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Ignition behavior of single coal particle in a fluidized bed under O_2/CO_2 and O_2/N_2 atmospheres: A combination of visual image and particle temperature

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HIGHLIGHTS

- Coal particle devolatilization was studied in a transparent fluidized bed.
- Experiments were conducted under O_2/N_2 and O_2/CO_2 atmospheres at 850 °C.
- Ignition delay time dramatically increases under CO_2 atmosphere.
- Devolatilization is unaffected by atmosphere, but controlled by heat transfer.

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ABSTRACT

Single coal particle ignition behavior was studied in a two-dimensional (200 mm × 20 mm × 400 mm) fluidized bed under O_2/N_2 and O_2/CO_2 atmosphere with O_2 volume concentration in the range of 0–40%, by a combination of visual observation of the volatile flame and measurement of the particle center temperature. A piece of transparent quartz glass was used as the front wall of the fluidized bed to allow visual observation. The investigated fuel particles were spherical sub-bituminous coal particles with diameter in a range of 6–13 mm, which were artificially carved from selected original coal particles. The volatile combustion flame was recorded by a color video camera to analyze its ignition time delay and extinction behavior. The temperature in the particle center was measured by a very thin thermocouple to follow the particle heating process. Results indicate that under O_2/CO_2 atmosphere the ignition delay time is much longer than in O_2/N_2 atmosphere. The devolatilization process is controlled by internal and external heat transfer but it is almost unaffected by atmosphere at the same O_2 concentration. The effect of volatile combustion on heating and extinction delay time can be neglected for larger coal particles.

1. Introduction

In the foreseeable future, coal would still be the predominant fuel in worldwide power generation. However, CO_2 emissions from coal combustion take up over 40% of global CO_2 emissions [1]. In view of high urgency to reduce CO_2 emissions, development of CCS (Carbon Capture and Storage) technology is promoted extensively in recent years [2,3]. Among various carbon capture technologies, O_2/CO_2 combustion (also known as oxy-fuel combustion) is one of the most competitive technologies, where fuel is burnt with oxygen and recycled flue gas [4]. Then the generated high concentration of CO_2 (>90 dry $\%_{vol}$) can be compressed and transported for utilization or storage.

Extensive studies [5–10] have been performed on comparison of coal combustion characteristics under O_2/N_2 and O_2/CO_2 atmosphere. They indicate that coal combustion reaction rate is considerably reduced when N_2 is replaced by CO_2 with the same oxygen concentration. However, most of the existing studies are limited to pulverized coal (PC). As an alternative clean coal utilization technique, fluidized bed (FB) boilers have been utilized in many power plants, where the fuel combustion conditions are much different from those in PC boiler, such as fuel particle size, furnace temperature, and fluid dynamic behavior. Currently, the O_2/CO_2 FB combustion technology is being actively developed in both academy and industry [11–16]. Canmet Energy from Canada reported pollutant formations and operating experiences in 100 kWth and 0.8 MWth pilot-plants with flue gas recycle under O_2/CO_2 atmosphere [17–20]. The transition from O_2/N_2 combustion to O_2/CO_2 combustion was smooth. CO and NO_x specific emissions were

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Nomenclature

A_e	evaporation surface area (m^2)	T_b	bed temperature (K)
$C_xH_yO_z$	lumped volatile	T_s	solid temperature (K)
c_s	solid thermal capacity (J/(kg K))	t	time (s)
E_{devol}	devolatilization activation energy (J/mol)	U	fluidization velocity (m/s)
E_{volcom}	volatiles combustion activation energy (J/mol)	U_{mf}	minimum fluidization velocity (m/s)
h_{conv}	convection heat transfer coefficient (W/(m^2 K))	V_{cell}	cell volume (m^3)
$\triangle H_{evap}$	heat of vaporization per unit mass of moisture (J/kg)	V^*	initial volatile content (%)
$\triangle H_{devol}$	apparent heat of devolatilization per unit mass of volatile matter (J/kg)	ε_r	emissivity of the particle
$\triangle h_{volcom}$	heat of combustion of volatiles (J/mol)	η	fraction of the enthalpy from volatile combustion reaching fuel particle
R_{evap}	evaporation rate (kg/s)	λ_s	solid thermal conductivity (W/(m K))
R_{devol}	devolatilization rate (kg/s)	ρ_s	solid density (kg/m^3)
r_{volcom}	volatiles combustion rate (mol/(m^3 s))	ρ_{s0}	initial solid density (kg/m^3)
k_{devol}	devolatilization pre-exponential factor (1/s)	σ	Stefan–Boltzmann constant (J/(m^2 s K^4))
k_{volcom}	volatile combustion pre-exponential factor (1/s)	σ_E	standard deviation activation energy (J/mol)
r	radius (m)		

lower than those under O_2/N_2 combustion. However, SO_2 emissions were significantly higher under O_2/CO_2 combustion. These results agree with the finding by Duan et al. [12] who conducted O_2/CO_2 combustion experiments in a 50 kWth circulating FB. They found that NO emission could be drastically reduced by O_2 staging.

