STUDY ON PREMIXED COMBUSTION ENHANCEMENT WITH DIELECTRIC BARRIER DISCHARGE

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ABSTRACT

In this paper, a coaxial cylindrical Dielectric Barrier Discharge (DBD) reactor is designed to investigate the enhancement processes of plasma-assisted methane combustion with activating premixed CH4/air mixtures. Flame shape and flame front structure are observed by digital camera and OH Planer Induced Fluorescence (OH-PLIF) technique, respectively. With plasma being off and on, the temperature profiles along the axis of flame are measured by a double platinum–rhodium thermocouple and compared with each other. Experimental results show that, without plasma assistance, the flame appears as conic shape. While plasma is applied, the height of conic tip decreases dramatically. Due to the height of flame edge not decreasing obviously, the flame exhibits an ‘M’ shape structure. The highest temperature position moves towards the tube when plasma is applied. But temperature value does not increase obviously.

1. INTRODUCTION

Recently, plasma-assisted combustion, especially non-thermal equilibrium plasma, has received increasing attention due to its advantage on improving combustion efficiency, stabilizing combustion process, as well as increasing burning velocity [1-4].

Several experimental researches have shown that non-thermal plasma can enhance flame combustion process by activating unmixed or premixed gases prior to combustion. L. A. Rosocha et al. have adopted a coaxial-cylinder, non-thermal, silent discharge plasma reactor to process a propane gas before combustion. The results indicate that fuel activation process can changes the physical appearance of the flame and enhance combustion processes [5]. Ombrello et al. applied a gliding arc plasma to the flame region which resulted in an increase in extinction strain rate of CH4/ air diffusion combustion [6]. Sy Stange ea al. have employed a dielectric barrier discharge to activated propane, and the results show that the flame propagates downward can suggest the burning velocity increases with plasma on [7]. Jie Tang et al. systematically study plasma assisted plasma by activating propane or air before they are mixed, respectively. It was found that combustion is enhanced in both activation methods, and active species generated by activating air play a more important role in combustion [8]. To date, the influences of plasma on flame and combustion have been investigated by various research groups. Nonetheless, the prospect of gaining insight into detailed characteristics of reaction zone within the flame is required for good resolution of combustion enhancement mechanism.

We have conducted a study of plasma-assisted methane combustion with activating premixed CH4/air mixtures. OH Planer Induced Fluorescence technique (PLIF) can precisely detect the edge of reactive zone with OH radical emissions. With plasma being off and on, we captured the flame direct images and flame front structure with digital camera and OH-PLIF[9]. Then temperature spatial distributions of combustion zone are also investigated.

This work is in part supported by the Fundamental Research Funds for the Central Universities (Grant No. xjj2013086), National Natural Science Foundation of China(Grant No. 51107096)..

2. EXPERIMENTAL SETUP AND TEST PROCEDURES

As shown in Fig. 1, a coaxial-cylinder DBD reactor is designed to generate plasma, which consists of grounded inner electrode, dielectric barrier, outer electrode and fixed element forinner electrode. The quartz glass tube (inner diameter of 10mm, wall thickness of 1mm and length of 300mm) is wrapped with a copper strip electrode of 50-mm width which connected to high voltage. The grounded stainless steel eletrode, with a diameter of 2 mm, is placed in the central axis of the tube. In order to eliminate effects of electric field on the flame, the end of quartz tube and the electrodes were separated with a 20mm distance.

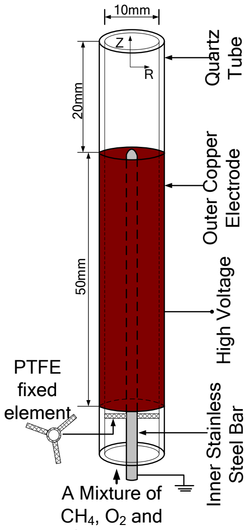


Fig. 1 The schematic of coaxial-cylinder dielectric barrier discharge combustor

Schematic of experimental platform can be seen in Fig. 2. It mainly consists of plasma reactor, electrical parameters measurement system, a gas delivery system, OH-PLIF system, temperature measurement device. Positive pulse voltage generated by CTP-2000K/P (Nanjing Suman Electronics) is applied to the electrodes to form non-equilibrium plasma The applied voltage is measured with a high voltage probe (Tek P6015A), and discharge current is captured via a current transformer (Person 2877, with a bandwidth of 200MHz). The voltage and current signal are record by a four-channel digital oscilloscope (Tektronix DPO4034, with a bandwidth of 350MHZ, 2.5-GSa/s sampling rate). In the following experiments, the frequency of applied voltage is fixed to 6 kHz, and the different deposited power is achieved by adjusting voltage of power source. The discharge power can be obtained by Lissajous diagram with charge-measuring circuit.

