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Microwave irradiation's effect on promoting coalbed methane desorption and analysis of desorption kinetics

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ABSTRACT

To enhance desorption of coalbed methane and increase extraction efficiency, a technique using microwave irradiation is proposed. Methane desorption experiments without and with microwave irradiation were carried out in the laboratory using an experimental system developed to study methane desorption. The experimental results show that microwave irradiation causes the total quantity of methane desorbed to increase from 1.91 to 3.92 times larger than the quantity desorbed without MI. Two hour trials were performed, applying microwaves for 4, 8 or 16 min, equivalent to output energies of 192, 384 and 768 kJ. These results show that 1 kJ of microwave energy can cause methane desorption to increase by 0.0088 ml per gram of coal. Under successive microwave irradiations of 40 s, the desorption rate increases by a factor of 10.2. Kinetic analysis also found that microwave irradiation enhances the methane diffusion coefficient and decreases the attenuation coefficient. Regardless of which diffusion model is used to determine the diffusion coefficient, the quantity of gas desorbed increases as the microwave irradiation time increases. The pore and surface features of coal samples exposed to microwaves were determined by using mercury intrusion porosimetry and nitrogen adsorption and specimens were examined by scanning electron microscopy. Methane desorption evidently results from both the microwave thermal effect and structural damage to the coal. The results reported herein reveal the mechanisms that promote methane desorption by microwave irradiation and suggest a new field technique for extracting coalbed methane.

1. Introduction

Coalbed methane (CBM), an unconventional but important natural gas resource, has gradually become a feasible alternative to conventional fuels and is attracting increasing interest worldwide [1,2]. CBM is contained in micropores in coal, primarily in an adsorbed state [3,4]. During CBM recovery or gas drainage prior to coal mining, methane initially desorbs from internal pores in the coal matrix and diffuses via the pore system in the surrounding coal to cleats [5,6]. The gas then flows through cleats and fractures to the CBM production well or drainage borehole. The two main factors controlling CBM extraction and methane gas flow are therefore the gas desorption and diffusion rates in the coal matrix and the gas permeability in cleats and fractures [7,8]. Thus, enhancing the desorption rate and permeability of coal is important if the extraction efficiency and economic utilization of CBM is to be improved [9].

The factors that affect the CBM desorption rate and the coal permeability include the coal's composition and structure (such as moisture [10,11], ash content and pore structure [12]), as well as the degree of metamorphism, gas pressure [13], gas content [14] and external environmental conditions (stress, temperature [15,16], and electromagnetic and acoustic fields [17–19]). Based on these factors, many methods have been proposed to enhance CBM desorption and so increase the extraction efficiency, including hydraulic fracturing [20], hydraulic seam cutting [21], blasting vibration [22], gas injection [23,24] and excitation of physical fields based on temperature changes or the application of electromagnetic or acoustic fields [17–19,25].

In the 1980's, several researchers began investigating the use of physical field excitation methods to accelerate methane desorption from coal. Sakurovs et al. demonstrated that the sorption capacity of coals tends to decrease with increasing temperature [26]. Liu et al. found that the amount of methane adsorbed on coals decreases in an AC electrical field while the permeability increases under a DC field [27]. He et al. showed that low frequency electromagnetic fields (8 MHz) reduce coal's gas adsorption capacity and increase its gas emission rate [17]. Jiang et al. found that acoustic waves promote the desorption of

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methane from coals [18]. These results show that each of these different methods is capable of enhancing gas desorption to some extent.

The term "microwave" is used to describe that portion of the electromagnetic spectrum between 0.3 and 300 GHz. The major advantages of microwaves include the energy efficient, rapid and uniform volumetric heating of certain materials as well as easy and instant operation, in contrast to heating by conduction [28]. Microwaves will selectively heat mixtures that are composed of materials with different dielectric permittivities and loss factors. Coal seams are a complex assemblage of a variety of elements and minerals, including carbon, water, sulfur and clay, and are dielectric. During microwave irradiation (MI), some of these components may act as "hot spots" for fracture initiation because of local thermal and mechanical stresses induced by selective heating. Microwave-induced differential heating in a heterogeneous medium will generate new fractures and induce changes at the grain level by increasing the pore volume [29]. Because of these effects, MI has numerous applications in coal drying/dewatering, grinding, floatation, coal-water slurry combustion, pyrolysis and liquefaction [30].

Based on the known effects of temperature and electromagnetic fields on methane desorption, and the ability of MI to heat/fracture coal, the use of microwaves to promote methane desorption and increase CBM extraction efficiency has been proposed [31,32]. Recently, Hu et al. found that the methane adsorption of coal samples subjected to MI was lower than that of raw coal samples [33]. However, the methane desorption characteristics during the MI of samples were not assessed in this prior work, and so the impact of MI on methane desorption kinetics is still not clear. For this reason, the present work performed a laboratory-scale study to investigate changes in methane desorption over time both with and without MI. The kinetics of methane desorption without MI and with different MI exposure times were compared and the manner in which MI promotes methane desorption from coal is discussed.

