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Research article

Kinetic analysis on the microwave drying of different forms of water in lignite

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ABSTRACT

A Chinese raw lignite with total water (RC) and molecular water (MWC) were prepared. Those samples were dewatered by a microwave drying equipment using constant power selected from 450–600 W. The first order reaction kinetic equation and ten thin-layer drying models were used to analyze the dewatering processes of MWC and RC respectively. Moreover, the effective diffusion coefficient of water, the activation energy of the water removal and the drying rate constant (k) were calculated. The first order reaction kinetic equation and the Two-term exponential model provided a better fit for the drying processes of MWC and RC respectively. The effective diffusion coefficient of water obtained by Fick's second law varies from 0.3708×10^{-8} to 1.6715×10^{-8} $m^2 \cdot min^{-1}$ for MWC and from 0.5099×10^{-8} to 3.3169×10^{-8} $m^2 \cdot min^{-1}$ for RC. The activation energy for the removal of the molecular water is 28.59 $kJ \cdot mol^{-1}$, and that for the total water is 24.25 $kJ \cdot mol^{-1}$. The k of MWC and RC are in the range of 0.0894–0.4364 min^{-1} and 0.2737–1.4740 min^{-1} respectively. From the energy consumption aspects, it is suggested the microwave power higher than 550 W should be used to remove the free water and capillary water, and 525 W used to remove the molecular water.

1. Introduction

With the consumption of high-quality coal increasing and the amount of its storage decreasing, the exploitation and utilization of lignite, being abundant reserves in China, has attracted more and more attention. However, its high water content (25%–65%) results in low heat value, high transportation cost and low utilization efficiency [1–3]. Therefore, it is necessary to effectively remove the water from lignite before its utilization [4,5]. The water in the lignite includes the free water in the external and macropores, the capillary condensation water in the capillary porosities and the multilayer and monolayer adsorption water bounded to the internal surface area of pore structure in the coal [6–11]. And the multilayer adsorption and monolayer adsorption water is also named the molecular water [12]. The different existent forms of water results in the variation of the activation energy of removing the water, which makes the various kinetic characteristics in different drying stages.

The drying methods are mainly divided into evaporation drying and non-evaporation drying. Evaporation drying methods generally include microwave drying, solar drying, steam-fluidized bed drying and flue gas drum drying. Non-evaporation drying methods include hydrothermal dewatering [13,14] and mechanical thermal expression dewatering [15,16] Among these drying techniques, microwave drying has some potential advantages such as the high drying efficiency, high selectivity and the homogeneity of heating [17], and thus has attracted many researchers, concentration. For the microwave drying, the heat transfer and mass transfer are in the same direction, which is different from other drying ways. These transfers would affect the kinetic behavior of the water removal. Some kinetic models were reported to describe the drying process of coal, e.g. semi-theoretical, and empirical models [18–24]. But almost all researches about the kinetics of microwave drying coal are about the whole drying process of removing the total water, and few researchers have studied the kinetic of the process of only removing the molecular water and its difference from dewatering the total water in the microwave drying process.

The free water can be removed by mechanical dewatering methods. The capillary condensation water can be removed partially, depending upon the size of the openings in the coal surface and the drying temperature, but the molecular water can be removed only by the thermal drying processes [25]. Therefore, after a period of storage, the free water and capillary water in lignite may have been removed partially. However, the molecular water is difficult to be removed in the natural environment. So, researching the drying behaviors of the lignite only with molecular water is necessary. It is effective to remove the molecular water with microwave because of the advantages of microwave radiation for drying lignite. For the purpose of gaining the further

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Nomenclature

A	pre-exponential factor
D_{eff}	effective moisture diffusivity ($m^2 \cdot min^{-1}$)
E_a	apparent activation energy ($kJ \cdot mol^{-1}$)
F	the value of F-test
k	drying rate constant (min^{-1})
L	radius (m)
MR	moisture ratio
P	power (W)
R^2	coefficient of determination
R	gas constant ($kJ \cdot mol^{-1} \cdot K^{-1}$)
RSS	residual sum of squares
t	time (min)
T	temperature (°C)
χ^2	reduced Chi-Sqr

understanding of the drying mechanism and kinetics, we explored the drying behaviors of a Chinese lignite in removing the molecular water process and the total water in microwave fields of different powers in nitrogen condition. What's more, a suitable condition for microwave drying of lignite with different water was proposed to reduce the energy consumption according to the analysis results. The comprehensive analysis for this process could help to design a suitable drying technological process and obtain optimized drying parameters, which are important for industrialization of microwave drying.

2. Experimental

2.1. Sample preparation

The lignite used in this study was from Inner Mongolia, which is the largest lignite producer in China. The raw coal was ground and sieved to the particle size in range of 0.38–0.83 mm in a nitrogen glove box. The raw coal sample with total water was prepared with this method and named RC. The proximate and ultimate analysis results of RC are shown in Table 1. The M_{ar} represents the total water content on received basis, which was measured at 393.15 K in nitrogen according to the Chinese national standard GB/TB 212-2008.

