Augmentation of pre-mixing process of combustion using dielectric barrier discharges

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Abstract: A method of pre-mixing process augmentation for fuel combustion using dielectric barrier discharges (DBD) is presented. The mixing process of fuel and air can be augmented by the edge electric field of the electrodes because its transverse component will exert an electric force on the charge particles generated by DBD. The experimental results show that the combustion can be drastically influenced by this augmentation of pre-mixing process. A hollow flame caused by non-sufficient mixing, in which the air flow velocity is much larger than that of fuel gas, is used to demonstrate this kind of augmentation effects. Once the discharge is ignited, the hollow region in flame will gradually disappear. And further, the flame can propagate backward into the quartz tube. In this paper, the dependences of this kind of augmentation on the applied voltage magnitude and on the distance \( d \) from the electrodes to mixing region are examined. The critical voltages for hollow elimination and onset of backward propagation of flame are measured. The augmentation effects will vanish once the value of \( d \) exceeds 2cm, the hollow flame can not be changed even the applied voltage is very high.

Keywords: Dielectric barrier discharge (DBD), Plasma assisted combustion (PAC), Pre-mixing process augmentation.

1. Introduction

In the last decade, there has been considerable interest in combustion enhancement using nonthermal plasmas [1]. It’s commonly believed that electrical discharge plasmas in a gaseous medium can activate a fuel or a fuel/oxidizer mixture and lead to improvement of characteristics of ignition and combustion. However, the precise mechanism by which combustion is enhanced is still not well understood. In the case of nonequilibrium discharges, the enhancement is usually attributed to the formation of excited species or radicals such as vibrationally hot molecular nitrogen \( \text{N}_2 \), as well as \( \text{O}, \text{H} \), and ground-state and electronically excited \( \text{OH} \). In papers [2, 3], A nonequilibrium ultrashort pulsed repetitive discharge has been employed to study its effects on fuel combustion, it’s observed that the discharge can extend the flammability limit and reduce the ignition delay. Other previous studies [1, 4, 5 and 6] demonstrated that the flame speed is increased and combustion stability is enhanced by the discharges. In this paper, pre-mixing process augmentation of combustion using dielectric barrier discharges (DBD) is studied. The mixing process of fuel and air can be drastically changed by the edge electric field of the electrodes because its transverse component exerts an electric force on charge particles generated by DBD.

2. The effects of DBD on the flame structure

A coaxial cylindrical DBD configuration used in these experiments is shown in Fig. 1. When high voltage is applied, self-terminating microdischarge streamers form in the gap and nonequilibrium plasmas can be generated. In this experiment, the outer electrode, a metal film, surrounds a quartz tube with an inner diameter of 12.5 mm and a thickness of 1.25mm. An oscillating high voltage with maximum amplitude of up to 20 kV and frequency of 20 kHz was applied to it. The fuel gas flows between the inner electrode and the quartz tube, and immediately flows into the mixing zone which is a length of 5cm region between the ends of the electrodes and the end of the quartz tube. The inner electrode is a hollow metal tube having an outer diameter of 10 mm and an inner diameter of 6.5mm, through which the air is conducted into the mixing zone. The mixed fuel-air mixture is finally ignited in the open end of the quartz tube.
The voltage across discharge gap is measured by Tek6015A voltage probe and the current is measured by a Rogowski coil (Pearson current monitor model 2877). All signals are recorded with digital oscilloscopes. Fig. 2 shows the applied voltage waveform and the corresponding discharge current together.

The photographs displayed in Fig. 3 are methane-air flames with an increasing applied discharge voltage. The air and methane flow rates were set to 400l/h and 9l/h, and their corresponding flow velocities were 0.0566m/s and 3.350m/s, respectively. Fig. 3(1) shows a methane-air flame in the absence of gas discharge. Because the flow velocity of methane is much smaller than that of air, the mixing of gases is not sufficient in the center region in which the mole fraction of methane is lower than the flammability limit. Thus the flame has a hollow annular structure and a very bright ring boundary can be observed. In figures from 3(2) to 3(8), one can observe that the flame structure changes drastically when the applied voltage varies from 4.3kV to 12kV. Fig. 3(2) shows the flame at applied voltage amplitude of 4.3kV, at which the dielectric barrier discharge is initiated. The ring boundary becomes vague. In fig. 3(3), the applied voltage is 5.6kV, the ring boundary disappears, and the downstream of flame is not hollow any more. After that, the hollow size becomes smaller. While the applied voltage increases to 7.4kV, as shown in fig. 3(5), the annular hollow region of flame is almost indiscernible.

In fig. 3(6)-(8), it is found that the flame propagates backward into the quartz tube when the applied voltage is larger than 9kV. Sy.Stange [4] and his colleagues found similar phenomenon in a study of DBD of gas flow to enhance propane–air combustion and attributed the downward propagation of flame to an increase of propagation velocity of the flame which results from the fuel activation effects of the nonequilibrium discharge plasmas. But S.M.Starikovskaia argued in her review paper [1] that in this separate fuel discharge circumstance, the typical time of recombination does not allow the ‘activated’ propane to be supplied into the mixing zone. Indeed, in our experiments, the time for activated species across the mixing zone to reach the combustion region, i.e. the open end of quartz tube, is about 0.88s according to the flow velocity of methane. This value is several orders of magnitude higher than the life time of the exited species. Thus, the mechanism for modification of the flame structure is not likely the increase of flame propagation rate.

Generally, there are four possible mechanisms of the plasma effect on combustion: 1) fast local ohmic heating of the medium, 2) nonequilibrium excitation and dissociation of gas molecules, 3) momentum transfer in electric and magnetic fields and 4) shocks/instabilities generation. However in DBDs, heat and shock effects are imperceptible. Therefore the electric field will be the only possible effect of discharge in the modification of the flame structure. Here we suggest that it is the edge electric field of the electrodes that cause the variation of the flame structure, in that the transverse component of it will exert an electric force on the plasma from DBD region and results in the methane-air mixing process augmentation.

3. Pre-mixing process augmentation effects

Fig. 4 shows the dependence of edge electric field $E$ of electrodes in DBD on the distance $d$ from, point A, the beginning of mixing region. One can find that the electric field decreases very fast as the distance increases. When $d$ equals 1cm, the value $E$ of point B, becomes very small, only 1/10 of the maximum electric field, i.e. the value $E$ of point A, $E_A$. And further, when $d$ exceeds 2cm, the value of edge electric field almost decreases to zero.

To demonstrate the effects of edge field on the flame, we use an insulator tube to separate the discharge region from the mixing region, as shown in fig. 5. The inner and outer diameters of the insulator tube are the same as the inner metal electrode and its material is epoxy. The length of mixing region keeps 5cm not changed, but the distance from the top end of inner electrode to the open end of quartz tube increases. Without the insulator tube, the air flow through the inner electrode will start to mix with the
methane exactly in the location of the largest edge electric field; on the other hand, when an insulator tube is used, the mixing region can keep away from the edge electric field range. With a longer insulator tube, the electric field of mixing region is smaller. There are three kinds of insulator tube used in experiments. Their length $L$ are 0.75cm, 1cm, and 2cm, and corresponding maximum electric field of mixing region are $1/6$, $1/10$, and $1/46$ of $E_A$.

4. Conclusions

The flame structure can be drastically influenced by edge electric field of DBD. A hollow methane-air flame is chosen to demonstrate this effect of DBD. A simple method is proposed to remove the effects of edge electric field from the methane-air mixing process. Experiment results show that the flame structure modification results from the mixing augmentation effect of DBD.

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References