



Effect of moisture on dehydration and heat transfer characteristics of lignite in low temperature carbonization furnace



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ABSTRACT

Dehydration of lignite primarily occurs in two stages, namely, removal of surface moisture and decrease in oxygen-containing functional groups and moisture stage. Moisture on the lignite surface could be removed at temperatures below 100 °C. However, parts of oxygen-containing functional groups were removed first followed by the removal of the adsorbed moisture at temperatures in the range 100–300 °C. Dehydration time increased with an increase in the dehydration load and heat transfer distance. At surface moisture of 7 wt.%, temperature of lignite increased rapidly. Higher temperature of combustion chamber yielded shorter removal times for surface moisture and oxygen-containing functional groups. Based on the rate of increase of lignite temperature and associated heat transfer process, coking chamber could be divided into three zones: the near, middle, and remote zones. The near zone temperature curve was determined to be a convex function ($\frac{\partial^2 T}{\partial r^2} \leq 0$); however, the middle zone temperature curve was determined to be a concave function ($\frac{\partial^2 T}{\partial r^2} \geq 0$). $\frac{\partial^2 T}{\partial r^2} = 0$ and $\frac{\partial T}{\partial r} = k$ were the boundary indices of the middle and remote zones. 100 °C isothermal surface movement rate was found to be affected by the heat transfer capacity and dehydration load. Center temperature distribution of coking chamber was made uniform by steam, and temperature of HM_{7%} was the most uniform distribution.

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1. Introduction

Lignite is a low rank coal which is mainly used for electricity generation because of certain advantages such as high reactivity and high amount of volatiles. However, high amount of moisture (10–50 wt.%) in lignite leads to lower plant efficiency, higher transportation cost, and potential safety hazards during transportation and storage. Moreover, lignite is also prone to air-slake and spontaneous combustion when it is air-piled. In order to completely utilize lignite and to improve its product quality, it must be dehydrated before transportation [1–3]. Low-temperature carbonization of lignite leads to the formation of valuable coke oven gas (caloric value, 16 MJ/Nm³), tar (3–12 wt.%), and semi-coke (W_{ad}, 45–65 wt.%), thus making the low-temperature carbonization of lignite to be one of the preferred methods in industry for many years. Therefore, recently, significant research efforts have been focused on the moisture content, dehydration characteristics, heat transfer, and low-temperature carbonization process of lignite [4–10].

Moisture present in lignite includes external moisture, inherent moisture, and water of constitution. Yu et al. [4] studied the fundamental aspects of moisture occurrence in lignite and its effects on physical and chemical structure of lignite. They concluded the existence of moisture in lignite, and reported that abundant hydrophilic oxygen-containing functional groups could generate hydrogen bonds with

water molecules and adsorb them on the coal surfaces, thus resulting in absorption of moisture by lignite. The macroporous structure and capillary tubes of lignite contain several oxygen-containing functional groups which adsorbed water molecules and formed about 4–5 molecular layers of water. With an increase in the temperature, a large amount of surface moisture was first removed, and then the moisture in these macropores and capillary tubes were squeezed out due to coal heating and channel shrinkage. Moreover, with an increase in the temperature, oxygen-containing functional groups, such as phenolic groups (>150 °C), carboxylate groups (>150 °C), alcoholic groups (>200 °C), and O–H and CO groups (250 °C) were partially removed [14,15]. A high-temperature drying model for a single particle was established by Chen et al. [5]. The order of removal of the four types of moisture in lignite was found to be bulk, capillary, physisorbed and chemisorbed moistures. It was concluded that the particle size, flow rate, and drying process temperature were significantly affected by the dehydration process. It was believed that oxygen-containing functional groups could be partially removed when the temperature was over 300 °C, the adsorbed moisture connected with them by hydrogen bonds and the hydrophilic or moisture-holding capacity of lignite could also be progressively removed from the coal. Jin et al. [6] proposed the occurrence of three stages of dehydration during the coking process: the moisture condensation period (T₀–T₁, 20–70 °C), the constant-rate drying period (T₁–T₂, 70–150 °C), and the deceleration drying period (T₂–T₃, 150–300 °C). Zheng et al. [7] investigated the drying kinetics of lignite in nitrogen environment, and the constant-rate time of drying

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Nomenclature

A	ash content, wt.%
M	moisture content, wt.%
FC	fixed carbon content, wt.%
Ad	air dried basis
h	convective heat transfer coefficient, (W/m ² · K)
H_i	heat transfer distance or length between furnace wall and S_i plane in coking chamber, (mm)
k_{gas}	gas correction coefficient
k_{air}	excess air ratio
L_{vapor}	vapor latent heat, (KJ/kg)
M_i	the mass of the lignite between furnace wall and S_i plane, (kg)
$t_{SM,x\%}$	the removal time of the Hemei lignite with 0, >0, 7, 15 or 30 wt.% surface moisture, (min)
t_{FG}	the removal time of the oxygen-containing functional groups, (min)
t_{total}	the total time including the removal of dehydration and oxygen-containing groups & moisture, $t_{total} = t_{SM} + t_{FG}$, (min)
q	heat flux, (J/m ² · s)
S_i	the $No.i$ surface isothermal in the coking chamber
T_i	the temperature of the $No.i$ thermocouple in the coking chamber, (°C or K)
$T_{R,average}$	the average temperature of the combustion chamber, (°C or K)
m_{vapor}	vapor mass flow, (kg or g)
$S_{100, °C}$	the lignite completes the dehydration and begins the functional groups removal stage in this 100 °C isothermal surface

