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Investigation of steam effect on ignition of dispersed coal particles in O_2/N_2 and O_2/CO_2 ambiences

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ABSTRACT

In this paper, we intensively investigate the influence of steam on the hetero-homogeneous joint ignition of dispersed coal particle streams in both O_2/N_2 and O_2/CO_2 conditions of an optically accessible flat-flame burner. Two differently ranked coals and one bituminous char were tested for a comparison. The effects of moisture content in the raw coal, steam content or diluents (N_2/CO_2) in the ambience, and fuel types were systematically examined under isothermal conditions. First, it is seen that the moisture content in raw coal delays its ignition because of endothermic vaporization, which becomes weakened at the high ambient temperature. Secondly, three main mechanisms are categorized to explore the profound effects of ambient steam content on ignition of coal particles, i.e., (*i*) the promotion effect of OH radical on the oxidation of volatile hydrocarbons, (*ii*) the inhibition effect of gaseous H_2O molecule on the equilibrium of hydrocarbon oxidation, (*iii*) the negative effect of endothermic surface gasification reaction (C-CO_2/C-H_2O). In O_2/N_2 ambience (1500 or 1800 K), as the steam content increases, the ignition delay of coal particles is rapidly reduced in an early stage of 0%–5% due to the positive effect of OH radicals, followed by an inappreciable reduction in 5%–13% stage because of both the steam inhibition effect and the endothermic surface gasification. However, in O_2/CO_2 ambience with sufficiently high steam content (5%–18%), the ignition delay even becomes longer with the further increment of steam. It is because of the synergistic effect between C-H_2O and C-CO_2 reaction at high temperatures (1500 K and 1800 K). Finally, for fuel types, the OH radical promotion effect of two lignite samples is obviously higher than that of low-volatile char samples, whereas with steam addition the sodium-rich Zhundong coal exhibits lower ignition delay than Hulunbel lignite due to catalytic effect.

1. Introduction

In a foreseeable future, the role of coal as one of major energy sources in China has gained renewed interest because of its reliability/stability in both supplies and prices [1]. However, public concerns over global climate change have led to mounting efforts on developing technologies to reduce carbon dioxide emissions from conventional coal-fired power plants [2–4].

As one of most promising carbon capture and storage (CCS) technologies, oxy-coal combustion is receiving considerable attention [5]. Instead of using air as oxidizer, pure oxygen (O_2) or a mixture of O_2 and recycled flue gas is used to generate high CO_2 concentration product gas. In contrast to conventional air combustion, the difference in oxy-fuel combustion is caused by various factors, like ambient components, thermodynamics, and chemistry processes [6–9]. Especially, studies have indicated that the ambient steam content in oxy-fuel combustion mode is significantly higher than that in conventional air combustion mode, being 15–30% [10–12] and even up to 40% under wet cycle conditions [13–15]. Considering the complicated and diverse combustion conditions, more fundamentals are still in need for the exploration of combustion characteristics in O_2/CO_2 ambience with relatively high steam content, in particular the ignition characteristics. It is because the ignition, as a crucial step of coal combustion, has a significant influence on the flame stability [2–4], and thus, determines the efficiency and safety of advanced coal-fired boilers under variable loadings.

Studies on the ignition behavior of isolated coal particles have already aroused substantial attention. Considering the ultra-high heating rate which is similar to that in practical combustor, the most widely used bench-scale devices for laboratory ignition studies are drop tube furnace (DTF) and flat-flame burner. Based on existing researches, coal ignition behavior is demonstrated to depend on the coal rank, particle size, heating rate, oxygen mole fraction, diluents, *etc.* [16–20]. Levendis