In view of laboratory-scale studies, Scala et al. [13,21] presented a systematic study of char particle combustion in a lab-scale FB under O_2/CO_2 atmosphere, and found that both gasification of CO_2 with char and homogeneous CO oxidation were significant. Guedea et al. [22] conducted single coal particle devolatilization under O_2/N_2 and O_2/CO_2 atmosphere in a thermo-gravimetric oven and found that O_2/CO_2 mixtures resulted in slightly longer devolatilization time.

However, regarding single coal particle devolatilization in FB under different atmospheres, there are few studies. Such information is critical for revealing the combustion difference between O_2/N_2 and O_2/CO_2 combustion, and is important for oxy-fuel FB design and operation. Traditionally for studies on single coal particle devolatilization characteristics in FB, there are three main methods: (i) by measuring particle temperature, the devolatilization time was defined as the time when the temperature in the particle center reached the bed temperature [23], (ii) by extracting coal particles suddenly from the reactor and quenching, the devolatilization time was defined as the time when the particle weight loss rate became less than 1% [22,24], (iii) by optical access of the reactor, the entire devolatilization and combustion process of fuel particle was observed visually. Prins et al. [25] designed a two-dimensional transparent FB for studying coal particle devolatilization and combustion and provided numerous of valuable results on coal combustion characteristics. Recently, based on visual measurements, Levendis' group [26] revealed coal devolatilization and combustion mechanisms under O_2/CO_2 atmosphere, but again their studies are limited to pulverized coal.

In this work, two of the above three methods are combined, those of particle temperature measurement and visual access, to investigate the effect of CO_2 and enhanced O_2 levels on single coal particle devolatilization characteristics. The experiments were performed in an electrically-heated FB with a transparent front wall; meanwhile, temperature at the coal particle center was recorded continuously for analyzing devolatilization characteristics.

2. Experimental methodology

The studies were carried out in a two-dimensional (200 mm × 20 mm × 400 mm) and electrically-heated (6.0 kW) FB (see Fig. 1). Two-dimensional FBs, which can provide intuitive information of bubbles and solid mixing, have been widely used [27,28]. Besides, two-dimensional bed is considered to be the appropriate device for the present study, as it allows the use of a single coal particle [25]. A piece of transparent quartz glass with size of 200 mm × 400 mm was fitted to serve as the front wall of the FB. One stainless steel plate, fixed with four bubble caps as the gas distributor, ensured uniform distribution of the inlet gas. The pressure drop across the distributor was 0.26 times the pressure drop across the bed. The furnace temperature profile was measured along the vertical axis of the furnace by four sensitive calibrated thermocouples, at the heights of 50 mm, 150 mm, 250 mm and 350 mm above the gas distributor. Thermal insulation material wrapped the reactor to reduce heat loss (see Fig. 1). A self-adjusting PID controller was applied for bed temperature control. Bed materials and fuel particles were fed into the bed through a stainless-steel funnel, which was located at the bed top.

Fig. 2 shows the schematic diagram of the experimental system. Three kinds of gases were supplied by different cylinders (nitrogen, carbon dioxide and oxygen) and calibrated rotameters were adopted to measure the gas flow rates. Before entering the bed, the gases were mixed in a mixing cylinder and heated to a desired temperature by an electric preheater (1.5 kW).

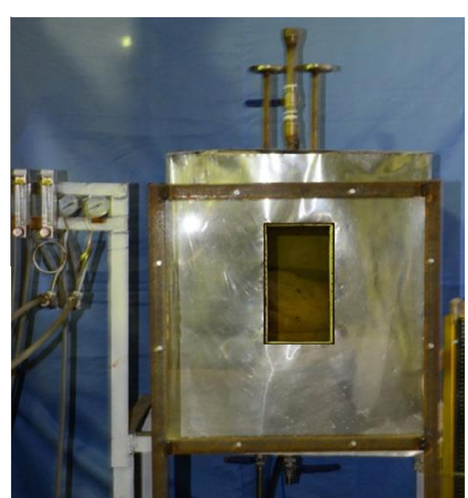

Fig. 1. Photograph of experimental apparatus.