Energy 149 (2018) 730–740

Contents lists available at ScienceDirect

Energy

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

Effect of microwave pretreatment on the combustion behavior of lignite/solid waste briquettes

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ARTICLE INFO

Article history:
Received 28 November 2017
Received in revised form
7 February 2018
Accepted 18 February 2018
Available online 20 February 2018

Keywords:
Isothermal combustion
Lignite
Solid waste
Microwave pretreatment
Kinetics
Fixed bed

ABSTRACT

Lignite is one of common applied fossil fuels worldwide, and solid wastes like biomass as well as sewage sludge are promising alternatives of fossil fuels. The isothermal combustion performances of lignite/solid wastes (eucalyptus bark and sewage sludge) briquettes between 500 °C and 800 °C in a bench-scale fixed bed furnace were examined based on a macro-thermogravimetric analysis approach. Compared with untreated samples, the average combustion rates of lignite and sewage sludge with the microwave treatment decreased, while those for treated eucalyptus bark increased. The drying, devolatilization and char combustion processes overlapped in the isothermal combustion for all samples. The treated lignite had a high aromatic hydrocarbon, while both the treated sewage sludge and eucalyptus bark had high hydroxyl and methyl group (CH_3). After the microwave pretreatment, the fuel rank of lignite was prompted, while that for eucalyptus bark and sewage sludge degraded. Through the microwave pretreatment, the activation energies of lignite, sewage sludge, and eucalyptus bark grew from 15.45 to 21.20 kJ mol^{-1}, 18.23–20.77 kJ mol^{-1}, and 13.27–14.22 kJ mol^{-1}. The study can provide some basic data for the energy utilization of lignite and solid wastes.

1. Introduction

The energy demand worldwide is becoming sharply more serious with development of society. Shortage of fossil fuels resources and environmental pollution has brought new challenge for human beings [1]. Reserves of high-rank coal are dwindling due to the overexploitation and hardly meet the energy demand over the world. The contradiction between energy shortage and demand can be moderated by developing alternative fuels such as biomass, sewage sludge, municipal solid waste, and utilizing lignite with large amount of storage and low price [2–4]. The reserves of lignite in China are more than 130 billion ton, which account for 13% of the total reserve in the world [5]. Biomass as the solar energy presented as chemical form in plant materials (agricultural residues, forestry residues, etc), which is considered as the best substitution of fossil fuels [6]. Different from traditional biomass, sewage sludge is a typical non-lignocellulosic biomass [7]. The combustion of sewage sludge with high yield can reduce its volume, destroy toxic organics and recover the energy stored in it [8]. Lignite and biomass have been used as fuels in some power plants, but inherent features of lignite and biomass limit their extensive application. For instance, high moisture content and low fixed carbon content result in the low calorific value of lignite, which can lower the burning efficiency and increase CO_2 emission for per unit of energy output [9]. Also, solid wastes with high moisture content and loose structure can lead to the limitation of its wide application due to low combustion efficiency, and problems for their storage and transportation [10,11]. Drying the low-rank coal, sewage sludge and eucalyptus bark can increase their calorific value, combustion efficiency, and reduce the cost of transportation/handing and emissions in the power generation [12,13]. The microwave drying technique has energy-efficient, pollution-free and rapid heat transfer compared with the traditional drying techniques such as hot air drying and oven drying [14]. Lekachaiworakul et al. [15] also emphasized that the power required for the microwave drying of samples is less than

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https://doi.org/10.1016/j.energy.2018.02.087

