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Investigation of mechanisms in plasma-assisted ignition of dispersed coal particle streams

Fengxuan Zhao [a], Shuiqing Li [a,*], Yihua Ren [a], Qiang Yao [a], Ye Yuan [a,b]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China
[b] CFB Department, Huaneng Clean Energy Research Institute, Beijing 102209, China

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ABSTRACT

The plasma-assisted ignition enhancement of pulverized lignite particles is intensively studied in a laminar, upward Hencken flat-flame burner. By applying a pair of pin-to-pin electrodes with a high-voltage DC power supply, the apparent reductions of ignition delay time, about 0.8–3.5 ms, are observed for all three ambient temperatures, 1200 K, 1500 K and 1800 K, across which the ignition mode transits from heterogeneous ignition (HI) to hetero-homogeneous combined one. Concentrated on 1200 K ambience where HI mode prevails, the plasmas-induced reduction of ignition delay time as a function of the applied voltage (0–20 kV) is explored, in which the chemical effect is found to play a key role in cases with voltage less than 3 kV. Then, under the conditions of different oxygen mole fractions, the discharge mechanisms and the reductions of ignition delay time are further examined to distinguish the chemical and thermal effects on the ignition enhancement. Finally, the gas temperature rise, both measured and predicted at a point located 6 mm above the electrodes, verifies the thermal effect. This paper provides a preliminary understanding of plasma-assisted ignition mechanisms on dispersed coal particles that may be applied in practical combustion system.

1. Introduction

In the past few years, the plasma has aroused increasing attention because of its potential application in the improvement of both ignition and combustion. A significant amount of experiment data in the gas-phase combustion have proved the feasibility of the ignition enhancement [1–3]. Generally, the plasma effect can be divided into two main parts: thermal effect and chemical effect. The application of thermal plasma can be originated to spark ignition system in combustion engines, gas turbines and scramjet engines because of the high temperature region [4,5]. Recently, the non-equilibrium plasma [6–8], characterized by the prominent chemical effect, has gained a lot of attention as it may provide a new possibility for combustion enhancement and flame stabilization by initiating new reaction path and dropping the chemical reaction potential barriers. The traditional *s*-shape ignition curve is changed by the non-equilibrium plasma generated from a nanosecond dielectric barrier discharge [8], which minimizes the thermal effect and supports a high reactive species production. Furthermore, plasma was reported to achieve much leaner combustion, extend the ignition limitation, and reduce NOx emissions in contrast to the conventional combustion [9]. In addition to the aforementioned effect of plasma, another effect, ionic wind, has also been gradually recognized and proposed to account for the combustion promotion [10].

Apart from the utilization of plasma in gas-phase combustion of hydrocarbons, it is noteworthy that the plasma-assisted ignition (PAI) technology has been rapidly developed and applied in coal-fired power plants. For instance, according to crude statistics at 2011, PAI technology had already been installed ignition systems of 560 power plants in China, including 25 units of 1000 MW, 220 units of 600 MW, etc. The traditional ignition energy supplied from oil can be replaced by the high temperature ambience generated from the plasma discharge [11–13]. It has been found that a 10 kW plasma torch can be used to ignite different kinds of coal and guarantee the burnout rate of the low-volatile coal, such as anthracite and lean coal [14]. It was also verified that plasma could intensify the gasification of coal [15–18] and reduce the pollution emission [19]. Therefore, the PAI power generation technology has exhibited advantages in the stable and efficient combustion [20]. As far as the simulation work is concerned, a numerical analysis of plasma-fuel system revealed that the char/carbon can be partially gasified by plasma thermo-chemical preparation and

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* Corresponding author.
E-mail address: lishuiqing@mail.tsinghua.edu.cn (S. Li).

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confirms the possibility of low-rank bituminous coal ignition without preheating primary air [21]. It was found in later simulations that plasma decreases nitrogen oxide formation and increases the incineration efficiency [22]. Generally, all those enhancements on combustion processes can be primarily attributed to either thermal or chemical effects. However, the basic principles and mechanisms for interpreting plasma-assisted coal combustion is still unclear, because of less detailed experiment data and few mechanistic analyses on such kind of complex phenomena. So far the fundamental studies on plasma-assisted coal combustion are scarcely reported, other than finely distinguishing the different thermal or chemical effects of plasma. It really becomes one obstacle for further process improvement and parameter optimization of PAI technology that has been widely used. In this paper, we aim to characterize the thermal and chemical effects in plasma-assisted ignition of pulverized coal streams, and provide a preliminary understanding of plasma-assisted ignition mechanisms on dispersed coal particles.

In contrast to dozens of studies on ignition of single coal particle [23–26], research on the ignition of dispersed coal particle stream, which is more comparable to actual process, is relatively scarce. According to our previous work based on Hencken flat-flame burner for coal particle streams, a transition from the heterogeneous ignition mode to the hetero-homogeneous one was observed along with the increment of ambient temperature [27]. The ignition delay time decreases from approximately 20 ms to 10 ms when the ambient temperature increases from 1200 K to 1800 K. Besides, an explicit ignition mechanism can be easily achieved through manipulating the operating parameters of our Hencken burner [28]. This is conducive to analysis the PAI mechanism since the coal plasma-assisted experiment is accomplished based on a specific ignition mode.

