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Microwave drying of a low-rank sub-bituminous coal

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ABSTRACT

The moisture contents of coals are often too high and need to be reduced before further processing. In this study, the application of microwave radiation as an alternative energy source for the drying of a sub-bituminous coal was investigated. Firstly, the permittivities of the coal were evaluated as a function of temperature and frequency. Secondly, the drying kinetics were studied in a 2.45 GHz microwave system and the effects of incident microwave power, sample mass and initial moisture contents were determined. The results demonstrated that microwave drying had several advantages over conventional drying such as increased drying rates and lower final moisture contents. In some tests, magnetite was added as a susceptor to increase the drying rates. Thirdly, the drying data were fitted to ten exponential decay models, and although reasonable agreement was observed with all the models, the best fit was obtained with the Midilli–Kucuk model. Finally, the effective diffusion coefficients of moisture and also the activation energy of the diffusion process were estimated and used to further elucidate the mechanism of microwave drying.

1. Introduction

Mined high-rank coals (HRC's) can have moisture contents in the range of about one to six percent. Some HRC's are cleaned, usually by wet techniques and these coals can have moisture levels between 12% and 25%. For a given set of conditions, the moisture content of the coal increases with decreasing particle size, because the larger surface area of the fine coal enhances its capacity to retain moisture. Furthermore, low-ranked coals (LRC's) can have moisture contents above 25%. Currently, LRC's are not widely exploited but their use is expected to increase as a result of the growing demand for energy. The presence of high levels of moisture results in higher transportation costs, greater energy requirements, increased off-gas volume, lower efficiencies, increased maintenance costs and increased friability of the coal, which interferes with separation, blending and pneumatic transportation. Additionally, dusting is enhanced and the potential for spontaneous combustion increases (Sevi, 1995). Consequently, the efficient removal of water is of significant importance in coal processing. Conventional mechanical dewatering techniques such as centrifuges and vacuum filters can reduce the moisture content of the coal to between 10% and 15%, but this still may not meet the quality specifications for subsequent processing. Thermal drying is the most widely employed method to lower the moisture content. In these types of processes, heat energy is transferred to the surface by convection and to the interior by conduction. Industrially, drying is generally achieved by contacting the wet coals with hot gases from a combustion process. The most common types of dryers are rotary dryers, multi-louver dryers, fluidized-bed dryers, screw conveyor dryers and flash dryers. Generally, traditional coal drying processes have environmental issues and in some cases potentially explosive stack mixtures.

Microwave radiation has a number of potential advantages for the processing of coal such as desulphurization (Viswanathan, 1990; Uslu and Atalay, 2003; Rowson and Rice, 1990; Hayashi et al., 1997) and in particular for drying. Conventional drying systems rely on heat transfer to the surface of the material followed by conduction of heat through the particles. This is a slow process and depends on the size of the particles, the properties of the material being heated and the process conditions. In order to heat the interior of the material and thus remove the trapped water, it may be necessary to overheat the surface. On the other hand, microwave radiation can provide a volumetric heating technique, in which the electromagnetic radiation transfers the energy into the interior of the particle. This facilitates the rapid removal of the water and also potentially lowers final moisture levels. Additionally, since the microwave absorption characteristics of water are superior to those of the coal, selective heating may be possible. Furthermore, the drying process could be self-limiting, since as the water is removed, then the amount of microwave energy absorbed decreases. Consequently, it may be possible to minimize overheating of the surface of the coal, which often occurs in conventional drying.

One of the earliest studies on the microwave drying of coals was performed by Lindroth (1986) at the U.S. Bureau of Mines. Bituminous, sub-bituminous and lignite coals were dried on a conveyer belt microwave oven at 2.45 GHz and 12 kW. Drying efficiencies,

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near the theoretical limit of 1.54 kg/kW h, could be achieved. Standish et al. (1988) reported that the rate of moisture removal from a brown coal was one to two orders of magnitude faster than conventional convective drying. Seehra et al. (2007) investigated the dewatering of a fine coal slurry sample by both conventional thermal and microwave drying at 2.45 GHz and 800 W. The comparative thermogravimetric analysis (TGA) results clearly showed a significant advantage of microwave drying, in terms of reducing the drying time by a factor of nearly ten. Zimmermann and Niemann-Delius (2007) showed that the microwave drying rates were extremely fast and some cracking of the particles was observed. Chatterjee and Misra (1991) developed a numerical model, which when combined with electromagnetic and thermal models, allowed calculation of the electromagnetic energy absorption profile. From this, the temperature distributions in the coal particles during drying could be predicted as a function of time, power and frequency. Harrison and Rowson (1997) demonstrated that the Bond Work Index could be reduced by 30% after short exposures of the coal to microwaves. The reduction in the relative Bond Work Index was attributed to the cracking initiated around pyrite grains and pressures generated by the superheating of water in the porous coal structure. Marland et al. (2000) reported an approximate 50% reduction of the Bond Work Index after microwave treatment. Again, they suggested that gaseous evolution (water and volatile matter) as well as gangue mineral expansion were the possible causes for the improved grindability. Lester and Kingman (2004) demonstrated that microwave radiation produced physical changes, such as cracks and fissures in coal, even for short processing times. Toraman and Depci (2007) treated a lignite coal with microwaves and found that the rapid expansion of moisture resulted in cracking and improvements in the grindability.

