface relaxivity, ms^{-1}.

For coals, $T_2 < 10$ ms corresponds to micropores; T_2 at 10–100 ms corresponds to mesopores, and $T_2 > 100$ ms corresponds to macropores and microfractures (Yao et al., 2014). The peak area of T_2 spectrum reflects the pore volume, and the continuity between peaks represents the pore connectivity (Frosch et al., 2000).

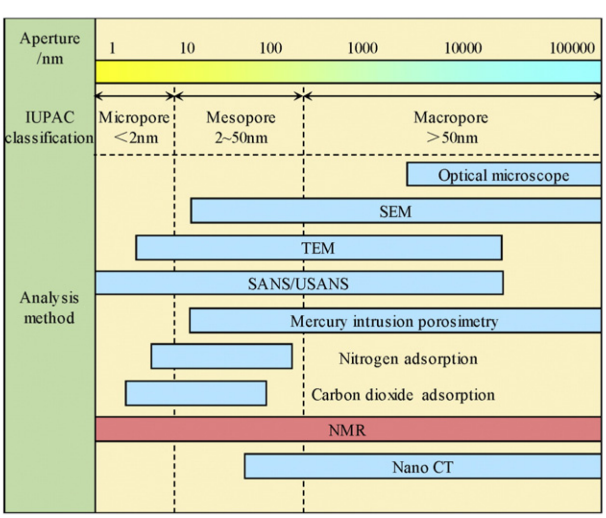

Fig. 1. Aperture ranges (nm) for coal petrophysical characterization methods.

3. Experimental

3.1. Coal samples

Four coal samples of various ranks (lignite, subbituminous, bituminous, and anthracite) were collected from three main coal-bearing basins in China. All samples were cut into cylindrical cores of 50 mm in diameter and 60 mm in length, and the end of each core was polished.

3.2. Test procedure

A cyclic microwave experiment was designed, as illustrated in Fig. 2a. In a single cycle, the unconstrained core was microwave-treated at a 2 kW power for 30 s. The P-wave velocity, digital and infrared thermal images, and NMR signals were captured before and after each cycle. (Infrared thermal images present surface temperature distributions. Compared to the contact making thermometer, the thermal camera can capture a complete temperature distribution across the coal surface instantaneously). Prior to NMR tests, cores were vacuumed at a constant absolute pressure of about 0.01 MPa for 8 h and then saturated in distilled water for another 8 h. Then, cores were air dried until the weight difference before and after measurements was less than 0.2%.

3.3. Microwave treatment

To avoid interference within the telecommunication devices, Federal Communications Commission regulates the microwave frequencies for industrial processing: 0.915 GHz, 2.45 GHz, 5.8 GHz, and 24.124 GHz (Meredith, 1998), while for domestic purpose it is 2.45 GHz (Faisal et al., 2014). Microwave treatment was performed in a microwave oven (MAS-II; Sineo Microwave Chemistry Technology Ltd., Shanghai, China), which generates bursts at 2.45 GHz (see Fig. 2b). Cores were placed in a high-strength Teflon container, which is linked to a vacuum pump through a silicone tube to create an inert atmosphere and to remove the generated vapors.

3.4. P-wave velocity tests

P-wave velocity tests were conducted outside the microwave chamber using a HS-YS4 Ultrasonic analyzer (see Fig. 2c), which consists of a pulse generator, signal reception channels, and a computer. Piezoelectric transducers (transmitter and receiver) were coupled to cores via Vaseline. Generated pulse is converted into a mechanical wave, which can be transmitted through the core.

3.5. NMR tests

NMR tests were conducted using a Meso MR23-060H-I NMR spectrometer. The parameters were: echo time, 0.3 ms; waiting time, 9 s; number of echoes, 5000; number of samplings, 64. Cores were first measured at the 100% water-saturated condition (S_w). Then, they were centrifuged to reach an irreducible water condition (S_{ir}) and were tested again.

4. Results and discussion

4.1. Coal characteristics

The maceral composition and proximate analysis of the four samples are presented in Table 1. The maximum vitrinite reflectance ($R_{o,\ max}$) values of the samples range from 0.32% to 3.21%. Low-rank coals are characterized by high moisture and low carbon contents. Chalmers