Greek symbols

α	thermal diffusion coefficient, (m ² /s)
λ	heat conductivity coefficient, (W/m · K)
τ	carbonization time, (sec)
ϕ	heat flux, (W/m ²)

Subscripts

COG	coke oven gas
CMC	coal moisture control
HM _{0%}	Hemei lignite is bought from Inner Mongolia and air dried, the added free moisture is 0 wt.%, but it has the initial internal and external moisture.

was found to decrease at higher temperatures. Simultaneously, high temperature prolonged the time of deceleration drying, which was indicated by the water vapor diffusion activation energy from 49.42 to 106.37 kJ/mol during dehydration process when the particle size was from 10 to 25 nm. Lignite was carbonized by the Nippon Steel Corporation to remove water using Coal Moisture Control (CMC) [8,9]. In this process, the pretreatment involved the combustion flue to dehydrate the lignite, and the moisture content of lignite was reduced by the CMC process. When the moisture content dropped to 6%, coke with the highest quality was obtained.

Atkinson et al. [10] used the one-dimensional heat flow equation to establish a coking chamber heat transfer model including several factors, such as the carbonization temperature distribution, energy consumption, the coefficient of thermal conductivity, and so on. The water evaporation model was proposed at 100 °C; however, the moisture of lignite could not be completely removed by the dehydration process of low rank coal. Yip and Jin et al. [11,12] studied the effect of temperature, moisture and ash on the moisture evaporation of lignite. The

moisture in in-situ gasification and the reforming reaction for semi-coke and volatiles have been discussed. In this study, water-semi coke gasification, water-pyrolysis gas reforming, and pyrolysis gasification dynamic models were obtained, respectively. The low-temperature carbonization process and the semi-coke characteristic have been described in the literature reports; however, moisture removal and heat transfer processes have rarely been reported. Based on a furnace body structure using high heat conductivity, cast iron furnace walls have been developed by our research group [13]. Increase in the lignite temperature affected the surface moisture. The characteristics of temperature curve with different moisture content were discussed during the low-temperature carbonization process, and the characteristics of 100 °C interface were analyzed.

2. Experiment

2.1. Material

Hemei lignite (HM) was bought from Inner Mongolia. The results of proximate analysis and ultimate analysis are listed in Table 1.

The diameter of HM ranged from 3 to 15 mm. Added water formed a monolayer or multilayer free surface moisture on the coal surface. Lignite with different amount of free surface moisture was described as HM_{0%}, HM_{7%}, HM_{15%}, and HM_{30%}; raw lignite was represented as HM_{0%} (i.e., free moisture dosage 0%; however, the initial moisture content of lignite was 11.34 wt.%).

The gas volume was adjusted by modifying the furnace wall and combustion chamber temperature. An air blower was used to provide a gas volume of 6–9 m³/h. The gas volume was measured by a rotameter. The gas volume was calculated by multiplying the gas rotameter readings by a correction coefficient k_{gas} equal to 1.587. The composition of the coke oven gas, used in the combustion chamber, is listed in Table 2.

2.2. Apparatus

In this study, a carbonization furnace consisting of combustion and coking chambers was used. Fig. 1 shows the side view of the combustion and coking chambers.

Fig. 1 exhibits that both these chambers have hollow box-like structures sharing a common cast iron wall (the furnace wall). The coking chamber is an 1180 × 310 mm slot to place coal, with a rectangular discharging port at the bottom. Inside of the coking chamber is made of refractory cast iron. The periphery of the combustion chamber is covered by a high-temperature-resistant clay brick and an insulating cotton material to reduce the associated heat loss. The carbonization furnace was developed by our research group [13]. The coke oven gas and air moved through the gas and fired in the combustion chamber, respectively.

There are rows of thermocouple slots (T_1 to T_6) at heat transfer distances of 10, 50, 150, 200, 250, and 300 mm. The thermocouples are inserted into the middle part of the coal bed. According to the temperature profile, the coking chamber could be divided into three zones: near, middle and remote zones. S_1 is located in the near zone; S_2 , S_3 , and S_4 in the middle zone; and S_5 and S_6 in the remote zone. The method used to divide the zones is illustrated in the subsequent sections.

Table 1

Proximate analysis and ultimate analysis (wt.%).

Sample	Proximate analysis				Ultimate analysis				
	A_{ad}	V_{ad}	FC_{ad}	M_{ad}	C_d	H_d	O_d^a	N_d	$S_{t,d}$
HM lignite	14.24	31.62	42.80	11.34	70.79	5.61	11.32	1.36	0.42

^a By difference.

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