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Combustion of single char particles from Victorian brown coal under oxy-fuel fluidized bed conditions

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HIGHLIGHTS

- The first ever study on oxy-fluidized bed combustion of brown coal char particle.
- The particle temperature found to increase in presence of H_2O in feed gas.
- A single particle combustion model was developed using H_2O in combustion atmosphere.
- The carbon consumption rate increased in presence of steam in oxidant.

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ABSTRACT

Combustion performance of individual and large spherical single char particles of 5–6 mm diameter during oxy-fuel fluidized bed (Oxy-FB) combustion is investigated. These char particles were prepared from briquetted Victorian brown coal. In these experiments, a thin thermocouple was inserted inside each char particle to monitor the particle temperature during the experiment. Particle temperature was observed to be higher compared to the bed temperature which varied between 880 °C and 925 °C. Up to 48 °C difference was noticed between the char particle temperature and the bed temperature using 15% steam in oxy-fuel combustion atmosphere. A kinetic model on char combustion was developed to calculate the combustion time, carbon consumption rate and the particle diameter as a function of time in an atmosphere consisting of O_2, CO_2 and steam. It was evident that boundary-layer oxygen diffusion controlled the carbon combustion rate during oxy-fuel fluidized bed combustion of these brown coal char particles. The gasification reactions were almost negligible for the feed gases and temperature range applicable for Oxy-FB combustion.

1. Introduction

Coal is a major source of energy for power generation, accounting for 42% of the world's electricity generation [1] and 75% of Australia's electricity generation [2]. However, high CO_2 emission is one of the major environmental issues in coal-fired power generation technologies. In capturing CO_2 emissions from coal-fired power plants, oxy-fuel combustion is a promising technology where a mixture of mainly O_2, CO_2 and water vapor is used as reactant in combustion. The resulting flue gas consists of essentially CO_2 and water vapor, which in turn allows easier and cheaper CO_2 separation from flue gas following condensation [3,4]. This technology, in conjunction with the well-established fluidized bed combustion, provides additional advantages, like fuel flexibility, uniform temperature distribution, and low SO_2 and NO_X emissions [5,6]. A combination of these two technologies, oxy-fuel fluidized bed (Oxy-FB) combustion, is an emerging technology for coal-fired power generation.

In coal-fired fluidized bed during oxy-fuel combustion in an O_2/CO_2 atmosphere, the following reactions are involved [7–9].

$$C + O_2 \rightarrow CO_2, \quad \Delta H_{298\ K} = -394\ \text{kJ/mol} \qquad (A)$$

$$C + \frac{1}{2}O_2 \rightarrow CO, \quad \Delta H_{298\ K} = -111\ \text{kJ/mol} \qquad (B)$$

$$C + CO_2 \rightarrow 2CO, \quad \Delta H_{298\ K} = +171\ \text{kJ/mol} \qquad (C)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2, \quad \Delta H_{298\ K} = -283\ \text{kJ/mol} \qquad (D)$$

where reactions (A) and (B) represent the exothermic carbon combustion reactions, reaction (C) represents the endothermic carbon gasification by carbon dioxide, and reaction (D) represents the homogeneous carbon monoxide oxidation reaction.

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Nomenclature

C	concentration
D	molecular diffusivity
d	particle diameter
$d(t)$	particle diameter as a function of time
E_a	activation energy
k_0	pre-exponential factor
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature
u	fluidization velocity
X	conversion
Symbols	
ε	bed voidage
$\dot{m}$	mass flow rate
ρ	density
μ	viscosity
ΔH	heat of reaction
Subscripts	
c	carbon
g	gas
i	denotes species
mf	minimum fluidization velocity
s	solid

When the combustion environment consists of H_2O vapor along with O_2 and CO_2, the following reactions are also involved [7].

$$C + H_2O \rightarrow CO + H_2, \quad \Delta H_{298\ K} = +130\ kJ/mol \tag{E}$$

$$CO + H_2O \rightarrow CO_2 + H_2, \Delta H_{298\ K} = -40\ kJ/mol \tag{F}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O, \quad \Delta H_{298\ K} = -242\ kJ/mol \tag{G}$$

where reaction (E) represents the endothermic carbon gasification reaction by steam, reaction (F) is the exothermic water–gas shift reaction and reaction (G) represents the exothermic H_2 oxidation reaction. Since steam is one of the main components in oxy-fuel combustion, it is important to consider its effect in experiments and analysis.