2. Experimental

2.1. Experimental apparatus

The laboratory equipment used for this methane desorption study, shown in Fig. 1, consisted of a microwave generator, a gas adsorption and desorption canister, gas supply and measuring units, temperature measuring and control units and a vacuum pump. The microwave generator was a microwave oven (MM823LA6-NS, Guangdong Midea Microwave Development Manufacturing Co., Ltd., China). The adsorption/desorption canister was constructed of quartz glass, specially thickened to withstand a temperature of at least 800 °C and a pressure of at least 2 MPa. A well was attached to the mouth of the canister to allow the temperature in the center of coal sample to be measured in real time, using a thermocouple. The gas supply unit consisted of a gas cylinder, a reducing valve, a buffer tank, a precision pressure gauge and piping. The adsorption gas was high purity methane (99.99%). The gas measurement unit collected desorbed gas and determined the gas volume using water displacement. The vacuum unit consisted of a vacuum pump and gauge. The temperature measurement and control unit was composed of a K-type thermocouple, a digital temperature regulator/display and a filter capacitor. The filter capacitor was added to the end of the thermocouple to eliminate high frequency interference and "sparking" in the microwave oven that would otherwise result from the device. The digital temperature regulator was used to ensure safety and would cut off power to the oven if the coal temperature became too high.

2.2. Sample preparation

The anthracite coal used in this study was obtained from the Jiulishan coal mine in Jiaozuo, Henan province, China. This coal seam has a loose, broken structure and the mine is subject to dangerous gas outbursts. The physical parameters of the coal samples were analyzed according to Chinese national standards (Table 1). The analyses included ash content (A_{ad}), volatile matter (V_{ad}), moisture (M_{ad}), apparent relative density (ARD_{20}^{20}), true relative density (TRD_{20}^{20}) and porosity. The coal was ground and sieved through 0.5–1 mm metal sieves and then dried in an oven at 105 °C. After drying, samples were stored in a dry environment for later use.

2.3. Experimental procedures

Methane desorption experiments were carried out without MI and with varying MI exposure times, in each case applying an adsorption equilibrium pressure of 0.9 MPa.

(1) Methane desorption experiments without MI
   a. Degassing. The entire testing system was calibrated, the seals checked for tightness, and a 110 g coal sample was transferred into the adsorption-desorption canister. Valves 14 and 15 were opened and the sample was degassed using the vacuum pump for at least 6 h.
   b. Adsorption. Valve 14 was closed and valves 13 and 15 (connected to the gas supply unit) were opened. The canister was filled with methane to the desired pressure and held at the designated temperature for approximately 24 h to allow the apparatus to equilibrate.
   c. Desorption. After equilibration, the canister was vented to the atmosphere to rapidly discharge any unadsorbed methane in the canister. When the pressure in the canister dropped to atmospheric, valve 20 was immediately opened to connect the canister to the methane measurement unit. The volume of methane desorbed over time was subsequently recorded so that the desorption rate could be calculated.

(2) Methane desorption experiments with MI

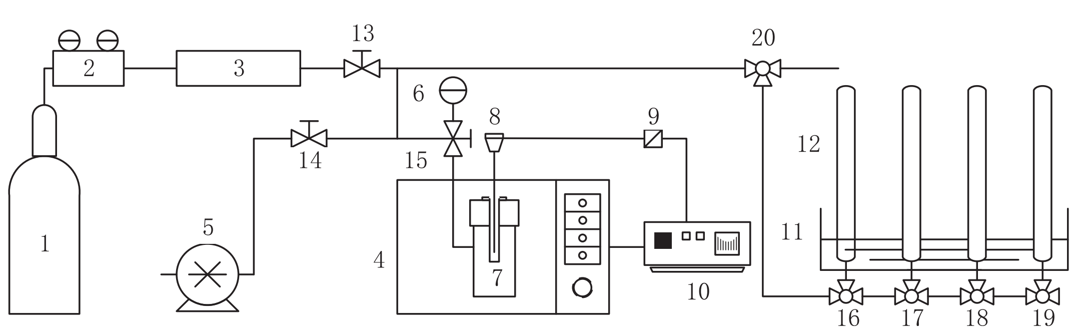

Fig. 1. Experimental apparatus used for measuring methane desorption during microwave irradiation. 1-Gas cylinder (99.99% CH_4), 2-Reducing valve, 3-Buffer tank, 4-Microwave generator, 5-Vacuum pump, 6-Precision pressure gauge, 7-Adsorption-desorption canister, 8-Thermocouple, 9-Filter capacitor, 10-Temperature digital display regulator, 11-Saturated salt water tank, 12-Gas measuring cylinder, 13–20-Valves.