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Research article

Integrated assessment on the characteristics of straw-based fuels and their effects on iron ore sintering performance

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ABSTRACT

Employing waste agricultural straw into iron ore sintering is a promising approach to realize efficient energy utilization and environmental protection. In this paper, the characteristics of four types of straw-based fuels including raw straw (RS), preformed straw (PS), straw char (SC) and preformed straw char (PSC) were assessed. The results indicate that RS and PS mainly consisted of volatile matters, which was pyrolyzed in the downstream of combustion zone. This property of RS and PS led to lower fuel utilization and then decreased the bed temperature for minerals melting. Recommended replacement percentage of RS and PS to coke breeze was restricted at 10%. Compared with RS and PS, SC had the advantage of improving fuel utilization and ensuring higher bed temperature. But SC showed considerably faster combustion speed than coke breeze, which accelerated sintering speed excessively when SC replacing coke breeze exceeded 20%, and the suitable replacement percentage of SC to coke breeze was 20%. PSC ingeniously integrated the advantages of PS and SC by joint preformation-carbonization process. Comparable sintering performance was achieved when improving the replacement percentage of PSC to coke breeze to 40%, and its capacity for reducing CO_2, SOx and NOx emissions achieved 24.5%, 26.6%, and 28.2% respectively.

1. Introduction

Biomass is widely regarded as a renewable and sustainable energy source throughout the world, which comes from living or living organisms such as plants, animals and their byproducts [1,2]. Unlike conventional fossil fuels, biomass can contribute to coping with global warming in as much as the balance of greenhouse gas production can be considered neutral [3,4].For the sake of environmental protection and alleviating energy crisis, biomass is likely the prevalent option to become the substitute for fossil fuels [5]. Indeed, recent studies show that biomass can sustainably supply between one quarter and one third of the estimated global primary energy demand for 2050 [6]. China has abundant biomass energy resources, and the total amount of available biomass equals about 5 billion tons of standard coal. However, the part of biomass being effectively used is less than 10%, and the majority has been directly wasted [7]. Among the wasted biomass energy, agricultural straw takes up a huge part. The total annual production for straw in China is about 800 million tons, which takes up 17.29% of the global total amount. If fully developed, it could be used as an energy equivalent of 300 million tons of standard coal [8]. However, the availability is less than 45% due to open burning and abandoning [9,10]. This improper disposal is one of the main reasons to cause the hazy weather [11]. Therefore, it is urgent to find an effective way to convert the wasted straw resources into usable energy.

China is the biggest manufacturer for crude steel throughout the world, during the making process of which large amount of fossil energy is consumed. The amount of CO_2 emissions generated from steelworks accounts for about 9.2% of the total amount in China and about 30% of that in Chinese industry. Besides, China's iron and steel sector contributes 51% of the world steel CO_2 emissions [12]. Iron ore sintering is one of the important steps on an integrate steelmaking chain, the purpose of which is to agglomerate fine iron ores into lumps for ironmaking in blast furnace [13]. However, this process characterizes energy-intensive and pollution-intensive in integrated steelworks. About 9–12% of the total energy in integrated steelworks is consumed in this stage, 75–80% of which is consumed in the form of solid fuels, including coke breeze and anthracite [14]. The combustion of fossil fuels has been widely known as the main source of greenhouse gases like CO_2 [15]. According to the estimate by Li et al. [16], China will need to cut 1651Mt of carbon emission in 2020 in order to achieve the target of reducing CO_2 emissions per unit of GDP by 40–45% compared to 2005, even in a slow economy growth scenario.

Therefore, replacing fossil fuels with biomass fuel has the fine potential to effectively reduce the part of CO_2 emitted from iron ore sintering process. Indeed, previous research proved that replacing fossil fuels with biomass fuels was an effective approach to reduce not only CO_2, but also SOx, and NOx in iron ore sintering process [17–20]. However,

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biomass fuel showed many differences from fossil fuels in terms of density, porosity, reactivity and combustibility [21,22]. How to replace fossil fuels with biomass fuels reasonably deserves deep consideration. Our research group has been engaging in the conversion of waste agricultural straw into desirable substitute for fossil fuels [23–25]. However, there is still little research to assess the characteristics and application of waste agricultural straw in iron ore sintering process. In this investigation, the well-round assessment including the basic physicochemical characteristics, combustibility, application effect and environmental impact of straw-based fuels was conducted. As a consequence, proper preparation techniques and proper straw-based fuels for replacing coke breeze have been determined. Besides, the environmental assessment of atmospheric emissions like SOx, NOx, CO and CO_2 was also reported.

2. Materials and methods

2.1. Materials

In sinter production, iron ores, fluxes (dolomite, limestone and quicklime), solid fuels (usually coke breeze and anthracite) and return fines (sinter with size range of −5 mm) are indispensable raw materials. In our study, they were all provided by an integrated steelwork in China. Table 1 gives the chemical composition and percentages of individual raw materials. Among them, mixed iron ores were mainly used to regulate the contents of Fe and SiO_2 in sinter, while fluxes were used to adjust the basicity (CaO/SiO_2, mass ratio) and MgO content. For meeting the requirements of ironmaking in blast furnace, the Fe, SiO_2 and MgO contents and the basicity were kept at 56.38%, 4.92%, 2.00% and 1.90% respectively in the finished sinter cake.

