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Research article

Effect of hydrogen gas addition on combustion characteristics of pulverized coal☆

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ABSTRACT

A promising approach to decrease CO_2 emissions from blast furnaces during ironmaking is to blow a reducing gas containing hydrogen into blast furnaces from their tuyeres. However, the combustion behavior of pulverized coal in the presence of a hydrogen-containing gas has not been elucidated. In this work, the combustion experiments of pulverized coal using a drop tube furnace were carried out to investigate the effect of H_2 gas addition on the combustibility of pulverized coal. The combustion ratio of char particles in the presence of H_2 gas (when introduced at a flow rate of 0.10 L/min) was larger than that in the absence of H_2 gas. This is because of the enhanced release of volatile matter from coal and the combustion of char due to an increase in the temperature of the coal particles, which was caused by the drastic combustion of H_2 gas. The combustion ratio of char particles when H_2 gas was added at flow rates higher than 0.21 L/min was considerably smaller than that obtained when H_2 gas was not added. It was found that the combustibility of coal was enhanced when an optimum H_2 gas flow rate was used.

1. Introduction

Recently, significant efforts have been made to reduce the emission of CO_2, which is a potential cause of global warming, from various sources. In Japan, the steel industry is responsible for about 17% of the total CO_2 emission [1]. CO_2 emissions from blast furnaces, coke ovens, and sintering machines during ironmaking contribute to about 70% of the total CO_2 emission from the steel industry. Therefore, CO_2 emissions in the ironmaking process, especially, those generating from blast furnaces should be reduced to avoid global warming. In order to decrease substantial CO_2 emissions from blast furnaces, a hydrogen utilization technology has been developed under the COURSE 50 project (CO_2 Ultimate Reduction in Steelmaking process by innovative technology for Cool Earth 50) to reduce iron ore by hydrogen in blast furnaces [2,3]. To reduce iron ore in blast furnace using hydrogen, it is necessary to blow a gas consisting of hydrogen into the blast furnace. Such a gas can be blown into the blast furnace from tuyere. Since in many blast furnaces pulverized coal is blown from the tuyere, it is believed that the combustion of pulverized coal in the blow pipe of the tuyere is affected by the addition of a hydrogen-containing gas.

Until now, studies concerned with blowing of waste plastic from the tuyere into the blast furnace for recycling of waste plastic and hydrogen utilization in the blast furnace have been investigated [4,5]. Their studies show that the combustibility of waste plastic deteriorates when waste plastic is burned with pulverized coal. Moreover, an injection of BOF (basic oxygen furnace) slag into the blast furnace has been studied to improve the basicity of the slag formation [6]. The research shows that the combustion efficiency is decreased when BOF slag is added to pulverized coal in a blowpipe model test. They made no mention of a combustibility of pulverized coal.

Many studies have focused on the recycling of waste plastic and hydrogen utilization in blast furnaces by blowing waste plastic into them from their tuyeres [4,5]. These studies showed that the combustibility of waste plastic deteriorates when it is burned with pulverized coal. Moreover, Ökvist et al. made efforts to improve the formation of slag by introducing basic oxygen furnace (BOF) slag into blast furnaces [6]. They showed that the combustion efficiency of pulverized coal decreases when BOF slag is added to it during a blowpipe model test. However, they made no mention of the combustibility of pulverized coal. Additionally, other researchers [7,8,9] have examined the combustibility of pulverized coal in the presence of natural gas (composed mainly of methane) and a blast furnace top gas consisting of hydrogen and CO (both blown from the tuyere) using numerical analysis. Hesketh et al. [10] carried out the experiment of the simultaneous combustion of char and combustible gas (propane) by using the fluidized bed

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combustion. However, only a few studies have investigated the combustibility and combustion behavior of pulverized coal in the presence of a hydrogen-containing gas experimentally.

Therefore, in this work, the combustion of pulverized coal was carried out using a drop tube furnace to elucidate the effect of H_2 gas addition on the combustibility of pulverized coal experimentally. We investigated the combustion behavior of pulverized coal in the presence of H_2 gas, and the effect of the H_2 flow rate on the combustibility of pulverized coal was also investigated experimentally.

2. Experimental procedure

2.1. Experimental sample

In this study pulverized bituminous coal was used as the coal sample. Table 1 shows the properties of the coal sample. The average particle diameter of the sample was 35.3 μm.

2.2. Experimental apparatus

The coal combustion experiments were conducted using a drop tube furnace, as shown in Fig. 1. The drop tube furnace which enables rapid heating of sample was used because pulverized coal injected into the blow pipe is heated rapidly. The pulverized coal sample could be continuously fed into an injector with a rotary table feeder. The coal passed through the injector equipped with water-cooling to the reactor with an entraining gas. The temperature in the reactor was controlled with an external electric furnace containing silicon carbide heating elements.

