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Electric fields effect on liftoff and blowoff of nonpremixed laminar jet flames in a coflow

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ABSTRACT

The stabilization characteristics of liftoff and blowoff in nonpremixed laminar jet flames in a coflow have been investigated experimentally for propane fuel by applying AC and DC electric fields to the fuel nozzle with a single-electrode configuration. The liftoff and blowoff velocities have been measured by varying the applied voltage and frequency of AC and the voltage and the polarity of DC. The result showed that the AC electric fields extended the stabilization regime of nozzle-attached flame in terms of jet velocity. As the applied AC voltage increased, the nozzle-attached flame was maintained even over the blowout velocity without having electric fields. In such a case, a blowoff occurred directly without experiencing a lifted flame. While for the DC cases, the influence on liftoff was minimal. There existed three different regimes depending on the applied AC voltage. In the low voltage regime, the nozzle-detachment velocity of either liftoff or blowoff increased linearly with the applied voltage, while nonlinearly with the AC frequency. In the intermediate voltage regime, the detachment velocity decreased with the applied voltage and reasonably independent of the AC frequency. At the high voltage regime, the detachment was significantly influenced by the generation of discharges.

1. Introduction

In an effort to develop an advanced combustion system with high energy efficiency, reliable ignition, and improved flame stabilization, plasma-assisted combustion has been extensively investigated and demonstrated that fundamental combustion behaviors, such as ignition, extinction, and flame speed can be significantly enhanced through the interaction between plasma and combustion [1–11].

The major enhancement mechanisms in plasma-assisted combustion have been explained based on three distinctive processes. First is overall thermal heating effect caused either by the hot arc-discharge of plasma or by the recombination reaction of active radicals produced by plasma [11–13]. In view of overall energy efficiency, the thermal heating effect may not be a promising way for the enhancement with a plasma system. Second is the kinetic enhancement by the interaction with active and electronically excited species produced by plasma [11–13]. Considering that the typical life time of these excited species is relatively short, the previous studies have implied that the direct in situ production of these excited species with combustion-plasma system is necessary to magnify the kinetic enhancement [11]. Recently, the enhancement of premixed flame speed in a counterflow burner was observed by using a microwave plasma system together with laser techniques [12]. Third is the hydrodynamic effect from electric fields mainly associated with the ionic wind effect which can induce the bulk motion of flow, thus possibly enhance the mixing characteristics [14,15].

When plasma is integrated in a combustion system for improved performance through the complicated interaction among the thermal, kinetic, and hydrodynamic effects, the understanding of the effect of electric fields on flame properties are essential. However, detailed understanding is still rather limited. Frequently, the effects of electric fields have been explained based on the hydrodynamic effect of the ionic wind, which arises from the acceleration of ions in electric fields by the Lorentz force and subsequent momentum transfer to neutral particles by random collision, resulting in a bulk flow motion [14,15].

Studies on the effect of AC electric fields on flame stabilization characteristics, however, are rather limited. Recently, it has been shown that the stabilization characteristics of flame reattachment [16] and the propagation of laminar lifted flame edge [17] can be significantly affected by AC electric fields with relatively small power consumption less than $O(1\ \mathrm{W})$ by using the single-electrode configuration. The experimental study on the liftoff of nonpremixed turbulent jet flames [3] showed that the liftoff velocity could be increased up to 50% by applying electric fields, thereby

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extending the nozzle-attached flame regime appreciably in terms of jet velocity.

The present study is an extension of the previous work [3] to laminar jet flames by applying both AC and DC electric fields to the fuel nozzle. The single-electrode configuration has been adopted as previously [3,16,17] with the emphasis on the effect of electric fields on liftoff and blowoff. Note that even for the case without having electric fields, the detailed understanding of liftoff mechanism in nonpremixed jet flames is rather limited, because of the complex nature in the mechanism including near-nozzle flow behavior and heat transfer to fuel nozzle [18,19]. Due to quenching effect, a nozzle-attached flame has a edge flame structure experiencing heat loss [20]. The characteristics of such flames are less known as compared to a lifted flame edge with tribrachial (or triple) structure. Combining with the inherent complexities in the liftoff mechanism, the effect of electric fields on liftoff or blowoff is expected to be much more complex to physically characterize in detail at the present stage. Thus, the present study is focused on extracting systematic experimental data which can serve as a fundamental data for future theoretical and modeling works.