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et al. [16–17] studied the single particle ignition of anthracite, semi-anthracite and bituminous coals in air and simulated oxy-fuel conditions in a DTF. It was found that higher rank coals (anthracite and semi-anthracite) ignited heterogeneously on the particle surface, whereas the bituminous coal particles ignited homogeneously in the gas phase. Moreover, the replacement of the background N_2 gas of air with CO_2 (i.e., changing from air to an oxy-fuel ambience) at the same oxygen mole fraction will lead to non-negligible ignition delay. Yuan et al. [18] observed a prevalent transition from heterogeneous ignition to hetero-homogeneous joint ignition for dispersed coal particle streams when the ambient temperature was increased from 1200 K to 1800 K in their experiments. Furthermore, they also examined the effects of ambient temperature, oxygen mole fraction and coal rank on characteristic ignition delay time. Likewise, Shaddix and co-workers [20] studied the ignition and devolatilization behavior of pulverized coal particles through particle imaging in both N_2 and CO_2 diluent gases. It was found that the presence of CO_2 retards coal particle ignition, but has no measurable effect on the duration of volatile combustion. Although the aforementioned effects on coal ignition behavior have been enormously addressed in both air- and oxy-fuel conditions, systematic investigations on the influence of ambient steam content are relatively limited. Basically, in a practical coal-fired boiler, steam in the ambience mainly originates from (*i*) moisture content in the raw coal which will evaporate during the drying process, (*ii*) oxidation of hydrocarbons in the coal, and (*iii*) steam contained in the carrier gas and recycled flue gas. More recently, several work have been conducted to specifically investigate the effect of H_2O (including moisture and steam) on the ignition and combustion characteristics of pulverized coal particles [21–25]. Firstly, Binner et al. [21] investigated the combustion behavior of air-dried and wet Victorian brown coal and found an ignition delay caused by the evolution and evaporation of moisture in the wet case. Then, for the ambient steam content, Riaza and co-workers [22] studied the effect of oxy-fuel combustion with steam addition on coal ignition and burnout in an entrained flow reactor. They found that steam addition can lead to an increase in ignition temperature due to the char-steam gasification reaction, but no relevant differences between different steam concentrations were detected. Yi et al. [24] explored the effect of steam on coal combustion behavior in a water vapor furnace and also found that the presence of steam would lead to a longer ignition delay. However, in another independent study, Prationo et al. [25] studied the influence of steam addition on ignition behavior of Victorian brown coal on a McKenna burner by using optical diagnostics. It was suggested that steam can accelerate the ignition of dense brown coal particle stream through the water–gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$). Though contradictory conclusions were drawn from existing researches, they indeed implied that steam truly plays crucial role in coal ignition process, which requires for intensive studies to further divulge the underlying mechanism. It is also noteworthy that the experiments referred above created a humid ambience by adding steam (usually with lower temperature) into a steam-free ambience directly, omitting the heat capacity divergence between H_2O and other component gases. However, this will definitely have significant influence on the ambient temperature profile and may bring non-negligible uncertainties due to temperature variations. Thus, in order to elaborately explore the effect of ambient steam content on the ignition process, it is necessary to conduct the experiments under isothermal conditions.

Based on the issues raised above, this paper aims to examine the influence of H_2O on the ignition behavior of dispersed coal particles under isothermal conditions in both O_2/N_2 and O_2/CO_2 ambience. An optically accessible flat-flame Hencken burner, coupled with an Intensified Charge-Coupled Detector (ICCD) was adopted here as the experimental rig. The effects of moisture content in the raw coal, steam content and diluents (N_2/CO_2) in the ambience, and fuel types were subsequently focused on.

Table 1
The proximate and ultimate analyses of the samples.

Fuel type	Hulunbel lignite	Zhundong coal	Char
Proximate analysis (on a dry basis)			
Fixed Carbon (%)	49.1	65.5	78.1
Volatile (%)	38.8	30.4	3.1
Ash(%)	12.1	4.1	18.8
Ultimate analysis (on a dry-ash-free basis)			
Carbon (%)	74.05	76.82	93.66
Hydrogen (%)	4.17	4.75	1.41
Oxygen* (%)	20.47	17.35	2.54
Nitrogen (%)	1.00	0.37	1.50
Sulfur (%)	0.31	0.71	0.89

* By difference.

2. Experimental set-up

2.1. Fuel properties

Two differently ranked coals and one typical low-volatile bituminous char were particularly used in this experiment for comparison. The proximate and ultimate analyses of the samples are presented in Table 1.

2.2. Optical Hencken burner system

Experiments were performed on a multi-elements non-premixed flat-flame burner system, briefly termed as Hencken burner. With hundreds of inner diameter 1.5 mm stainless steel tubes embedded in an outer diameter 64 mm super-alloy honeycomb, the Hencken burner used in this work can provide a uniform hot-gas environment for coal combustion. The experimental set-up is schematically shown in Fig. 1. A particle feeder, based on the principle of de-agglomeration via high-frequency vibration, was utilized to offer a well-dispersed coal stream with a steady flow rate of 0.07 g/min. The coal and char particles, carried by N_2 (or CO_2 in O_2/CO_2 ambience, about 30 ml/min), were injected into the burner through a 2.5 mm stainless steel tube located in the center of the honeycomb. The detailed description of the Hencken burner can be found in our previous literature [18,26].

In this paper, experiments were conducted in both O_2/N_2 and O_2/CO_2 ambiences. The burner offers a reasonably single variable method to investigate the influence of ambient steam content on coal ignition characteristics. Three typical ambient temperatures, 1800 K, 1500 K,

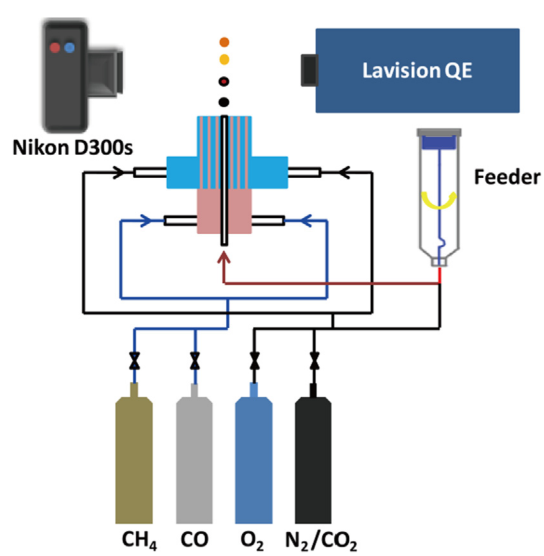

Fig. 1. Schematic of the in-situ optical diagnostics of coal particle ignition.