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Effect of high-frequency alternating electric fields on the behavior and nitric oxide emission of laminar non-premixed flames

Yang Zhang, Yuxin Wu, Hairui Yang, Hai Zhang *, Min Zhu

Key Laboratory for Thermal Science and Power Engineering of the Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China

HIGHLIGHTS

- ▶ We studied the effects of AC electric fields on non-premixed flames.
- ▶ Flame image, FTIR pattern and chemiluminescent emissions were obtained.
- ▶ There exist three distinct regimes across the tested voltage range.
- ▶ The flame behaved non-monotonically as the increasing voltage.
- ▶ The flame behavior was explained by the competition of three effects.

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ABSTRACT

This paper examined the behavior and NO emission of laminar non-premixed methane/air jet flames when subjected to high frequency alternating electric fields of 10 kHz over the voltage range of 0–4.0 kV. In particular, this paper examined variations of flame shape and luminosity, CO and NO molar fractions in the downstream flue gas, and chemiluminescence from OH^* and CH^* in the voltage-influenced flame zone. The results showed that with no application of an alternating electric field, flames were stable at the nozzle exit, bluish at the base and yellowish at the conical tip. However, once applied, different voltage regimes produced different responses from the flame. In the low-voltage regime of 0–1.0 kV, increasing the voltage narrowed the top yellowish zone of the flame and sharpened its conical tip, increased the CO molar fraction in the flue gas, decreased the NO molar fraction in the flue gas, and decreased the chemiluminescence intensity of OH^* and CH^* in the flame zone by ~50%. At 1.0 kV, both CO and NO molar fractions reached extreme values, and the flame was at its weakest. In the mid-voltage regime of 1.0–3.0 kV, increasing the voltage resulted in an inverse response from the flames compared to the low-voltage regime. In the high-voltage regime of 3.0–4.0 kV, increasing the voltage resulted in the gradual disappearance of the top yellowish zone of the flame, increased the CO molar fraction in the flue gas and decreased the NO molar fraction. The transition mechanisms between the regimes are discussed within the context of the high-frequency discharge theory. Three competing effects explain the non-monotonic flame response to the voltage: thermal, ionic wind, and electrical–chemical. The analysis showed that the ionic wind effect majored in the low-voltage regime, the electrical–chemical effect dominated the mid-voltage regime, and all three effects were highly coupled in the high-voltage regime.

1. Introduction

The interaction between an electric field and flame behavior has attracted wide attention in the last few decades. Research shows that electric fields affect flames in three major ways: the thermal effect [1–3], which is caused by electrical energy input; the ionic wind effect [4–8]; and the electrical–chemical effect [9–12]. The thermal effect dominates when there is a large current across the electric field, such as a spark plug [3]. The ionic wind effect causes fluid dynamic changes in the flow field, inducing an "ionic wind" [4–8]. The electrical–chemical effect produces high speed electrons, radicals, ions and excited molecules in the pre-flame zone, which directly change the chemistry of the flames [9–12].

Various experimental and numerical studies have been conducted on the influence of direct-current (DC) electric fields on flame behaviors. Experiments showed that the DC electric field strongly affected flame shape [6,13,14], flame propagation speed [5,15], NO_x emissions [4,6,14,16] and soot formation [4,13]. Numerical simulations showed that the ionic wind effect dominated [17–20].

* Corresponding author. Tel.: +86 10 6278 8523; fax: +86 10 6278 1743.
E-mail address: haizhang@tsinghua.edu.cn (H. Zhang).

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Studies on the effects of an alternating-current (AC) electric field on flame behaviors are few. Previous studies mainly focused on the ionic wind effect. Chung et al. published a series of works [21–27] on the effects of the AC electric field on flame stabilization, and produced the following findings. The speed of tribrachial flame propagation increased under AC voltage [24]. The edge structure and the detachment velocity of the nozzle attached non-premixed propane/air flame were both affected by an AC electric field. The detachment velocity changed non-monotonically with the voltage increase at 60 Hz [25]. The lift-off height presented an oscillation characteristic when lower than 30 Hz, due to the direction-alternating ionic wind [26]. No oscillation was found in the range of 60–1500 Hz [25]. The height of the diffusion flame decreased with the increasing AC voltage at 400 Hz. Kono et al. [28] noted a delay time in the formation of ionic wind, normally in the order of 10 ms, indicating that the ionic wind did not form when the alternating frequency was higher than 50 Hz.

Flame behavior was significantly different to that of the DC and low-frequency AC electric fields when the frequency of the AC electric field was high (e.g. >2000 Hz). This may be because time was insufficient for momentum transfer from the charged particles to the neutral ones. As a result, the electric field did not introduce significant bulk flow motion [25,28]. Alternatively, it may be because the charged particles could not easily reach the electrodes due to high-frequency alternating properties. Therefore, a large amount of charged particles existed within the space between the two electrodes [29].

