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Flow instability in laminar jet flames driven by alternating current electric fields

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Abstract

The effect of electric fields on the instability of laminar nonpremixed jet flames was investigated experimentally by applying the alternating current (AC) to a jet nozzle. We aimed to elucidate the origin of the occurrence of twin-lifted jet flames in laminar jet flow configurations, which occurred when AC electric fields were applied. The results indicated that a twin-lifted jet flame originated from cold jet instability, caused by interactions between negative ions in the jet flow via electron attachment as $O_2 + e \rightarrow O_2^-$ when AC electric fields were applied. This was confirmed by conducting systematic, parametric experiment, which included changing gaseous component in jets and applying different polarity of direct current (DC) to the nozzle. Using two deflection plates installed in parallel with the jet stream, we found that only negative DC on the nozzle could charge oxygen molecules negatively. Meanwhile, the cold jet instability occurred only for oxygen-containing jets. A shedding frequency of jet stream due to AC driven instability showed a good correlation with applied AC frequency exhibiting a frequency doubling. However, for the applied AC frequencies over 80 Hz, the jet did not respond to the AC, indicating an existence of a minimum flow induction time in a dynamic response of negative ions to external AC fields. Detailed regime of the instability in terms of jet velocity, AC voltage and frequency was presented and discussed. Hypothesized mechanism to explain the instability was also proposed.

Keywords: Electric field; Jet flow instability; Twin jet flame

1. Introduction

For several decades, researchers have been interested in the electrical properties of flames and how they can be controlled by the application of electric fields [1–3]. The bidirectional electric body force that acts on negative and positive charge

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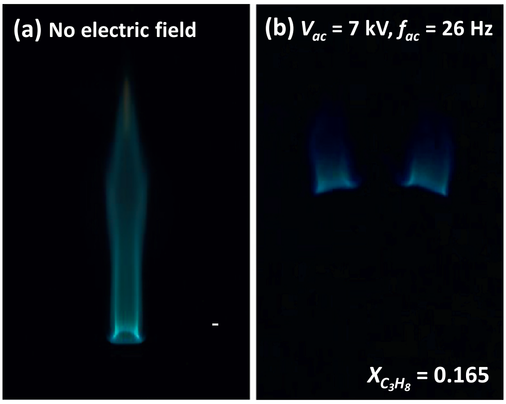

Fig. 1. Dramatic changes in flame morphology with applied electric fields for a nozzle diameter of 4.4 mm; the mole fraction of C_3H_8 in nitrogen was 0.165, and the jet velocity was 1.5 m/s: (a) without an applied voltage and (b) applying 7 kV with an alternating current (AC) frequency of 26 Hz to a fuel nozzle.

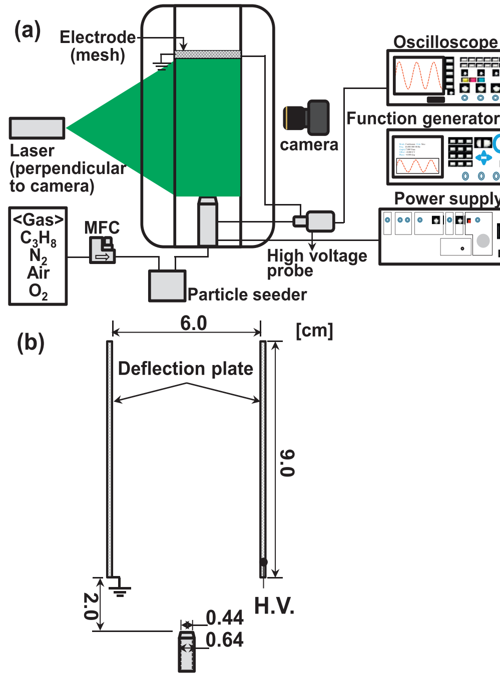

Fig. 2. Schematic diagram of the experimental setup: (a) overall setup and (b) deflection plates used to detect the charged species.

carriers is a fundamental physical mechanism that occurs when a flame is subjected to an external electric field. Basically, this selective external force on the ions generated in a flame zone produces ionic wind, resulting in a dynamic response by the flame. The effects of external electric fields can be used to achieve various phenomenological and practical improvements in combustion characteristics [4–6].

Among the many flame configurations studied by applying electric fields, lifted jet flames have been studied extensively, due to their intrinsic stabilization features: a tribrachial flame comprising liftoff and blowout. Investigations for laminar jet flames under electric fields can provide validation data for multi-physics simulations as well as fundamental understanding of a controlling method for jets and flames. The jet configuration is also of practical importance in various burner systems. Both laminar and turbulent jet flames with alternating current (AC) have shown liftoff stability, indicating a significantly enhanced velocity range for a stable nozzle-attached flame [7–9]. An increase in the displacement speed of the lifted flame edge with AC and direct current (DC) electric fields has also been observed [10,11]. Most related studies have focused on the flame characteristics when electric fields are applied. While Won et al. [10] observed cold flow modification caused by electric fields; specifically, the breakup of a cold flow away from the jet nozzle, visualized by Schlieren imaging using an AC frequency of 60 Hz with a root mean square (rms) voltage of 12 kV.

When a 26-Hz AC field with 7 kV (rms) was applied to a fuel nozzle in a preliminary experiment, as shown in Fig. 1, a nitrogen-diluted propane flame exhibited a drastic transition from a normal laminar-lifted flame with a typical tribrachial structure at the edge to twin-lifted flames that appeared to be stabilized in separate branches. As will be shown later, the 26-Hz AC frequency was such that the visual variation of the flame was maximal. We determined that this effect originated from cold flow instabilities caused by the electric field, which indicates that the characterization of cold flows should be understood prior to investigating lifted flames in this situation. Note that combustion phenomenon is appreciably influenced by flow field. Although potential influence of electric fields on jet flow field was reported previously [10], the mechanism of flow instability caused by applied electric fields, which eventually affects flame behavior, has not been systematically reported yet.

In the present study, we focused our attention on identification of the effect of electric fields on cold jets. Both AC and DC fields were considered; the cold jets were visualized and the flow field was quantified via particle image velocimetry (PIV). As a result, we identified the key parameters affecting the flow, in turn, influencing flame behavior and proposed a mechanism to explain the cold flow instability.

2. Experiment

Figure 2 schematically illustrates the experimental setup. A nozzle was made of a 55-cm-long

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