A water-cooled sampling probe with an inner diameter of 10 mm was inserted from the bottom of the reactor tube. The char particles entrained in the combustion gas were extracted from the reactor using this sampling probe based on the principle of the isokinetic sampling method. The sampling point of the probe head could be scanned at distances ranging from 100 to 1300 mm from the injector. The sampled gas was diluted with argon gas after suction at the probe head to quench the sampled gas and to prevent the condensation of water in the sampling line. The char particles were separated from the sampled gas by a quartz thimble filter and analyzed for carbon and ash contents to estimate the combustion ratio of the coal in the coal combustion reactions. The composition of the combustion gas (O_2, CO_2, CO, and H_2) was determined by using TCD-GC (VARIAN 490-GC) at the downstream end of the thimble filter.

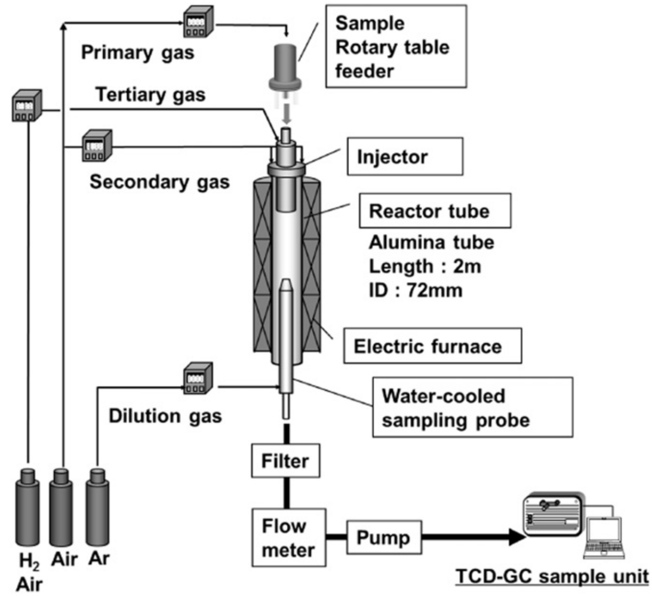

Fig. 1. Schematic diagram of the drop tube furnace.

2.3. Experimental conditions

Table 2 shows the conditions for the coal combustion experiment for sampling at different sampling points. In the case of H_2 gas addition, a part of the heating value of the coal sample was converted into that of H_2 gas, and the heating value when H_2 gas was added was almost the same as that when H_2 gas was not added. H_2 gas was mixed with primary air at the entrance of the injector. The H_2 gas and primary air mixture passed through the injector to the reactor along with the pulverized coal. The sampling points (reaction distances) were at a distance of 100, 200, 300, 400, 700, 1000, and 1300 mm from the exit of the injector.

Tables 3 and 4 show the conditions for the coal combustion experiment with different tertiary gas flow rates under with- and without- H_2 gas addition conditions, respectively. In these experiments, an injector capable of maintaining a high H_2 flow rate was used. H_2 gas was introduced into the reactor from the exit of the injector as the tertiary gas and was mixed with air and the pulverized coal sample at the same point. In the case of air atmosphere (H_2 gas non-addition), air flow rates of tertiary gas were the same as H_2 gas flow rates of tertiary gas in the case of air + H_2 atmosphere (H_2 gas addition). In this experiment, the sampling point (reaction distance) was at a distance of 1000 mm from the exit of the injector.

2.4. Measurement of combustion ratio of char particles

In order to estimate the combustion ratio of the char particles sampling, the carbon and ash contents in the char particles were determined by a thermo-balance (JIS M8812). The combustion ratio was calculated using the following equation based on the ash tracer method.

$$\eta = 100 - (X_a \times A_b / X_b \times A_a) \times 100 \quad (1)$$

where η [%] is the combustion ratio, X_a [wt%] and X_b [wt%] are the carbon content in the char particles and raw coal, respectively, and A_a [wt%] and A_b [wt%] are the ash content in the char particles and raw coal, respectively.

Table 1
Properties of the coal sample.

Proximate analysis		
Moisture	mass%, a.r.	2.72
VM	mass%, d.b.	32.83
FC		54.99
Ash		12.18
Ultimate analysis		
C	mass%, d.a.f.	81.40
H		5.26
N		1.83
S		0.50
O (balance)		11.01

Table 2
Experimental conditions for sampling at different sampling points.

		H_2 gas non-addition	H_2 gas addition
Atmosphere		Air	Air + H_2
Sample feed rate [g/min]		0.50	0.48
Furnace temperature [°C]		1200	
Air ratio [−]		1.1	
Gas flow rate [L/min]	Primary gas	1.19 (Air)	1.15 (Air) + 0.06 (H_2)
	Secondary gas	2.71 (Air)	2.75 (Air)
Heating value ratio (Coal:H_2)		100:0	95:5