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The stabilization of partially-premixed jet flames in the presence of high potential electric fields

James D. Kribs [a], Parth V. Shah [a], Andrew R. Hutchins [a], William A. Reach [a], Richard D. Muncey [a], M. Sean June [b, *], Alexei Saveliev [a], Kevin M. Lyons [a]

[a] Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695-7910, USA
[b] School of Engineering, Christian Brothers University, Memphis, TN 38104, USA

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ABSTRACT

Numerous research efforts have focused on flame stabilization and emissions. Based on initial experiments, specific mechanisms resulting from DC electric fields were chosen to be investigated, namely the chemical, thermal, and ionization mechanisms. Numerical simulations were performed on premixed propane-ozone-air flames to characterize ozone effects on flame speed resulting from the formation of ozone in high potential electric fields. These results were compared against partially premixed flame experiments to observe the dominant influences within leading edge stabilization within high potential electric fields. It was found that the electromagnetic or ionization influences, serve as the dominant effect on the combustion zone.

1. Introduction

Lifted jet flame stabilization and emissions control have become key issues for industrial boilers and energy generation. To improve the stability of a lifted jet flame or to decrease emissions, it has been found that the application of high potential electric fields provides some useful results [1–3]. Previous investigations into jet flames have focused on the fluid dynamics and heat transfer influences in jet flame stabilization, as well as the thermochemistry [4,5]. The lifted jet flame scenario provides a unique combustion problem with premixed lean, premixed rich, and non-premixed flames occurring simultaneously at different positions along the flame, which permits the stabilization of the flame at a downstream location from the jet nozzle. Brown et al. detailed the stabilization mechanisms of pure jet flames at different locations relative to the issuing nozzle (the near, mid, and far field) [6]. Reustch et al. investigated the effect of heat release on triple flames, the confluence of a premixed rich, premixed lean, and non-premixed flame, showing that accounting for heat release shows a significant increase in the flame speed [7]. There have been many theories involving the fluid dynamic influences in lifted jet flames, highlighted in Lyons' review of experiments in flame stability [8]. For the purpose of this investigation, the turbulent intensity theory, proposed by Kalghatgi [5], and the large eddy theory, from Broadwell et al. [9], will be considered due to considerations on fuel-mixing within the experimental setup. The turbulent intensity theory postulates that the flame speed of a lifted jet is augmented by the presence of turbulence, which increases the flame speed from the nominal laminar value, to a higher value, listed as a turbulent flame speed [5]. The large eddy theory describes the recirculation of hot products of combustion into the cooler reactants, by eddy vortices, to increase the temperature of the reactants, therefore increasing the flame speed [9]. For the purposes of this study, a non-premixed flame is a non-jet flame, such as a candle flame stabilized on the flammable limit boundary of the fuel and air, a premixed flame, is fully premixed fuel air mixture, and a partially premixed flame is a jet flame issuing from a central nozzle into air burning with attributes of both premixed and non-premixed flames, as shown in previous studies including those by S.H. Chung [10].

Prior to understanding the high potential electric fields influence on a system as complex as a lifted flame, it is necessary to understand how the electric fields influence neutral fluids. In early discussions on the "ionic or electric wind' was a term used to describe a fluid flow driven only from the difference in electric potentials at two locations, Chattock [2] and Robinson [11]. To

* Corresponding author.
E-mail address: mjune@cbu.edu (M.S. June).

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produce ionic wind, a high potential combined with a favorable electrode geometry, forms an ionizing plasma region in which local molecules are charged [2]. These particles are then attracted to a secondary electrode, which has an opposite charge [2]. This creates a bulk flow from one electrode to the other, as described by Rickard et al. [12] and Carleton and Weinberg [13]. The forces of this bulk flow, F, have been shown to be equal to

$$\overrightarrow{F} = \overrightarrow{E} e(n_+ - n_-) \tag{1}$$

where $\boldsymbol{E}$ is the electric field vector, e is the fundamental charge, and n is the number density of positive and negative ions, as denoted by the subscript [13]. The local current density, j, can be calculated as

$$\overrightarrow{j} = \overrightarrow{j_+} + \overrightarrow{j_-} = (K_+ n_+ - K_- n_-) \overrightarrow{E} e \tag{2}$$

where K is the electron mobility [13]. The maximum current density that can be achieved prior to secondary ionization has been shown to be

$$\mathrm{j_{max}} = (\mathrm{E_b^2} - \mathrm{E_0^2})\varepsilon_0 * \frac{\mathrm{K}}{\mathrm{2x}} \tag{3}$$

If the potential between the primary and secondary electrode increases beyond a critical value, at the maximum current density, the discharging at the secondary electrode occurs at a rate slower than the charging at the primary electrode. The secondary electrode then assumes a charge, creating a reverse flow. The charging of the secondary electrode will be referred to as "secondary ionization" for this purposes of this study, which can be observed through the formation of corona discharges on the secondary electrode. Beyond the formation of the ionic wind, it has been observed that high potentials in ambient air can produce ozone, changing the constituent particles of air [14].

