Journal of Analytical and Applied Pyrolysis 117 (2016) 228–235

Contents lists available at ScienceDirect

Journal of Analytical and Applied Pyrolysis

journal homepage: www.elsevier.com/locate/jaap

Characteristics of lump lignite pyrolysis and the influence of temperature on lignite swelling in underground coal gasification

Jianfen Xi[a,b], Jie Liang[a,*], Xunchao Sheng[a], Longxi Shi[a], Shuang Li[a]

[a] School of Chemical and Environmental Engineering, China University of Mining & Technology (Beijing), Beijing 100083, PR China
[b] ENN Coal Gasification Mining Co., Ltd., Langfang 065001, PR China

ARTICLE INFO

Article history:
Received 14 June 2015
Received in revised form
20 November 2015
Accepted 21 November 2015
Available online 2 December 2015

Keywords:
Underground coal gasification
Fissure
Swell
Lump coal
Pyrolysis
Lignite

ABSTRACT

Underground coal gasification (UCG) allows *in situ* conversion of unmineable coal deposits into a combustible gas. UCG involves a number of steps, including combustion, oxidation–reduction (REDOX) reactions, pyrolysis, and drying, within the gasification channel at high temperatures. Pyrolysis, in particular, plays a vital role in UCG. We herein investigated the pyrolysis behavior of lump lignite from Inner Mongolia, China, and investigated the influence of pyrolysis on the swelling behavior of the lump lignite. The samples ($50 \times 40 \times 40\,mm^3$) were studied at a heating rate of 3 °C/min. The resulting chars were analyzed by scanning electron microscopy and Fourier transform infrared spectroscopy. In addition, the composition of the pyrolysis gas released from lump lignite was compared with that released from particle lignite (particle diameter = 1 mm). The results showed that obvious swelling between 100 and 600 °C, followed by subtle swelling events between 600 and 900 °C. The concentrations of H_2 and CO gases in lump lignite were higher than those in particle lignite when exposed to elevated temperatures, and the main functional groups disappeared at high temperatures due to thermal cracking. Consequently, pyrolysis occurring in the gasification channel converted the coal around the channel into a highly porous char whose permeability aided the transport of gasification agents and product gases in coal seam.

1. Introduction

Underground coal gasification (UCG) converts unmineable coal deposits *in situ* into a combustible gas using controlled thermal effects and chemical reactions. The gas obtained from the UCG process can subsequently be used to generate electricity or serve as a chemical feedstock [1–5]. UCG integrates shaft construction, traditional mining, and surface coal gasification to exploit coal deposits located within steep, highly inclined seams or whose economic value is cost prohibitive for conventional mining recovery [6–9]. The UCG setup consists of two vertical shafts drilled into a coal deposit, which are connected by a gasification channel. The gasification channel includes either a directional drilling channel or forward/reverse combustion channel formed by thermal penetration. The degree of thermal penetration is primarily influenced by pre-existing flaws, cracks, and cleats within the coal deposits, affecting the flow of gasifying agents such as oxygen, air, or steam, and the transport of the resulting product into the gasification channel [10].

The coal present around the gasification channel undergoes a range of processes, including combustion, oxidation–reduction (REDOX), pyrolysis, and drying [11], resulting from the high temperature associated with UCG [12]. Coal pyrolysis from the gasification channel enhances the heating value of the gas and affects the remnant char structure for subsequent combustion and gasification activity [13]. The newly formed cracks and apertures originate from the release of volatile matter and moisture content within the coal deposits [11].

Lignite accounts for approximately 23% of the world's coal reserves [14] and economically is considered unrecoverable in terms of mining *via* traditional methods, such as opencast mining, due to its relatively high volatile matter and moisture content. However, it is suitable for use in UCG due to its high permeability index of 28.8 md at 25 °C, attributed to the presence of naturally developed cleats and cracks compared to other coal ranks such as bitumen and anthracite, among others [14]. Hence, lignite coal can

* Corresponding author at: School of Chemical and Environmental Engineering, China University of Mining & Technology (Beijing), Xueyuan Road D11, Beijing 100083, PR China. Fax: +86 10 62331601.

E-mail addresses: xijianfen@yeah.net (J. Xi), ucgrc@sohu.comb (J. Liang), simon_st@163.com (X. Sheng), guangzonglongxi@163.com (L. Shi), lishuangwendy@163.com (S. Li).

http://dx.doi.org/10.1016/j.jaap.2015.11.011

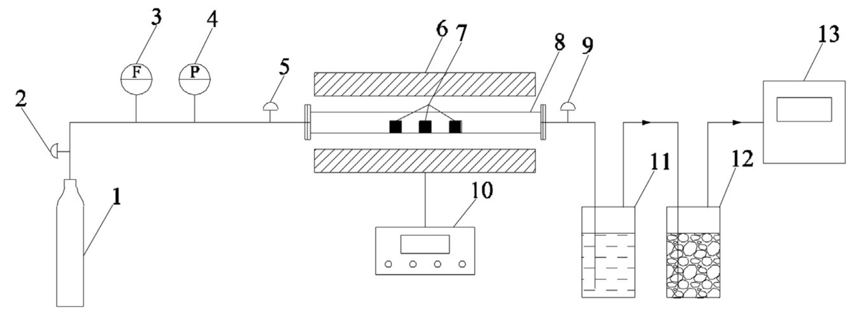

Fig. 1. Schematic diagram of the pyrolysis apparatus. Key: (1) nitrogen; (2,5,9) spherical valve; (3) flow meter; (4) pressure gauge; (6) heater; (7) lump lignite; (8) gasifier; (10) temperature controller; (11) gas cleaning; (12) filter and drying; (13) gas chromatography.

be regarded as the most suitable candidate for use in UCG process [7]. This clean technique has captured the attention of countries such as India and China as a means to generate clean energy from lignite-type coal resources [15].