2.2. Methods

2.2.1. Preparation of straw-based fuels

For assessing the influences of preparation techniques on the properties of straw-based fuels, preformation and carbonization processes were employed. When used as the substitute for coke breeze in sinter pot trials, the raw straw was manually cut into small pieces with size range of 3–5 mm. During preformation process, a pulverizer, model TY-36 (Tianyang, China) was employed to mill raw straw into smaller particles with the mass percentage of −2 mm exceeding 90%. Specifically, the size distribution of milled straw consists of +2 mm of 5.5%, 1–2 mm of 5.6%, 0.5–1 mm of 10.3%, and −0.5 mm of 78.6%. After that, a laboratory-scale briquetting machine, model XKJ320 (Huaxiang, China) was used to mold milled raw straw into briquettes of 10 mm long and 10 mm in diameter without any binder at room temperature. The briquettes were produced at a maximum pressure of 180 MPa and maintained for 1 min. During carbonization process, raw straw with size range of 3–5 mm or preformed straw was initially charged into a quartz reactor, which was then moved into an electrically-heated shaft furnace. Raw straw or preformed straw then underwent a two-stage carbonization process. In the first stage, they were heated to 500 °C at a rate of 25 °C/min for a residence time of 30 min, and then improving the temperature to 700 °C with the same rate and residence time. The whole process was conducted under the inert atmosphere with an argon flow of 0.1 L/min. Preformed straw (PS) was obtained after the preformation process, while straw char (SC) was obtained after the carbonization process. Preformed straw char (PSC) was obtained after the joint preformation-carbonization process.

2.2.2. Evolution of fuel properties

The ultimate analyses of fuels were performed using a CHNOS Elemental Analyzer, model Vario EL III (Elementar, Germany), while proximate analyses were performed with an Automatic Proximate Analyzer, model SDTGA5000 (Sundy, China). The calorific values of fuels were measured by an automatic calorimeter, model SDACM4000 (Sundy, China). The density of fuels was selected to evaluate the preformation process. Eq. (1) was used to calculate the apparent density of fuels, and Eq. (2) was used to calculate the energy density of fuels. During the examining process, 20 individual pellets were tested, and the average value of which was regarded as the effective results. Eq. (3) was used to calculate the value of porosity. A physical and chemical adsorption analyzer, model Autosorb-1 (Quantachrome Instruments, America) was employed to measure the specific surface areas of fuels. Fuel samples were first undergone vacuum degassing at 150 °C for 5 h, and then cool the samples to room temperature for helium gas backfilling. After that, fuel samples were conveyed into the analysis station for analyzing with nitrogen gas as the adsorbate at 77 K, thereby obtaining the isothermal curves of adsorption and desorption. Three parameter BET equation was adopted to calculate the specific surface area of fuels.

$$D_0 = 4m_0/\left(3.14d^2L\right) \tag{1}$$

$$D_E = D_0C \tag{2}$$

$$P = 100(D_1 - D_0)/D_1 \tag{3}$$

In Eq. (1), D_0 is the apparent density of fuels (g/cm^3), m_0 is the mass of fuels (g), d is the diameter of fuels (cm), L is the length of fuels (cm); In Eq. (2), D_E is the energy density of fuels (kJ/cm^3), C is the calorific value of fuels (kJ/g). In Eq. (3), P is the porosity of fuels (%), D_1 is the true density of fuels (g/cm^3), which was measure by an automatic true density meter, model UPYC1000 (Quantachrome Instruments, America).

The combustibilities of fuels were examined using a simultaneous TG-DSC analyzer, model STA449C (Netzsch, Germany). Before analysis, 10 ± 0.1 mg samples with a size range of 0.125–0.25 mm were accurately weighed and then charged into an Al_2O_3 crucible. The crucible was placed in a sample holder inside the furnace of the analyzer, and the analyses were conducted under the same conditions using appropriate baseline correction. The samples were heated to 1000 °C to achieve complete combustion. Throughout the process, the heating and airflow rates were kept at 10 °C/min and 0.1 L/min, respectively. Therefore, differential scanning calorimetry (DSC), derivative thermogravimetry (DTG) and thermogravimetry (TG) curves were obtained. Combustion parameters, including the peak values V_{max} and Q_{max} on the DTG and DSC curves and the initial burning temperature

Table 1
Chemical composition and percentage of raw materials in mixture (mass %).

	Chemical composition							
Raw materials	TFe	SiO_2	CaO	MgO	Al_2O_3	FeO	LOI[a]	Percentage
Mixed iron ores	60.74	4.65	1.90	1.54	1.92	9.24	2.64	64.93
Dolomite	0.21	0.87	31.57	19.68	0.22	0.13	46.91	0.53
Limestone	0.14	1.31	50.19	3.30	0.32	0.10	42.27	3.05
Quick-lime	0.40	2.85	77.92	3.64	0.75	0.23	11.29	4.56
Return fines	56.38	4.92	9.36	2.00	2.07	8.58	0.00	23.08
Coke breeze	2.34	5.95	0.93	0.20	3.55	0.10	84.76	3.85

[a] LOI = loss on ignition in air atmosphere at 950 °C.