For this study, the impacts of the electric fields on a lifted jet were broken down into three major areas, the thermal, ionic, and chemical mechanisms (resulting from the electric fields), results in changes in flame stabilization. The chemical mechanism results from the changes in chemical kinetics and species present resulting from the high potential electric fields, such as the creation of ozone in ambient air in electric fields or the changes in pollutant emissions discussed above. This mechanism was investigated through premixed flame simulations below on propane-air flames with increasing amounts of ozone addition in the oxidizer. The thermal mechanism, where the electric field provides resistive heat transfer from the current passing through the flame, has been extensively investigated as part of previous jet flame studies, and is highlighted below. The ionic mechanisms, such as the ionic wind and other ionic transport properties, are caused by the electrohydrodynamic forces acting within the flame, in conjunction with the applied electric field. The ionic wind has been observed and documented in previous research, shown in the discussion of the ionic wind later in the study. A graphic illustrating the effects of each mechanism is shown below in Fig. 1.

2. Experimental methods

All experiments were conducted in the Reacting Flows and Turbulent Jets Laboratory in the Department of Mechanical and Aerospace Engineering at North Carolina State University, in conjunction with simulations run by the High Pressure and Laser Diagnostics Laboratory.

Experiments on partially premixed flames used propane (CP Grade, 99.0% Pure) issuing from a central nozzle with an inner diameter of 0.8255 mm (0.0325 in). The flow rate of the propane was measured through a King 7430 flowmeter and controlled through a MicroLine UHP Gas Panel controller. The primary electrode consisted of a delrin plastic case surrounding a 10 AWG solid core copper wire charging up to 12 needle electrodes on the same loop, though only the one and two needle electrode setup was used in this experiment, as shown in the figure below. The secondary electrode was the nozzle for the issuing jet. The copper wire was inlaid within the electrode case at a diameter of 11.43 cm (4.5 inches) and the internal diameter of the case is 9.60 cm (3.78 inches). The applied voltage was created using an Acopian Positive High Voltage Power Supply (PO30HP2), using voltage control to adjust the power of the electric fields, while allowing the applied current to vary freely. The voltage and current were monitored using dual Agilient Technologies U3401A Multimeters.

The electrode polarity of the jet flame experiments was varied, switching between a positively charged primary electrode, and the primary electrode acting as the negatively charged ground. The position of the electrode, relative to the issuing nozzle was held constant at 64.262 mm (2.53 inches) above the nozzle and 23.622 mm (0.93 inches) radially from center of the nozzle to the tip of the needles. The setup of the burner is shown in Fig. 2. The images of the jet flames were taken using a Nikon D80 digital SLR camera with an 18–135 mm Nikkor Lens, in order to observe the downstream location of the leading edge of the flame, as well as changes in chemiluminescence. The downstream location was determined using Adobe® Photoshop® using the ruler attached to the burner to determine a comparable length scale.

The experimental apparatus above is electrically insulated at the base to prevent accidental grounding, and all experiments were conducted with a shroud placed over the device to isolate the influences of external air flows, while providing access to outside oxidizer, as well as providing protection from electrical arching during the experiment.

3. Results and discussion

3.1. Non-premixed flame experiments

Initial observations, made on candle flames using the same power supply from the partially premixed flame, from the experimental apparatus shown in Fig. 4, were made to prove the effectiveness of high potentials to adjust flame shape, chemiluminescence, and the possibility of flame suppression. Using paraffin candles, the experiments focused on qualitative observations made at observed voltages. During the initial testing, the flame behavior, shown in Fig. 3, was observed (see Fig. 5).

In this single needle electrode configuration, it was observed that the flame was repelled by the presence of the high potential. This effect became more pronounced at higher voltages. The experiment was limited to 20,000 V, as the air surrounding the electrodes would begin to carry a charge and cease acting as a dielectric, creating sparks, which would travel between the clamp for the candle and the grounded ring. While the candle flame responded in a similar way as though there were a counterflowing air acting on the system, the intermittent flickering that would be expected from a non-premixed flame in a flow of air was not present, but rather the flame maintained a consistent shape at each applied voltage.

Further observation of the results of the candle flame experiment has shown that not only is the flame shape influenced by the electric field, but also, the products of combustion, specifically soot accumulation. Fig. 4 is a still image taken after the experiment was concluded.

As shown in Fig. 4, there is a pronounced buildup of soot on the grounded electrode, away from the needle. This effect has been