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Full Length Article

# Microwave irradiation on pore morphology of coal powder

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ABSTRACT

An innovative microwave irradiation device is developed to investigate effect of microwave irradiation on pore morphology of coal powder. This device with several distinguished highlights, such as real-time infrared temperature measurement, gas replacement, process parameters controls, and large size samples testing. Specifically, results of effect of temperature (25–300 °C) and microwave power (1–6 kW) on pore morphology was evaluated by the mercury intrusion porosimetry method. The pore connectivity decreases at first then increased with incremental processing temperature or microwave power. The percolation threshold increases with increased heating temperature or microwave power. The total pores volume increases with increased processing temperature or microwave power. The total specific surface area increases firstly then decreases with increased temperature or microwave power. These suggest that effect of microwave irradiation on pore morphology is obvious. Several possibilities for microwave energy application in the field were discussed, including drilling borehole from the ground to the payzone, drilling up-hole or down-hole from the roadway to the payzone, drilling borehole along the coalbed. The process economics were also discussed. It implies that as a new technology microwave energy may have the potential for the degassing coal seams.

## 1. Introduction

As one of the most abundant fossil fuel in the world, coal plays an important role in the energy supply, especially in developing countries [1]. Nowadays, in the coal mining, there could be a series of gas accidents, such as gas outburst and explosion [2,3], which shows the importance of degassing coal seams before mining. Furthermore, coalbed methane (CBM) is a highly valuable and clean energy [4,5] and a more effective greenhouse gas than carbon dioxide [6]. Therefore, degassing coal seams could be a double-win strategy for coal mines safety and fulfilling energy consumption [7]. Currently, extremely low reservoir permeability of coalbed limits the production of CBM, especially in China [8]. Some measures are employed to assist mining CBM, such as deep-hole blasting [9], hydraulic fracturing [10], hydraulic slotting [11], $CO_2$ flooding [12], and $N_2$ flooding [13]. However, these methods may be not always effectively when the coal seam has faults, caves, or large cracks penetrating the ground [14]. A microwave heating method, based on a downhole radiating antenna, is less affected by geology formation and is capable to distribute heat over a large reservoir volume due to the propagation of electromagnetic energy through the medium [15]. This microwave heating method has the advantages of rapid heating, material selective heating, volumetric heating and high efficiency in energy transfer [16].

Pore morphology, including pore volume, surface area, pore size distribution, pore shape, connectivity and fractal dimension, are crucial for gas adsorption and transport behaviors [17,18]. Microwave irradiation has effects on pore morphology of coal. Zhao et al. [19] found that a large number of volatiles were released during microwave pyrolysis, which results in an increase in pore volume and specific surface area of lignite. Ge et al. [20] also indicates pore volume and surface area of low-rank coal increased after microwave irradiation treatment. Kumar et al. [21] observed fracture volume increased after microwave exposure by X-ray computed tomography. In addition, pore size of low-rank coals would increase with microwave energy and the fractal dimensions of low-rank coals would decrease after microwave treatment [22,23]. These results above simply reveal qualitative relation between microwave irradiation and pore parameters of coal. Unfortunately, there is poorly work focus on the quantitative effect of processing temperature and microwave power on pore morphology of coal. This aspect is critical in optimizing the microwave heating for degassing CBM.

In this study, we developed a microwave irradiation device for investigation of temperature and microwave power affecting on pore morphology of coal powder. Involved indexes in the experiments include pore connectivity, pore volume distribution, percolation threshold and specific surface area distribution. The pore structure of

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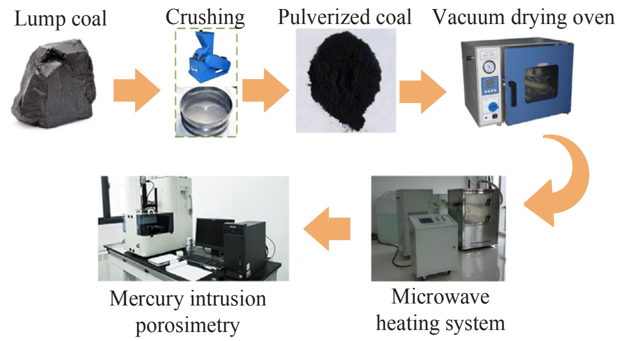


**Fig. 1.** Experimental procedure.

coal powder was measured by the mercury intrusion porosimetry (MIP). Then we discussed the effect of heating temperature and microwave power on pore morphology of coal samples.

## 2. Experimental methods

In these experiments, coal powder samples were treated by a microwave heating system. The pore structure (mainly including pore size, pore connectivity and specific surface area) was measured by mercury intrusion porosimetry (MIP) in order to determine the effect of microwave irradiation on pore morphology of coal samples.