While a number of studies are available investigating the combustion characteristics of single char particles in air-fired fluidized bed combustor [10–14], only few studies have been carried out in the context of oxygen-fired fluidized bed combustion [8,9]. However, the effect of steam on char particle combustion was not considered in these studies. Moreover, prior studies considered mainly bituminous coal. Studies on the combustion characteristics of single char particles using brown coal in Oxy-FB combustion are non-existent.

This paper presents the combustion characteristics of individual and large Victorian brown coal char particles in a small fluidized bed reactor under different oxy-fuel combustion conditions. The effects of oxygen and steam in feed gases in the combustion atmosphere, and bed temperature are considered in this study. Moreover, the particle temperature was also monitored to examine the difference between the bed temperature and the char particle temperature during char combustion.

2. Experimental section

2.1. Materials

Experiments were carried out with single char particles prepared from briquetted Victorian brown coal. The composition of this char is given in Table 1.

Initially the single coal particles were shaped into almost spherical of approximately 8–10 mm diameter. Then the coal particles were devolatilized in a thermo gravimetric analyzer (TGA) with N_2 at 600 °C for 1.5 h to form char particles (5–6 mm in diameter). A hole was drilled to the centre of each char particle (see Fig. 1) and a thin Type-K stainless steel sheathed thermocouple (<0.5 mm in diameter) was inserted into that hole, and secured carefully. The true density of these briquetted char particles was 1682 kg/m^3.

As bed material, quartz sand of 106–150 μm was used in the reactor. The particle density of this sand was 2657 kg/m^3. The minimum fluidization velocity was 0.05 m/s which was determined by varying different gas flow rates during calibration at the temperature range of operation. At minimum fluidization, the bed voidage was 0.48.

2.2. Experimental procedure

The schematic diagram of the experimental installation is shown in Fig. 2. This installation consisted of a small fluidized bed reactor made of quartz, electric furnace, systems for gas supply, and flue gas analysis system. The inner diameter of the reactor is 40 mm and the height of the reactor is 550 mm. Prior to entering the reactor, all gases (O_2, CO_2 and H_2O) were pre-mixed, and fed into the reactor through a distributor plate. The H_2O was fed using a pre-calibrated HPLC pump and the flow rate was controlled with a pre-set position identified during calibration.

At the beginning of an experiment, the bed was loaded with 20 g sand as bed material and the char particle coupled with a thermocouple was inserted to the reactor through the side arm. Another thermocouple was inserted through the side arm of the reactor to monitor the bed temperature during the entire experiment. The gas compositions were set to their desired value and the reactor was electrically heated at a rate of 15 °C/min to the desired temperature. The bed temperature during experiment was controlled with the pre-calibrated electric furnace controller. When the bed temperature reached around 500 °C, steam was introduced (in experiments with steam). During the experiments, the gas velocity was 1.66 m/s at the entrance of the reactor, whilst at the bed the velocity was 0.07 m/s. The start-up period was around 1 h and the steady state period was 30 ± 10 min.

Table 1
Composition of the char used in the experiment.

Proximate analysis (wt.% dry basis)		Ultimate analysis (wt.% dry and ash-free basis)		Minerals and inorganic (wt.% ash basis)	
Volatile matter	4.00	Carbon	87.92	SiO_2	14.40
Fixed carbon	89.22	Hydrogen	3.06	Al_2O_3	10.70
Ash	6.78	Nitrogen	0.89	Fe_2O_3	13.60
		Sulphur	0.63	TiO_2	0.69
		Oxygen	7.50	K_2O	0.62
				MgO	12.40
				Na_2O	6.40
				CaO	11.20
				SO_3	22.30