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Parametric studies on corn straw combustion characteristics in a fixed bed: Ash and moisture content

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ABSTRACT

This experiment was conducted on fixed bed combustion in a one-dimensional bench. The effects of ash and moisture content on the combustion characteristics of corn straw were determined. The two parameters directly relate to the burning rate and affect combustion efficiency and the release of gas. The bed temperature distribution, mass loss rate and gas composition were measured in the bed. The results show that the optimum char combustion efficiency was achieved at 10% moisture content of corn combustion. A slight increasing the moisture content to 10% can obtain a higher bed temperature and accelerate the ignition rate in the char oxidation stage, while there is also a slight decrease in the conversion ratio of C to CO. The conversion rate of S to SO_2 for 10% moisture content was higher with the temperature zone above 1000 °C. With the increased ash content, there was a slight increase in the average ignition rate; the bottom bed temperature increased with a serious ash slagging. C was converted to CO and presented a slightly increasing trend for higher ash content and the conversion of N to HCN. This work provides an overall understanding of corn combustion for large boiler system.

1. Introduction

With the increase of fossil fuel consumption, it is imperative to use biomass energy as a renewable resource. According to the International Energy Agency, the world's energy consumption will continue in a sustained growth trend until 2040 [1], which means there will be a huge energy demand for all fuels. The utilization of dominant fossil fuels is the leading cause of global warming and pollutant emissions [2,3]. Meanwhile, compared with 23% today, power generation from renewables will increase to 37% in 2040 with a strong concentration on renewable overtake coal as the largest source of electricity generation by the early 2030s [1,4].

Therefore, biomass (as renewable energy) has been developed to alleviate the pressure on energy demand [5] and is widely used in the production of heat, power generation, liquefaction and gasification to produce biofuels. Also, biomass can be deemed as the CO_2 neutral energy resource [6]. China, which is a large agricultural country with 300 million tons of biomass waste generated each year [7], only uses a small part of that biomass waste to produce power [8]. Especially in northern China, most wastes are used directly for heating or are burnt in the field, resulting in low efficiency energy conversion and air pollution [9,10]. In addition, most of the fuels are dirty with various ash and moisture content, which affects the thermal conversion efficiency of the boiler [11], therefore, it is meaningful to study the fuel properties of moisture and ash content in corn straw.

Direct combustion technology is the primary traditional technology of biomass energy conversion, and a typical grate furnace can be used to generate power at the industrial scale [12]. Sefidari et al. [13,14] investigated wet woody residue burning in a moving grate boiler and observed that the measured temperatures showed an intense combustion at the bottom of the bed. Buchmayr et al. [15] also studied wood in the first burning stage in a small grate boiler, which provided reliable data for simulation. Moreover, the fixed-bed combustion test rig, which is a smaller lab-scale unit, can be used for research and is similar to the moving grate process because of the finite bed distances along the length, namely, the

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relatively small horizontal gradients (horizontal biomass moving direction) [16].

In comparison, a large scale fixed-bed used for research makes it easier to take advantage of data acquisition equipment and minimizes operation and maintenance costs. When utilized, parameters, including primary air flowrate, air distribution systems and fuel specifications, have an overall impact on the performance of the fixed-bed. Therefore, it is easier to improve our understanding of bed temperature variation, burning rate, gas release, and combustion efficiency [17].

Both fuel types and properties can impact combustion behavior of solid fuels and flue gas emissions in moving grate or fixed bed (small scale) systems in a complex manner. Li et al. [18] investigated the combustion characteristics of the different corn stalk lengths using a fixed bed, and they found that the average combustion rate and flame propagation velocity increased with shorter corn stalk combustion in a fixed bed. Khor et al. [19] reported that uncut straw burning increased flame instability and the changeable propagation of the ignition. Karim [20] found that pine shavings gained the highest ignition front because of the smaller particle size and the solid bed fraction. Pérez et al. [21] analyzed the temperature distribution and flame propagation velocity by changing the operating parameters (moisture content, particle size, and shape) during the pine wood gasification/combustion process in fixed bed downdraft reactors. However, most of the studies of biomass combustion behavior are limited in fuel types.

In addition, flue gas emissions should be considered in the process of biomass combustion in the fixed bed. It has been previously reported that the primary gas species emission is H2O, CO, CO2, CH4, NO*x* and other hydrocarbons in the flux gases [22–24]. Gort [25] indicated that the emissions of CO_2 and CO have sharply increased when char started to combust in a fixed bed. The formation and reduction of NO during straw combustion was studied by Zhou et al. [26] and showed that an amount of NO was decreased in the thin flame front zone, which resulted from changes of NO, NH_3, HCN and HNCO concentration in the ignition flame front. As the main fuel properties, moisture and ash content played a dominant role in biomass combustion characteristics and flue gas emissions in the biomass combustion process in a fixed bed combustor.

