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Experimental and theoretical analyses on ignition and surface temperature of dispersed coal particles in O_2/N_2 and O_2/CO_2 ambients

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ABSTRACT

An experimental and theoretical investigation is conducted on the combustion of pulverized coal particle streams in either conventional or oxy-fuel conditions. The laboratory setup consisted of a Hencken flat-flame burner operated at the same temperatures of 1200, 1500 and 1800 K in N_2 and CO_2 environments. The visible light detection technique and the calibrated three-color pyrometry are separately used to characterize the ignition delay time and the luminous char surface temperature. First, experimental results indicate that the ignition delay time is relatively longer in CO_2 environment in heterogeneous mode or even heterogeneous-controlled joint mode. The ignition delay is obviously enhanced in O_2/CO_2 ambient when the volatile-flame controlled joint mode is prevalent. The model predictions of particle temperature history further reveal that the extra gas flame radiation of CO_2 and the declined difference between the thermal conductivity are two main reasons. Then, during char combustion, the measurement shows that the char surface temperature is lower in an O_2/CO_2 environment than in an O_2/N_2 environment. It is noted that the temperature difference between N_2 and CO_2 environments enlarges with the increasing ambient temperature. In contrast to conventional O_2/N_2 conditions, the lower O_2 diffusivity in CO_2, the endothermic carbon reaction with CO_2 and the higher heat capacity of CO_2, which are all temperature dependent, synergistically contribute to the enlargement of char surface temperature differences at high ambient temperature.

1. Introduction

The reduction of pollutant emissions and the potential for lower-cost CO_2 separation have prompted the study of oxygen/carbon dioxide recycle (O_2/CO_2) firing for existing pulverized coal (pc) systems [1,2]. The oxy-fuel pc combustion is economically promising and technically feasible with current technologies [3]. 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. As such, the combustion process is significantly changed. In contrast to conventional combustion, the difference in oxy-coal combustion is caused by various factors, like thermodynamics, transport and chemistry processes [4–6]. Due to the complicated and diverse combustion conditions, more fundamental work is still needed for the clarification of differences in O_2/N_2 and O_2/CO_2 ambient, especially the ignition characteristic and surface temperature.

Ignition and combustion behaviors of pulverized coal particle depend on the coal rank, particle size, heating rate and oxygen concentration in the environment. Coal particles may experience a homogeneous gas-phase ignition (GI), heterogeneous ignition (HI) and hetero-homogeneous joint ignition (HGI). The former refers to gas-phase ignition of pyrolytic vapors from coal that is similar to oil drop ignition, whereas the HI represents the direct oxidation of char and in-situ volatiles at the particle surface. Coal particles usually ignite in heterogeneous mode for smaller-particle at low temperature and homogeneously for larger-particle diameter at higher temperature [7–9]. For the homogeneous mode, the ignition process of stoichiometric CH_4 - 21% O_2 /79% CO_2 is longer than that of CH_4 - 21% O_2/79% N_2 mixtures using the closed homogenous reactor model of CHEMKIN with GRI-Mech 3.0 reaction mechanism [4]. There have been also many experiments on coal particle ignition delay in O_2/N_2 and O_2/CO_2 by using wire-mesh reactor, drop tube and laminar entrained flow reactor [10–14]. Most of results showed that the ignition delay time is longer in an O_2/CO_2 environment than in O_2/N_2 and under both conditions, the ignition delay time decreases with increasing oxygen concentration [3,13]. However, it should be

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noted that coal particles are heated by the hot gas in drop tube. The longer ignition delay is attributed to the slower heating rate of the high volumetric heat capacity of O_2/CO_2. In contrast, the significantly higher ignition temperature in wire-mesh reactor is because of the substantially higher thermal conductivity which effectively cools down the particles. Even though the phenomenon is similar, the dominated factors are different in these diverse conditions. Therefore, specify and sufficient analysis is inadequate under different circumstances. Besides, most of the ignition experiments on oxy-fuel combustion mainly focused on the different ignition delay time without the combined analysis in different ignition modes. Actually, except for the heating rate which is the dominated factor in heterogeneous ignition, the ignition time variation should also account for the effects, such as volatile flame, CO_2 thermal dissociation and chemical effect of CO_2 on radical formation. In the following section, multi-alternative experiments, including hetero-homogeneous joint ignition, and systematic theoretical method are carried out to study the oxy-fuel ignition behaviors.

As for the temperature, many experimental studies have been performed in recent years to investigate the effect of a CO_2-rich environment on the char temperature [14–16]. Most experimental and modeling results showed lower particle temperatures and longer burnout times under O_2/CO_2 conditions. Moreover, the higher the furnace temperature, the higher the recorded char temperature, but the differences are small. However, there remains a need for an efficient and accurate measurement of the temperature just at char surface. The CO_2 may influence char surface combustion temperature via several possible mechanisms: (a) the reduced oxygen mass transfer in CO_2, (b) the lower temperature due to the higher heat capacity of CO_2, and (c) the char-CO_2 gasification reaction [17–20]. Moreover, few studies have addressed the detailed theoretical explanation with the experimental results on the basis of accurate char surface measurement.