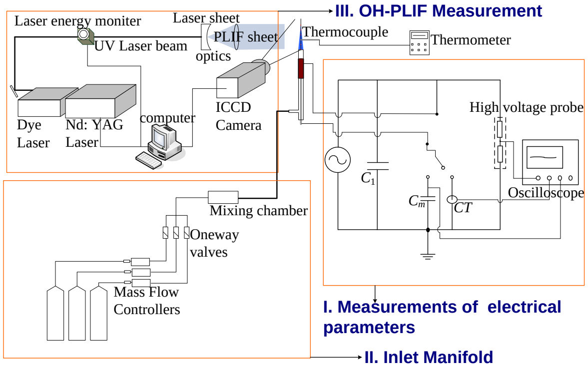


Fig. 2 Schematic layout of OH-PLIF Measurement, Inlet Manifold, Measurements of electrical parameters

The flow rate of methane, oxygen and nitrogen was adjusted by a mass flow controller (MKS 647C, with accuracy of 0.5%). Those three gases from different line enter a stainless steel chamber (500 ml stainless steel) to mix each other. Then the premixed gases are activated in DBD region, and the premixed gases are ignited and combustion on the top of the quartz glass tube.

The flame appearances are obtained with an ordinary CMOS camera (Canon EOS 60D). The flame front structures are investigated by the OH-PLIF technique, as shown in Fig. 2, A laser sheet of 80mm in height as the excitation of OH fluorescence is induced by a Nd:YAG laser (Quanta-Ray Pro-190) and a tunable dye laser (Sirah PRSC-G-3000). Then an ICCD camera (La Vision Image Prox) captures the LIF signals of OH emission. In each specified case, 100 OH-PLIF images are obtained, and ensemble average of all OH-PLIF images revised through removing background noise with the energy monitor.

The temperature profiles are measured with a double platinum–rhodium thermocouple with a temperature range of 0–1800 ℃. The central position at the top of the quartz tube is designated as the original point for vertical temperature measurement with a 2 mm interval for each point along the vertical axis of the flame.

3. RESULTS AND DISCUSSION

The waveforms of applied voltage and discharge current are shown in Fig. 3. The applied voltage is 7.5kV, and frequency is 6 kHz. The rising time of applied voltage is about 8μs, and pulse duration is 20μs at full width half maximum. Discharges occur twice during one pulse voltage: one in the rising time, the other in the falling time of the applied voltage. The peak value of the pulse increases with increasing the applied voltage.

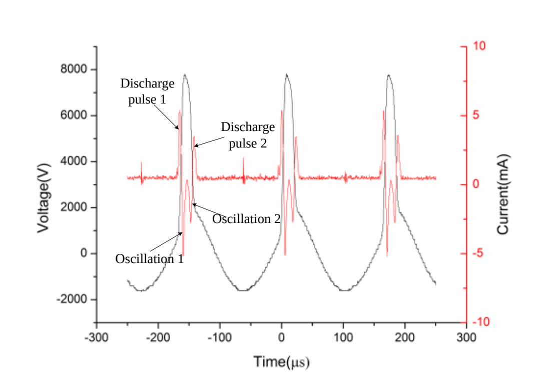
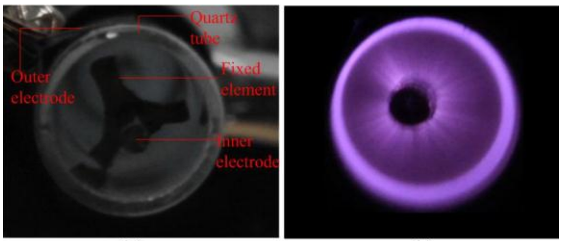


Fig.3 Waveforms of Applied voltage and discharge current

Discharge image captured from the top of tube is presented in Fig. 4, where the applied voltage is 18 kV and the exposure time is 1/4s. In a coaxial-cylinder DBD reactor, the highest electric field is located near the inner electrode. Therefore, lots of filamentary discharge presents as radical distribution in the tube. The intensity of optical emission from discharge is strongest along the inner electrode. It is noted that optical intensity along quartz tube wall is strong because of reflection of glass tube.



(a) (b)

Fig. 4 (a) Image of electrode configuration; (b) Image of plasma discharge

Here, the flow rate of methane, oxygen and nitrogen are fixed to 1.030L/min, 2.060L/min and 7.749L/min, respectively, with the equivalence ratio of 1. With plasma being off and on, the flame shape and flame OH-PLIF image are obtained in this experiment. Fig. 5(a) gives the direct physical appearance images of the premixed $CH_4/N_2/O_2$ flame by the digital camera. The premixed gases combustion steadily when the plasma is off, and in such case, the flame appears as conic shape. While the flame tends to burn more dramatically and flame height decreases when plasma is applied, as clearly shown in Fig. 5(a). In addition, the conic tip of flame get fuzzy and the flame structure becomes wider with a 10-W plasma compared to that without plasma assistance. These changes of flame shape indicate that the combustion process is enhanced with plasma.