### 2.1. Experimental processes

The experimental procedure, including coal samples preparation, microwave treating, and MIP measurement was carried out in accordance with the scheme (Fig. 1). Coal samples preparation is described in Section 2.2. The microwave treating is carried out by a microwave heating system, which is presented in Fig. 2. And mercury intrusion porosimetry is presented in Section 2.4. The research objective was to quantitatively evaluate effect of heating temperature and microwave power on pore morphology. Experimental program is as shown in Table 1 including two groups of experiments (A and B in Table 1). A is a group of experiments considering temperature effects; B is a group of experiments considering microwave power effects. It should be noted that nitrogen is charged into the resonator until the oxygen concentration is zero. This is to reduce the possibility of coal burning during microwave heating. In addition, the design of maximum experimental temperature (no more than 300 °C) is avoid occurrences of coal pyrolysis, forming gases and tars [24]. The pyrolysis gas could influence the accuracy of temperature measurement by the infrared radiation thermometer. The pyrolysis tars may block the pore structure and influence mercury intrusion porosimetry measurement.

**Table 1**
Experimental program.

| Number | *T* (°C) | *MP* (kW) | *OC* (%) | *W* (g) | Container | |
|---|---|---|---|---|---|---|
| | | | | | material | dimension |
| A | 100, 200, 300 | 3 | 0 | 100 | quartz | 50 mm in diameter and 100 mm in height |
| B | 150 | 1, 2, 3, 4, 5, 6 | | | | |

*Notes*: *T* is the processing temperature; *MP* is processing microwave power; *OC* is oxygen concentration; *W* is mass of coal samples.

### 2.2. Coal samples

Several raw coal samples were collected from underground mines of the Guandi Coal Mine, Taiyuan, China. Raw coal samples were crushed and sieved in the range 1.00–2.00 mm prior to experiments. The reason to crush coal samples is analytical methods/techniques used for estimating porosity and pore size distribution have their own sample size ranges [25]. It should be noted that for the coal sample crushed, the whole pore structure did not get destroyed, especially the micropores and mesopores. Therefore, the experimental results can indicate the effect of microwave heating on the pore morphology of coal samples. Coal maceral compositions are as shown in Table 2.

### 2.3. Microwave heating system

Microwave radiation is the term associated with an electromagnetic radiation in the microwave frequency range (300 MHz–300 GHz). However, the most commonly used frequencies for heating purposes are 915 MHz and 2450 MHz, which were chosen by international agreement to minimize the interference with communication services [26]. The experiments were carried out in a microwave heating system with a frequency of 2450 MHz ± 25 MHz (Fig. 2). This system consists of a heating subsystem, a temperature measurement subsystem, a gas exchange subsystem, a cooling subsystem, and a control subsystem. And the heating subsystem consists of two magnetrons, two rectangular waveguides, and a multi-mode cavity. The microwave power varies from 0 to 6 kW with defined exposure time. The temperature measurement subsystem consists of an infrared radiation thermometer and a data collecting instrument. The measuring probe is equipped in the cavity. The gas exchange subsystem consists of a vacuum pump, gas

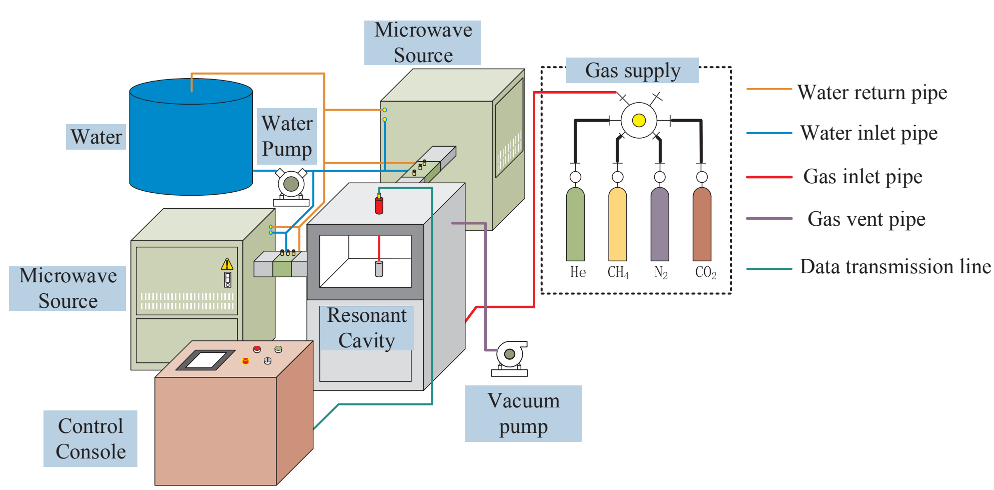


**Fig. 2.** Schematic of microwave heating system.