This work aims to build a single variant experimental and theoretical method to study the ignition characteristic time and surface temperature of coal particles. The clean Hencken burner system is firstly used here to eliminate the effect of steam on coal ignition for both air- and oxy-conditions by using CO flat-flame. Under a smart designing, the comparison of coal ignition between air- and oxy-condition under the same ambient T and O_2 are reported in this paper. The approaches used in this study contain the ignition characterization based on visible light detection technique [9] and non-intrusive three color pyrometry on particle temperature measurements [21–23]. Non-intrusive three color pyrometry (RGB pyrometry) is a promising method for particle temperature measurements. Incandescence from the particles is imaged at the three channels of the camera and the temperature is calculated from the color ratios. In addition to investigate the CO_2 effect on ignition and burnout temperature, the particle temperature history and char combustion temperature calculation are also performed, offering a good correlation and explanation.

2. Experimental methods

A multi-element non-premixed flame burner, briefly termed as Hencken burner, is constructed to provide a steady high-temperature environment also with good optical access. The experiment setup is shown schematically in Fig. 1. The burner uses CO as fuel and the mixture of O_2 and N_2 as oxidant and dilution gas for conventional combustion. The N_2 is replaced by CO_2 for oxy-fuel combustion experiment. The gas ambient temperature and the particle velocity have been measured by the B-type thermocouple and Phase Doppler Anemometry (BSA P60 from DANTEC dynamics). A novel particle feeder is developed based on de-agglomeration principle in order to obtain a well dispersed particle

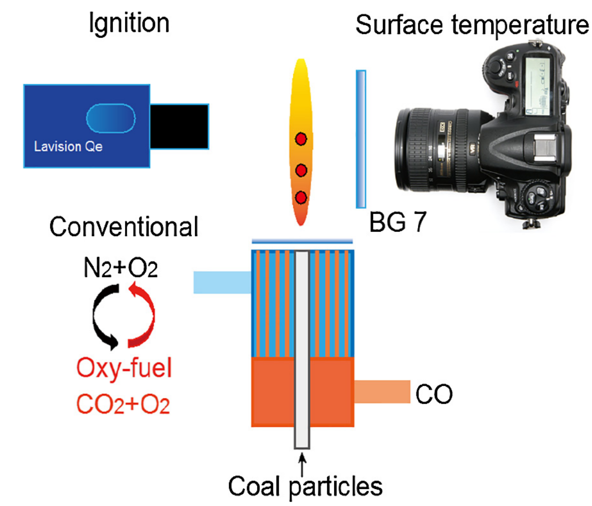

Fig. 1. Schematic of the *in situ* optic diagnostics setup on Hencken burner.

stream [9]. In practical system, 1 g/min standard bituminous coal approximately corresponds to 7 slpm (standard liter per minute) air under a stoichiometric condition, which enables the particle volume fraction c to be about 1.1×10^{-4} at room temperature and then about 3.0×10^{-5} at 1000 K. The large particle spacing ratio implies that the ignition of coal particle streams can be regarded as a statistical summation of ignitions of all isolated particles under a well-dispersed condition. It is of great interest to develop a simply well-dispersed coal particle stream system for studying the ignition mechanisms of particle streams. Besides, in terms of different parts of industrial boiler, the coal particle ignition mechanism is usually different. Thus, the detailed analysis on ignition delay time in different ignition modes is very useful for the practical system.

In fact, the gas ambient temperature will become lower after the equivalent replacement of N_2 by CO_2 due to the high thermal capacity of CO_2, which can be found in Fig. 2. To produce the matching temperature profiles, 30% O_2 concentration is usually adopted in practical oxy-fuel combustion technique [24]. However, it may introduce an oxygen varying error during ignition and surface temperature research, which is obviously a dominate factor in coal combustion. In this work, both the same oxygen and temperature ambient can be satisfied by taking the advantage of

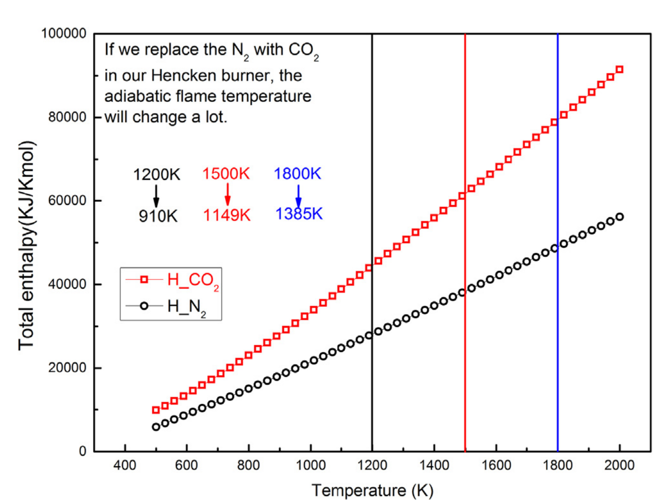

Fig. 2. Total enthalpy of CO_2 and N_2 in different ambient temperature [5] and comparison of calculated gas temperature after the N_2 equivalent replacement by CO_2.