In the absence of a magnetic field, microwaves generate an electric field in the material of interest and the interaction of this electric field with a given material is fundamentally determined by the complex permittivity (ε), which is defined by the following equation:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

Here ε' is the real part of the permittivity and is referred to as the dielectric constant, ε'' is the imaginary part of the permittivity and is called the loss factor or dielectric loss, and j is the imaginary component in the +j-axis direction ($j = \sqrt{-1}$). The dielectric constant (ε') determines the penetration depth of the applied electric field into the irradiated material. The dielectric loss (ε'') controls the amount of microwave energy converted to heat in the material. The permittivities are dependent on the mobility of the dipoles within the structure, and therefore are functions of temperature, frequency and composition. Although knowledge of the permittivities is useful for understanding the interaction of microwaves with any given material, the actual microwave processing of a material is much more complex. Other factors which influence the interaction are; the thermal conductivity of the sample, the heat capacity of the sample, the geometry of both the sample and the microwave cavity, the bulk density, the power level, the particle size, the sample mass or sample size, the presence of susceptors or coupling agents and the occurrence of chemical reactions or phase changes.

Although considerable research has been performed on the potential advantages of microwave drying of coal, there is a paucity of information regarding the underlying fundamental processes. In the present work, firstly permittivity studies were performed on the Highvale coal, in order to determine the effects of frequency and temperature. Secondly, the microwave drying rates of the coal were studied as a function of incident microwave power, sample mass, initial moisture content and magnetite additions and also compared to conventional drying. Thirdly, the microwave drying data were fitted to a number of thin-layer exponential decay drying models. Finally, the drying rate data were utilized to determine the diffusion coefficients and the activation energy for the process. This information was utilized to further understand the microwave drying process.

2. Experimental

2.1. Raw materials

The sub-bituminous coal sample was obtained from the Highvale Mine in Alberta, Canada. The coal was processed in a manner so as to produce a homogeneous sample for the drying tests. A total of 27.5 kg of the coal with an average particle size of over 25 mm was reduced to a size range of 2.36–4.75 mm (8–4 mesh) using a laboratory jaw crusher followed by a gyratory crusher. Then the coal sample was passed through a roll crusher and screened with a 10 mesh (1.7 mm) sieve. The oversize coal was repeatedly returned to the roll crusher until the entire sample passed through the 10 mesh screen. The sample was homogenized in a mixing drum for 20 min and placed into two sealed containers to limit moisture changes as much as possible. The homogeneous sample was screened to provide a control size fraction of $-12+16$ mesh ($\bar{x} = 435$ μm), plus an additional size fraction of $-200+270$ mesh ($\bar{x} = 63.5$ μm). The samples were sealed in plastic bags to minimize moisture changes. The proximate and ultimate analyses of the coal are shown in Table 1. The coal has medium level volatile matter and fixed carbon, with relatively low ash and sulfur contents. The moisture content of the $-12+16$ mesh ($\bar{x} = 1435$ μm) as-received coal was 12.5%. In order to investigate the effect of initial moisture content, an additional two coal samples were prepared with the following moisture contents: partially dried; 10.5% ($\bar{x} = 1435$ μm) and hydrated; 21.3% ($\bar{x} = 1435$ μm).

2.2. Microwave and conventional drying systems

A schematic diagram of the microwave drying system is shown in Fig. 1. A programmable Sylvania SM80704 microwave oven with a maximum power output of 800 W was used. The magnetron produces microwaves with a frequency of 2.45 GHz from a 120 V to 60 Hz AC power supply. The multimode cavity dimensions were: 30 cm in length, 30 cm in width and 23 cm in height. The samples were suspended from an Ohaus Adventurer™ Pro balance, which had an accuracy of 0.01 g and provided a continuous record of the mass of the sample as a function of drying time. The coal sample in a quartz crucible was suspended on a Teflon thread, which passed through a 6 mm diameter central hole in the top of the cavity. The quartz crucible had the following dimensions: 8.5 cm in height, 3.2 cm in diameter and 0.15 cm in wall thickness. The quartz crucible and Teflon thread used in the microwave drying system were essentially transparent to microwaves. Preliminary tests showed that in the microwave system, the coal sample would not dry at low sample masses, low incident powers and/or low irradiation times. On the other hand, the coal would evolve volatile matter, exhibit hot spots and combust at long irradiation times, high incident powers and/or large sample masses. Since the aim

Table 1
Ultimate and proximate analyses of as-received Highvale coal on a dry basis.

Ultimate analysis	Mass%	Proximate analysis	Mass%
Carbon	61.00	VM	33.21
Hydrogen	3.64	Ash	16.85
Nitrogen	0.63	FCM	49.81
Sulfur	0.31	Total water	12.78
Oxygen	17.26		