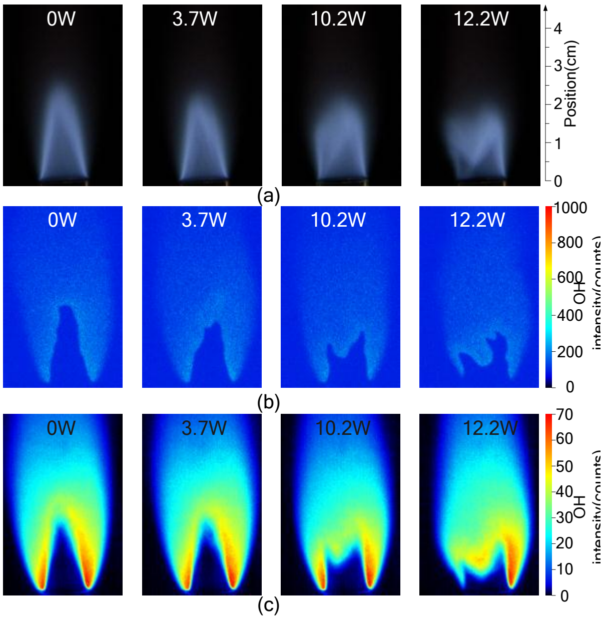


Fig. 5 (a) Flame images captured by digital camera; (b) Single OH-PLIF images as a function of plasma power; (c) Averaged OH-PLIF images as a function of plasma power

The single and averaged OH-PLIF images at different discharge power under the same experimental conditions of Fig. 5(a) are shown in Fig. 5(b) and Fig. 5(c). Generally, the average OH-PLIF images are used to investigate combustion because of randomness of the flame front structures. From the clear outline of combustion reaction zone, we can find that the height of flame edge decreases slightly with the increasing discharge power, the height of conic tip and along the central region of reactive zone decreases more fiercely than that of flame edge. Thus the flame front structure is varied from conic shape to "M" shape with discharge power increasing, which suggests that the propagation speed in the center of flame is higher compare to that of flame edge. Combining with the discharge image in Fig. 4, discharge intensity near the inner electrode is highest and gradually decreases along the radial direction, which significantly promotes burning velocity and affects the flame structure.

The temperature of combustion zone is measured by a double platinum–rhodium thermocouple in this paper. The flow rate of methane, oxygen and nitrogen are fixed to 0.269L/min, 0.540L/min and 2.014L/min, respectively, with the equivalence ratio of 1.

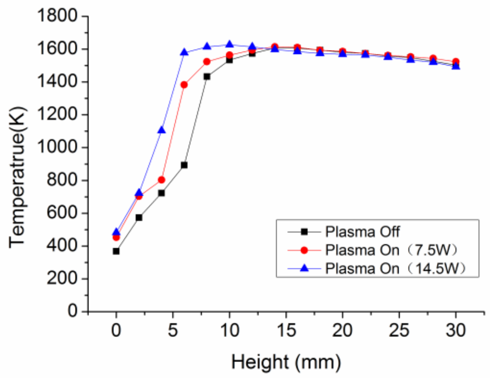


Fig. 6 Temperature distribution of the central axis of the flame

Fig. 6 shows measured temperature profiles in the centerline of flame with and without plasma. As shown in Fig. 6, in the preheat zone, the temperature rises quickly and has great gradient, then reaches the highest value in combustion zone. Due to the cooling by gas flow from high-temperature to lower-temperature environment, negative temperature gradient appears at the rear of flame zone. The maximum temperature reaches about 1606K at the height of 14 mm when no plasma is present. If a 14.5W plasma is applied, there is only a small temperature increase in this flame, approximately 25K. It indicates that Joule heating from the plasma discharge is small. However, the highest temperature position moves towards the tube when plasma is applied. This phenomenon is in agreements with the flame front structure that tend to propagate downward.

4. CONCLUSIONS

In the experiment, a DBD reactor is employed to explore the enhancement processes of plasma-assisted premixed CH4/air mixtures combustion. With plasma being on and off, the flame shape, temperature distributions are investigated, respectively. Due to the decreasing distribution of discharge density along the radial direction, flame height in the flow centerline decreases and the flame structure is varied from conic shape to “M” shape with discharge power increasing. It is also noted that the flame surface is not ideally symmetric because of the non-perfectly plasma reactor. Results suggest that the increase of the discharge intensity significantly promote burning processes. In addition, the highest temperature position moves towards the tube when plasma is applied. But temperature value does not increase obviously with plasma assistance, which indicates that Joule heating from the plasma discharge is relatively small.

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