Regarding the parameters of moisture and ash, some [27] reported that the biomass cannot ignite in a 600 °C reactor when the moisture content of biomass is over 20%. Additionally, as reported by Ryu et al. [28] and Patino et al. [29], the heating value is related to the moisture and ash content of biomass. Yang et al. [30] showed that the burning rate decreased with increased moisture in the solid waste. Porteiro et al. [31] revealed that both moisture and ash content affected the ignition velocity, but there was little effect on a low content of ash in the fuel. Moreover, the ash and moisture content in the solid fuel can affect the thermal conversion efficiency of the boiler [11]. Bahadori et al. [32] conducted that the effect of biomass moisture content on the direct combustion of sugarcane bagasse, and they reported that flame temperature is directly related to the amount of heat for moisture evaporation, and the boiler efficiency. Saito et al. [33] also investigated the effect of the water content on the combustion properties of waste fuels, and they found that additional water impacted the volatile combustion, and the char combustion rate increased with increasing water.

Finally, the authors previously performed experimental and numerical studies [34,35] of the different parameters (ash and moisture content), which affect the combustion characteristics of Municipal Solid Waste (MSW) in a one-dimensional fixed bed. The bed temperature distribution, the mass loss of fuel and the concentration of gas components (O_2, CO, CO_2 and NO) have been investigated.

In summary, as the main parameters of fuel properties, the moisture and ash contents will impact the combustion efficiency and the flue gas emissions. However, most of the previous studies regarding the parameters of moisture and ash contents are lacking, especially the data of obtained gas composition. Moreover, most studies involved numerical studies of moisture and the ash content of wood and MSW, but there is a lack of experimental studies on corn straw. According to the situation in North China, it is significant to systematically study corn straw with different moisture and ash content for a better understanding of the combustion characteristics: mainly, bed temperature variation, burning rate, combustion efficiency, and flue gas release (CO, CO_2, CH_4, C_2H_6, NO, HCN, and SO_2).

Therefore, the aim of the current experiment was to more comprehensively investigate the biomass properties of moisture and ash content on corn straw combustion behaviors and flue gas emissions in one-dimensional fixed bed. In addition, the aim was to increase corn straw combustion efficiency and reduce gas pollutants through the analysis of the burning rate, ignition propagation velocity, and gas composition, which are discussed by changing the moisture and ash content. This provides a theoretical and experimental base for the clean and efficient use of corn straw in a large biomass boiler by studying the combustion characteristics in a fixed bed.

2. Experimental test rig and measurement methods

Fig. 1(a) shows the schematic view of similarity between the moving grate and a small fixed bed. For the moving grate, fuels on the upper layer ignited first because of the radiation heat. However, the primary air from the bottom reacted with fuels and resulted in the flame front moving downward for both the moving grate and the fixed bed. Therefore, there are similar ignition front speeds for both. The temperature gradients in the horizontal direction were relatively small because the slow velocity of the moving grate can be ignored. Considering this, some simplifying assumptions can be applied as follows: the movement direction of the fuel extension grate is uniform; the fuel mass flow rate of the entering grate is constant; the direction of heat and mass transfer are only vertical to the grate. Based on these assumptions, the combustion process in a fixed bed can be used to simulate the combustion process in the moving grate system. Therefore, we built the fixed bed experimental device system [17].

A one-dimensional fixed bed experimental device system is employed for combustion tests in this study and is shown in Fig. 1(b). The fixed bed combustion occurs in a vertical cylinder combustion chamber, which is hung by a weighing sensor. The test bench can be divided into three parts: the furnace section, the air supply part, and the measuring system. The fuel gas (propane) and the combustion air are introduced into the furnace through a gas burner to heat the tested corn bed.

2.1. Combustion chamber furnace

The fixed bed reactor in this experiment is a vertical cylinder-type combustion chamber, which is hung on a load-weighing sensor. The combustion chamber is 1.30 m high with an inner diameter of 180 mm, which is composed of three layers of material. The inner layer is made of high alumina refractory pouring with a thickness of 50 mm, and the flame temperature of this material can withstand temperatures up to 1300 °C. The middle layer is a protective sleeve which is made of 1Cr18Ni9Ti steel with a thickness of 5 mm. The outer layer is the insulating layer and is composed of aluminum silicate refractory fiber cotton with a thickness of 150 mm, and then the iron sheet is used to wrap the insulation