The swelling and structure of lignite changes with an increase in temperature during the pyrolysis process, thus affecting the porous structure of char and its permeability [16–18], and the UCG process overall. Research interests have recently focused on changes in coal structure and coal swelling during the pyrolysis process [19–22]. For example, Ndaji et al. [23] studied the swelling of coal particles ranking from lignite to anthracite, and observed that the ratio of maximum swell increased with increasing coal rank (*i.e.*, the degree of metamorphism that occurs as coal matures). Gale et al. [24] investigated the effect of temperature on the swelling of particle bituminous coal at high heating rates (10^4 K/s) and demonstrated that the swelling ratio of coal samples decreased with increasing temperature. Furthermore, Yu et al. [25] observed that the bubble phenomenon caused the swelling of particle coal. However, to date, the majority of studies have focused mainly on coal powder or small coal particles. To the best of our knowledge, few studies have investigated changes in the structure and swelling of lump coal, and in particular lignite-type coal.

The devolatilization experiments of a cubic coal lump (25–30 mm edge length) was carried out by Minkina et al. [26]. Results showed that swellingcommenced at 400 °C, and reached a maximum at 500–600 °C, with the new cracks being perpendicular or parallel to the coal bedding plane due to shrinkage. Coetzee et al. [27] compared the swelling behavior of large coal particles with powdered coal and theorized that large coal particles and powdered coal showed different swelling behavior.

It should also be noted that the change in pore structure of low-rank coal during water removal can significantly affect the mass transport and chemical reaction mechanisms for both combustion and conversion processes [28]. This is because the mesoporous coal structure is composed of pore channels that control the transport of gaseous reactants and products within the structure [29].

It was therefore clearthat limited research had been carried out regarding the swelling of lignite and its characteristics upon pyrolysis in the UCG process. Thus, we herein report studies into lump lignite coal from Inner Mongolia, China, to determine the swelling ratio of the lignite under UCG-like heating conditions. This should give a better understanding of the possible swelling mechanism of the lignite employed in our study.

2. Experimental

2.1. Coal samples

The lignite coal samples were collected from an opencast coal mine located in Ulanqab, Inner Mongolia, China. The samples were cut into cubes of 400 mm length, carefully sealed against moisture loss, and packed immediately for transport to the laboratory. The results obtained from the proximate and ultimate analyzes of the lignite samples are given in Table 1.

Table 1
Analysis of lignite coal from Ulanqab.

Proximate analysis (wt.%)				Ultimate analysis (wt.%)				
M_{ar}	A_{ad}	V_{ad}	FC_{ad}	C_{ad}	H_{ad}	O_{ad}	N_{ad}	$S_{t,ad}$
26.6	29.10	28.47	30.93	43.70	3.11	11.59	0.57	0.65

Note: M = moisture; A = ash; V = volatiles; FC = fixed carbon; C = carbon; H = hydrogen; O = oxygen; N = nitrogen; S_t = total sulfur; ad = air-dry basis; ar = air received basis.

Table 2
Final temperatures for lump coal heating.

Group	1	2	3	4	5	6	7	8	9
Final temperature/°C	100	200	300	400	500	600	700	800	900

2.2. Analysis of mineral matter in lignite coal

A range of mineral matter with different thermal expansion coefficients are present in coal, resulting in swelling when the coal is heated. To determine the types of mineral matter present in the lignite employed in our study, the following process was followed. The raw lignite sample (10 g), taken from the cubic lignite block, was dried for 60 min at 120 °C, and then ground to below 200 mesh (75 μm). The various types of mineral matter of the coal particle were then determined by X-ray diffraction (XRD, Ultima IV X-ray diffraction system, Rigaku, Japan).

2.3. Experimental procedure

A schematic representation of the experimental setup are shown in Fig. 1. A large cubic lignite block from the opencast mine was selected and cut into 27 samples of 50 × 40 × 40 mm. The lump lignite samples were then divided into 9 groups, with each group containing 3 samples. These samples were used as-received due to careful sealing and packaging. The three lignite samples were heated to a target temperature between 100 and 900 °C in the laboratory gasifier under a nitrogen atmosphere, as indicated in Table 2. The gasifier was mainly composed of a stainless steel tube with a radius of 40 mm (length: 1 m), an electric heating jacket, and a programmable temperature control unit (SR253, Shimaden, Japan). The heights of all lump lignite samples perpendicular to the bedding plane were measured both before and after heat treatment, using a Vernier caliper to calculate the swelling ratio according to the following equation:

$$S_i = \frac{(H_i - H_{0i})}{H_{0i}}$$