2. Experiment

The experimental apparatus consisted of a coflow burner and flow controllers, a power supply system, and a measurement setup as schematically shown in Fig. 1. The coflow burner had a central fuel nozzle with flush end, as indicated in the inset of Fig. 1, made of stainless steel with its inner and outer diameters of 0.254 and 1.588 mm, respectively. The nozzle length was 10 cm to ensure the fully developed velocity profile at the nozzle exit in the present range of jet velocity. Coflow air passed through meshes, beads and a honeycomb for uniform velocity profile. A concentric acrylic cylinder with 90 mm i.d. was installed at the exit of coflow air to suppress external flow disturbance. The coflow velocity was fixed at 3 cm/s to achieve a stable flame, as yet to maintain the resemblance to the free jet experiment [21]. The whole body of the coflow burner was made of acetal resin for electrical insulation except the fuel nozzle. The fuel was chemically-pure grade propane. The flow rates of fuel and air were controlled by mass flow controllers calibrated with a bubble meter and a wet-test gas meter. Direct images of lifted/nozzle-attached flames were taken with a digital camera, and the liftoff height was determined as a distance between the flame base and the nozzle tip.

A DC and AC power supply (Trek, 10/10B-FG) was utilized as an electrical source and the frequency of AC was controlled in the range of 60–1000 Hz by a function generator to obtain sinusoidal wave pattern of AC voltage. The applied voltage was varied up to 7 kV in the RMS value. The high voltage terminal of the power supply was connected to the fuel nozzle, thus the fuel nozzle served as a high voltage electrode. The other terminal was connected to the building ground such that the system can be regarded as an open electric circuit [3,16,17]. In this case, the electric fields can be assumed to be formed between the nozzle electrode and infinite ground far away from the nozzle [17]. The intensity of electric fields will be proportional to applied voltage. Because the intensity spreads out from high voltage electrode into the space, the intensity is higher near the electrode and lower as moving away from the nozzle. Actual electric field intensity exerted on a flame, however, will be much more complex by the existence of ions and electrons in the flame zone, which is typically in the order of 10^9–10^{12} cm^{-3} [1,2]. Moreover, the charges in a flame zone can distort the electric fields, especially near the quenching zone of the flame base. Therefore, the data will be presented in terms of the experimental variables of applied voltage and frequency.

The electric power consumption was monitored at various applied voltages and frequencies by using a current probe (Tektronix, TCPA300) and an oscilloscope (Tektronix, TDS1012B). The behavior of flame was observed by varying the jet velocity for specified electric field conditions. To visualize the change in flame structure by electric fields, a planar laser-induced fluorescence (LIF) technique for OH radicals was adopted. Details of the LIF setup have been reported previously [22].

3. Results and discussion

In a laminar jet with small jet velocity, a nozzle-attached flame can be formed at the exit of fuel nozzle. As the jet velocity increases, the flame length increases linearly with jet velocity. When

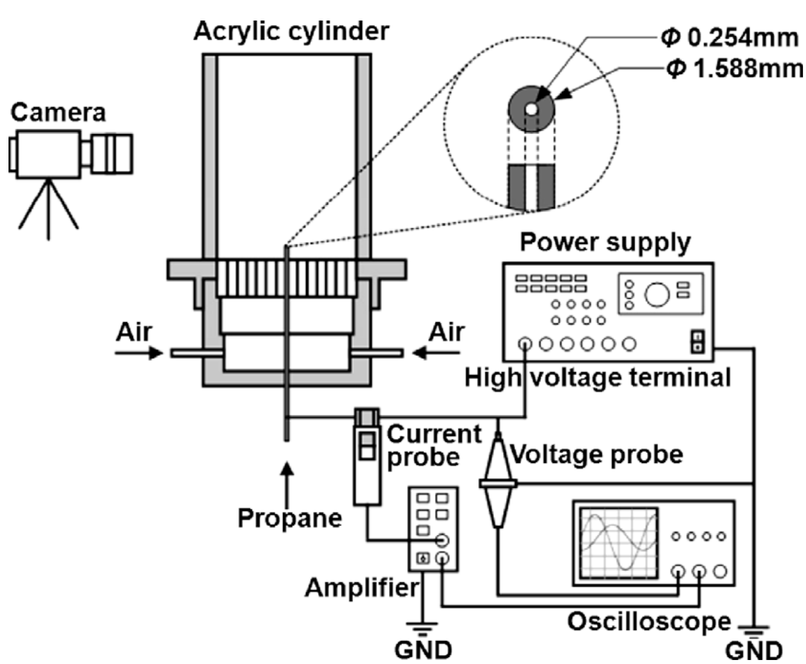

Fig. 1. Schematic of experimental setup.