For the generation of plasma, the alternatives of power supply and electrodes configuration are critical to the plasma characteristic [29]. Direct current (DC) power supply has usually been chosen to generate spark discharge which reflects a strong thermal effect [30]. A dielectric barrier discharge with nanosecond pulse power supply was used to study the plasma chemical effect, and exclude the thermal effect by confining the breakdown current [31]. In this work, a high voltage DC supply with a current-limiting resistance is introduced here for a purpose of differentiating the thermal and chemical effect by manipulating the input plasma energy. The electrode is a pin-to-pin configuration, which minimizes the influence on flow and temperature field. The oxygen mole fraction, ambient temperature, and supply voltages are manipulated to specify the PAI mechanism.

2. Experimental methods

A multi-element non-premixed flat-flame reactor [32] has been established to support a steady high-temperature environment which is convenient for optical measurement. Fig. 1 shows the schematic of the experimental set-up. The burner contains a ceramic honeycomb with stainless steel tubes to sustain the non-premixed flame let. For these hundreds of multi-element diffusion flames, CO is used as a heat-support fuel to eliminate the noise on the detected emission signals in an early coal ignition stage, while a mixture of N_2 and O_2 is used as the oxidant. The ambient temperature and oxygen mole fraction of the gas products can be flexibly adjusted by changing the mass flow rate of CO, O_2 and N_2. A well dispersed coal particle stream can be achieved by the highly-frequent vibration of the syringe outlet tube in our novel particle feeder [27] so that the particles in the entrained flows can achieve a relatively good monodisperse status. The mass flow rate of coal particle stream was calibrated and is kept constant at about 0.03 g/min. The carrier gas is N_2 and the coal particle streams are injected through a 2 mm steel tube located at the centerline of the burner. The velocity of the gas and particles is about 1.5 m/s, which is measured by a Phase Doppler Anemometry (BSA P60 from DANTEC company). The coal particle residence time in a certain distance above the burner can be calculated as $t = \int 1/v_p\, dl$. The gas flow rate under three conditions, 1200 K, 1500 K, and 1800 K can be seen in Table 1.

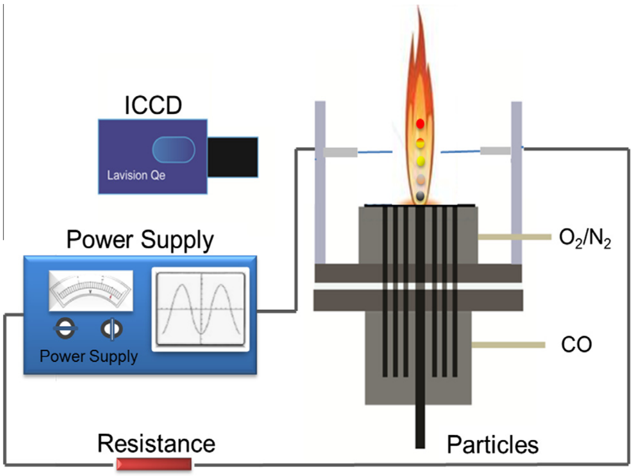

Fig. 1. Configuration of experimental setup including a plasma generation system.

A DC discharge plasma is used in our experiment as shown in Fig. 1. Two pin-to-pin Tungsten needles, located symmetrically 12 mm above the center of burner with a 5 mm gap, are used as the electrodes for the plasma generation. The width of the gap and the height of the electrodes are designed to avoid the excessive breakdown voltage and the thermal influence of CO flame on electrodes. The uniform discharges between two electrodes are supported by a DC electrical source with a maximum voltage of 20 kV. The needles are surrounded by insulative ceramics, in case the burner is charged. The voltage and current waveforms are separately detected by an oscilloscope and a coupling current probe. A ten megohm current-limiting resistance is linked in series with the power supply, as an effective method, to restrict the dramatic current growth and the plasma input energy (single pulse energy) once the voltage exceeds the breakdown limitation.

The optical emission signal from the coal particles, containing the intensity of blackbody emission and other chemiluminescence light, is collected by an Intensified Charge-Coupled Device (ICCD) from Lavison Company to characterize the ignition delay. The exposure time is set as 50,000 ns to prevent the saturation of combustion signal and minimize the interference of CO flame. The ICCD continuously captures 600 pictures at the rate of 10 Hz in order to get rid of the influence of the coal feeder instability. The environment background signal from Hencken flame and plasma discharge without coal particle combustion is also measured by ICCD before each experiment. The peak of signal intensity from coal combustion emission is about ten times of the averaged background signal, which means a relatively high signal/noise ratio. The final measured intensity-residence time curve is obtained after subtracting the background signal. The residence time when the coal particle combustion intensity reaches the 10% of the maximum peak intensity value is considerably used to indicate the characteristic ignition position. This ignition criterion was described in detail and validated in our recent work [27], which, more recently, has been adopted by Simoes et al. [33].

The Hulunbel lignite is used in this work. To match the size of pulverized coal in industrial power plant, the coal particles have