Studies on the effects of high-frequency alternating electric fields remain limited in number. Consequently, this paper examined the behavior and NO emission of laminar non-premixed methane/air flames when subjected to high frequency AC electric fields of 10 kHz over the voltage range of 0–4.0 kV. In particular, this paper applied different voltages at different fuel and co-flow velocities to study variations of flame shapes and to study CO and NO molar fractions in the downstream flue gas. This research also measured chemiluminescence from two excited radicals, OH^* and CH^*, in order to provide insight into the effects of high-frequency AC electric fields on combustion.

2. Experimental apparatus and methodology

2.1. Experimental apparatus

Fig. 1 shows the experimental apparatus, which consisted of three main parts: (1) a coaxial burner and associated gas supply system; (2) a high frequency AC power supply system; (3) a measurement system.

2.1.1. Coaxial burner and associated gas supply system

The fuel nozzle was made of a quartz tube with an inner diameter of 8.0 mm and thickness of 1.0 mm (Fig. 1). The tube length was 250 mm to ensure that the velocity profile of the fuel stream was fully developed at the nozzle exit. The fuel used in the experiments was high purity CH_4 (>99.99%). Compressed air, as the oxidizer, was supplied around the fuel tube from a concentric quartz tube with an inner diameter of 65 mm. The flow rates of the gas streams were controlled by mass flow meters that were pre-calibrated by a wet gas meter.

2.1.2. High frequency AC power supply system

An AC electric field was applied in the experiments. A metal mesh plate located at 50 mm above the upper rim of the burner was used as the anode and another metal mesh attached to the outside surface of the fuel nozzle was used as the cathode. A sinusoidal AC electric field with 10 kHz alternating frequency was supplied. The magnitude of the field (AC voltage) was adjustable. The AC wave was measured and recorded by an oscilloscope.

2.1.3. Measurement system

A flute-shaped probe located 750 mm above the burner sampled the combustion products. A Fourier transform infrared spectrometer (FT-IR) with the model of NETZSCH STA 409C analyzed the flue gas introduced into the probe. The CO and NO molar fractions in the flue gas were measured. A grating spectrometer with the model of ZOLIX SPB300 equipped with a photomultiplier tube (PMT) analyzed the chemiluminescence from the flame. The chemiluminescence intensity of OH^* and CH^* in the flame zone was measured. A digital camera recorded the flame images (exposure time: 0.5 s; resolution: 72 dpi).

2.2. Experimental conditions

Experiments were conducted at four different air flow velocities and four different fuel flow velocities (Table 1).

3. Results and discussion

3.1. AC voltage effect on flame shapes and luminosities

Fig. 2 shows images of the non-premixed laminar jet flames at various AC voltages. A typical non-premixed jet flame was stabilized at the exit of the nozzle when no electric field was applied (peak voltage 0.0 kV). The upper portion of the flame was a yellowish color due to the radiation of the soot formations. The base part of the flame was a bluish color due to the radiation of CH radicals. The flame shape and luminosity distinctly changed when an AC electric field was applied. Based on the variation of flame luminosities under different applied voltage, there existed three different regimes depending on the AC voltages: (1) the low-voltage regime with voltage lower than 1.0 kV; (2) the mid-voltage regime with voltage in the range of 1.0–3.0 kV; (3) the high-voltage regime with voltage higher than 3.5 kV. Case 1 is taken as an instance to describe the flame behaviors in each of these three regimes.

In the low-voltage regime, as voltage increased, the upper yellowish zone of the flame became narrower and the base bluish zone became wider. Also, the conical tip of flame became sharper. The flame top was sharpest at 1.0 kV. Under these conditions, the yellowish zone was the smallest and the overall flame was the darkest, indicating that soot formation was minimized. The experiments showed that the flame became unstable and that the flow perturbations even extinguished the flame in some instances.

In the mid-voltage regime, as voltage increased, there was an inverse response from the flames compared to the low-voltage regime. The upper yellowish zone became larger and the base bluish zone became narrower. The flame top gradually became a plump arc again and the flame was more stable compared to its state at 1.0 kV.

In the high-voltage regime, as voltage increased, the AC electric field zone typically started to produce a hissing sound between 3.0 and 3.5 kV. This indicated a slight corona discharge from the sharp tips of the electrodes, which generated a certain amount of plasma. The sound-producing pressure fluctuation affected the flame. The upper yellowish zone of the flame quickly disappeared and the flame tip dispersed (Fig. 2). This result indicated that soot formation was suppressed by the AC corona discharge, similar to the phenomenon found in the dielectric barrier discharge [22]. Furthermore, the flame partially detached from the nozzle and randomly rotated around the nozzle rim. This phenomenon was consistent with the observation by Chung et al. [25] for low AC frequency. However, where Chung et al. observed lift-off as voltage