In order to prepare coal samples only with molecular water, the isothermal drying experiments were conducted with MB45 Halogen water meter (OHAUS Rich Ocean International Trading Limited, USA). The equipment contains a balance to weigh the sample, a rapid-heating system to heat the sample, and a computer to record the sample mass online. For this experiment, 3 g RC was heated to 110 ± 2 °C rapidly in nitrogen with a flow rate of 1 $L \cdot min^{-1}$. The water content (M, $g \cdot g^{-1}$ db) of sample and the drying rate (DR, $g \cdot g^{-1} \cdot min^{-1}$ db) at an arbitrary time (t, s) during the drying process are calculated by Eqs. (1) and (2), respectively. The drying rate (DR) vs. water content (M) during isothermal drying of the RC sample is shown in Fig. 1.

$$M = \frac{m_t - m_{db}}{m_{db}} \tag{1}$$

$$DR = -\frac{dM}{dt} = -\frac{M_{t+dt} - M_t}{dt} \tag{2}$$

where, m_t (g) is the sample mass at t; m_{db} (g)is the mass of the dry basis of RC. M_t and M_{t+dt} ($g \cdot g^{-1}$ db) are the water content at the t and $t + dt$, respectively.

As shown in Fig. 1, the isothermal drying process of RC at 110 °C consists of four stages, which are the increasing rate stage, the short constant rate stage, the rapid decreasing rate stage and the slow decreasing rate stage. As reported by our previous study [26], the water liberated in the increasing rate stage and the short constant rate stage is free water in the external and macropores of the raw coal, the water dewatered in the rapid decreasing rate stage is the capillary condensation water, and molecular water is removed in the slow decreasing rate stage. The free water, the capillary condensation water and the molecular water content of RC are M_0–M_1 (0.16 $g \cdot g^{-1}$ db), M_1–M_2 (0.15 $g \cdot g^{-1}$ db) and M_2 (0.23 $g \cdot g^{-1}$ db) respectively. Then RC samples were dried at 110 °C in nitrogen. When the water content decreased to M_2, the dried samples were rapidly cooled to room temperature. The coal samples only with the molecular water prepared by this method were named MWC.

Table 1
Proximate and ultimate analyses of RC.

Proximate analysis (wt%)				Ultimate analysis (wt%, daf)				
M_{ar}	A_{ad}	V_{ad}	V_{daf}	C	H	O[a]	N	S
35.15	22.27	24.83	45.06	74.07	3.77	19.31	1.07	1.78

M, A and V refer to the moisture, ash and volatile content respectively.
ar: as received basis; ad: air-dried basis; daf: dry ash-free basis.
[a] By difference.

2.2. Microwave drying experiment

The microwave drying equipment consist an electronic balance, which was connected to a computer to record the sample mass online designed by ourselves, a microwave furnace to generate the microwave, an infrared thermometer to measure the temperature and a columniform crucible made of quartz glass with a height of 40 mm and diameter of 32 mm to contain the coal sample, as shown in Fig. 2. The infrared thermometer directly measures the temperature of the wall of the crucible, which is different from the real temperature of the coal sample. Therefore, before performing the experiment, the temperature needs to be calibrated. The calibration result is shown in Fig. 3, the temperature in this experiment is the temperature after calibration. For the microwave drying experiments, the mass of the coal sample (MWC or RC) was 3 g. The microwave power used was 450 W, 500 W, 525 W, 550 W, 575 W, or 600 W for each run. The microwave drying experiments were carried out under constant power. The drying experiment is non-isothermal. Fig. 4 shows the temperature and the drying time of the coal sample in different microwave power. The drying time for RC is 4.25 min. The drying time of MWC under 450–525 W, 550–575 W, 600 W is 9.75 min, 6.75 min and 3.75 min respectively.

Before microwave drying, the sample was put into the quartz

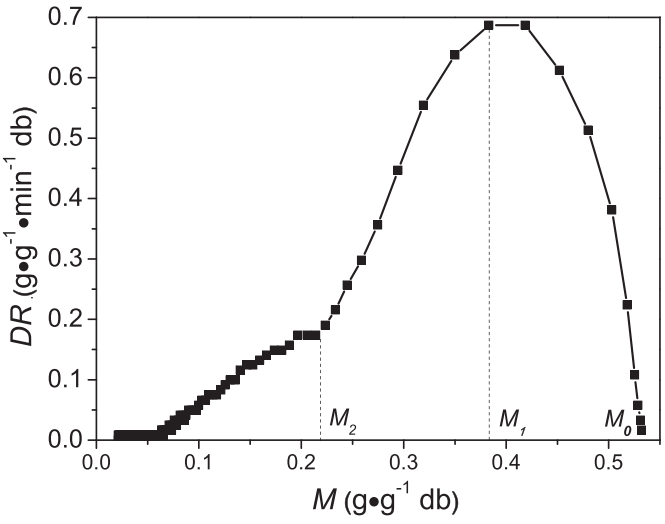

Fig. 1. Drying curve of RC in isothermal drying process at 110 °C.