that of the hot air drying. The traditional drying is to transfer the thermal energy to the material slowly due to high thermal resistance in it, while the microwave can penetrate materials and generate heat throughout the volume of material [16,17]. Liu et al. [9] noted that the microwave pretreatment technique can change the internal structure of food wastes and improve their combustibility (DTG_{max}/T_i^2) and comprehensive combustion characteristics. For this reason, the high dielectric loss for water and certain minerals in samples compared with other components, as well as their uneven distribution in samples, can result in high thermal gradient and then cause thermally induced stresses and strains [18]. Marland et al. [19] pointed out that the microwave radiation can enhance the grindability of coal fuels especially for the low-rank coal derived from the expansion of gangue mineral and gaseous evolution. Based on a micro-thermogravimetric analysis technique, Yu and Li [20] noted that the comprehension combustion index of sewage sludge through microwave pretreatment can increase by 8.2% compared with hot air drying pretreatment. Through a micro-thermogravimetric analyzer, Ge et al. [21] also examined the combustion behavior of three kinds of lignite through being dried by microwave, and indicated that the ignition and burnout temperatures of the samples are increased after microwave pretreatment. Pang et al. [22] noted that there is an increase in hydroxyl contents for bitumite powder after microwave irradiation, while other high activity radicals in anthracite powder also increase although its hydroxyl contents slightly decrease, which would lead to the enhancement of the combustibility for the two fuels. Liu et al. [2] figured out that the ignition temperature of lignite increases with increasing the microwave pretreatment time. Barmina et al. [23] addressed the influence of the microwave pretreatment on wood biomass, and concluded that the carbon content increases in the sample through the microwave pretreatment, which can grow the heating value of the sample. For solid wastes with loose structure, the briquetting technique can lead to the samples having superior physicochemical properties and better combustion behavior [24], including higher energy densities, little volume, lower emission, as well easy to storage and transport [25]. Compared with the fuel powder, briquetting can decrease the spontaneous combustion tendency of lignite in storage, long-distance transportation and thermal drying, and also reduce dust pollution [26]. The low-rank coal and other solid wastes briquettes can be used favorably in grate and fluidized bed furnace [27]. Lee and Bae [28] addressed the isothermal combustion of sewage sludge pellets in a lab-scale stoker incinerator. Based on a TG technique, Morin et al. [29] addressed the isothermal char combustion kinetic of beech bark between the temperature range of 330 °C and 400 °C, and noted that the shrinking Core Model and the Random Pore Model can describe well the kinetic behavior. Ogada and Werther [30] noted that the drying, devolatilization and char combustion stages of sewage sludge overlap during the combustion process in both lab-scale and semi-pilot-scale fluidized bed combustors a fluidized bed. Based on a large-scale thermo-gravimetric analyzer, Jamal et al. [31] revealed the isothermal combustion kinetics of sewage sludge at temperatures ranging from 400 °C to 700 °C by assuming the reaction orders ($n = 1$ or $n \neq 1$). Altun et al. [32] evaluated the non-isothermal combustion kinetics of lignite briquettes, and noted that the activation energy increases with the enlargement of the particle size. Evaluation of the reaction kinetics for solid fuels is one of most useful approaches, although the combustion process is a very complex reaction involving successive sequence of many components.

However, the evaluation about the isothermal combustion kinetics of solid fuels briquettes is still insufficient. Especially, several limited literature mainly focus on the influence of the microwave pretreatment technique on the combustion characteristics of some solid fuels powders by using micro-thermogravitric analysis approach.

The current work aims to assess the effect of the microwave pretreatment on the isothermal combustion kinetics of lignite, two typical solid wastes-sewage sludge and eucalyptus bark briquettes in a bench-scale fixed bed furnace at temperatures ranging from 500 °C to 800 °C. The combustion performance in terms of the combustion rates, activation energy, dominant mechanism function, and combustion rate constant, as well as pre-exponential factor of the samples is addressed, and the comparison in between the different samples is revealed further.

2. Methods

2.1. Test samples

The raw lignite was collected from a colliery (Inner Mongolia, China), and eucalyptus bark was purchased from a biomass processing factory (Guangdong, China). The raw sewage sludge with the initial moisture content of about 82.6% (wet base) through mechanical dehydration pretreatment was collected from a water reclamation plant (Beijing, China). The raw sewage sludge was kept in an oven (KUNTIAN; 101-00B, China) under 105 °C for half an hour until its moisture content was about 38% (wet base), which would be helpful for briquetting it. The proximate analyses of all samples are tested according to the ASTM D 3172-89 standard. Ultimate analyses and heating value are performed on Element Analyzer (Vario EL III, ELEMENTAR) and oxygen bomb calorimeter (Parr 1281, PARR Instrument, America), respectively. Each test was repeated three times. All the results are depicted in Table 1. Each sample with 5 g was briquetted by a hydraulic jack (XL140118, China) under the pressures up to 10 MPa into cake (40 mm in diameter). The thicknesses of lignite, sewage sludge and eucalyptus bark cakes were 3.5, 3.3 and 6.2 mm, respectively, while the values for their density were 1137.40, 1206.33 and 642.07 kgm^{-3}, respectively.

The temperature distribution in microwave oven is uneven which would result in local overheating during the continuous heating. Therefore, the microwave pretreatment of the briquettes was carried out intermittently in a microwave oven (Midea, MM721NH1-PW, China) at a power level of 119 W until the mass difference between two continuous tests was less than 0.01 g. The cakes before the microwave pretreatment are shown in Fig. 1. The power level for the microwave pretreatment was maintained at 119 W. The briquettes were placed into the microwave and kept about 3 min, then the samples were taken away the oven in order to prevent high temperature in them. The procedure was repeated until the mass difference between two continuous tests was less than 0.01 g. The pretreatment time for the lignite, sewage sludge and eucalyptus bark were 42, 78 and 15 min, respectively. The energy required for the pretreatment of the lignite, sewage sludge and eucalyptus bark are 0.083, 0.155 and 0.030 kW h, respectively, which would be needed to cost about 0.12, 0.23 and 0.04 CNY.

2.2. Fourier transform infrared spectroscopy (FTIR)

The chemical properties of the samples with or without microwave pretreatment were measured through a FTIR instrument (Thermo Nicolet, Nexus-670, America). After mixing each sample and potassium bromide with the ratio of 1:100, the blend was ground by using agate mortar and pestle, and then it was briquetted by a powder compressing machine (Tuopu, FW-4A, China). The software, OMNIC 8.0 (Thermo Nicolet, America) was used to collect data.