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Full Length Article

Investigation of the effect of DC electric field on a small ethanol diffusion flame

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HIGHLIGHTS

- Effects of DC electric field on a small ethanol diffusion flame are analyzed.
- A numerical study has been performed to elucidate the experimental observations.
- Applied electric field increases flow velocity, promotes the fuel/oxidizer mixing.
- Applied electric field enhances combustion resulting in higher flame temperature.

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ABSTRACT

A small ethanol diffusion flame exhibited interesting characteristics under a DC electric field. A numerical study has been performed to elucidate the experimental observations. The flow velocity, chemical reaction rate, species mass fraction distribution, flame deformation and temperature of the flame in the applied DC electric field were considered. The results show that the applied electric field changes the flame characteristics mainly due to the body forces acting on charged particles in the electric field. The charged particles are accelerated in the applied electric field, resulting in the flow velocity increase. The effects on the species distribution are also discussed. It was found that the applied electric field promotes the fuel/oxidizer mixing, thereby enhancing the combustion process and leading to higher flame temperature. Flame becomes shorter with applied electric field and its deformation is related to the electric field strength. The study showed that it is feasible to use an applied DC electric field to control combustion and flame in small-scale.

1. Introduction

The characteristics of micro- and meso-scale combustors with different configurations or under different external conditions have attracted lots of attention, e.g. [1–5]. The effects of an electric field applied on flame have been studied recently, e.g. [6–9]. Researchers found that the electric field can improve the stability of combustion. The external electric field was also used as a means for flame control, such as taking flame as an electrically active component based on voltage-current characteristics in the circuit [10]. The effects of electric fields on flame included stabilizing the combustion, increasing flame speed, reducing the soot production and emission, changing the flame temperature and shape [11–15]. These findings also imply that the efficiency of practical non-premixed combustion systems could be improved by applying an electric field [16]. It has been identified that there are three major effects produced by the electric field on the flame, including the thermal effect, the ionic wind effect and the electrical-chemical effect [17].

Experimental and numerical methods have been used to study the effects of electric fields on flame behavior. Meng et al. [18] found that the flame propagation and combustion properties were significantly affected by the DC electric fields and the flame shape would become a prolate spheroid by the electric body force in the electric field. Imamura et al. [19,20] investigated the flame deformation of ethanol droplets in different vertical electric fields experimentally and the relation between the applied voltage and electrode distance was observed. Kim et al. [21] considered the stabilization characteristics of liftoff and blowoff in nonpremixed laminar jet flames in a coflow for propane fuel by applying AC and DC electric fields experimentally. van den Boom et al. [22] studied the influence of a DC electric field on the laminar burning

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Nomenclature

c_P	constant-pressure specific heat capacity
D	diffusivity
d_i	inner diameter of burner nozzle
d_o	outer diameter of burner nozzle
E	electric field strength
e	electron charge
F	body force
H	height of flame
h_i	enthalpy of species i
$\mathbf{J}_i$	diffusive flux of species i
k	effective heat transfer coefficient
L	electrode spacing
n_c	net charge density
n_+	positive charge density
n_-	negative charge density
p	pressure on the element
r	radial direction
R	correlation coefficient
R_e	radius of electrode
R_i	net reaction rate of species i
S_h	volume heat source term
S_i	additional generation rate caused by source terms
T	flame temperature
u	axial (x) direction of flow velocity
v	radial (r) direction of flow velocity
W	width of flame
Y_i	mass fraction of species i
Greek letters	
α	aspect ratio
μ	dynamic viscosity
ρ	density of liquid ethanol
$\boldsymbol{\tau}$	viscous dissipation stress

velocity and found that the electrode configuration can influence the laminar burning velocities and the system requires a relatively low power input. Belhi et al. [23] improved a simplified mathematical model, where negative ions and the stabilization mechanism of a diffusion lifted flame in the applied DC or AC electric fields were analyzed. The effects of electric fields on the reattachment of lifted flames have been investigated experimentally by Won et al. [24] and they reported that the stabilization limit of attached flames was extended by the AC electric field and the effect of DC was found to be minimal. Karnani and Dunn-Rankin [25] discussed the relationship among flame shape, combustion intensity, soot formation, and the ion production rate. They found that those parameters are related to the voltage–current relationship for a coflowing non-premixed methane/air flame. Vega et al. [26] studied the electro-physical means of controlling the nitrogen oxide pollutant formation and emission composition of premixed flames in the combustion process.

Most of these studies considered hydrocarbon fuels, especially gaseous fuels. Although diffusion flames with liquid fuels are important in terms of the effects of electric fields on combustion phenomena, the investigation is limited in the literature and there is still a lack of understanding on this topic. A small ethanol diffusion flame with an applied electric field was investigated in this study, investigating the effects of electrical field on combustion and the potential application in system control. The effects of DC electric field on the flame characteristics, such as flame shape, temperature, species distribution, flow velocity and reaction rate, were investigated experimentally and numerically. The combined experimental and numerical results enhance the understanding of the effects of electric field on the small ethanol diffusion flame. When small combustors are considered in transport applications such as a drone, liquid fuel is preferred because of the very large energy density (in comparison to gas fuels). The results and understandings obtained can be used to improve the performance of meso-scale combustors controlled using electrical fields.

2. Experiment

2.1. Experimental system

The schematic of experimental apparatus and a simplified electrical circuit are shown in Fig. 1. The system consists of four main parts, including liquid fuel supply system, small-scale combustion system, DC power supply system and measurement system. The fuel used in these experiments was high purity ethanol (C_2H_5OH, molecular weight of 46.07, purity >99.5%) and it was controlled and supplied from the base into the burner nozzle with an inner diameter (d_i) of 0.9 mm and outer diameter (d_o) of 1.2 mm by a syringe pump (KDS 100) with an uncertainty of 1.0%. Air around the burner nozzle as the oxidizer was supplied from the ambient. The flame was ignited near the nozzle outlet and was located between two parallel horizontal brass plate electrodes with radius (R_e) of 40 mm. A potential difference applied by a DC power supply (Boher HV, Model 71030P) between the two electrodes produced the DC electric field. The measurement system consisted of a digital camera (Cannon, EOS 5D Mark III) to observe the flame shape, an S type platinum-rhodium thermocouple with the node diameter of 0.3 mm, and a data acquisition instrument (Agilent, 34970A) to measure the flame temperature, which also could collect data of current and voltage. The system is similar to that used in our previous work [27–29].

2.2. Experimental method

The applied voltage, normalized electrode spacing L, the nominal electric field strength (E) are the key electrical parameters to describe the system. A positive electric field is defined as electric field vectors directed from the burner to the downstream electrode and reversely negative. When the power supply voltage or electrode distance was changed, the electric field strength would change accordingly and some different electric field conditions were produced. A small-scale diffusion flame in different electric field conditions was observed and the data such as flame shape, temperature variation and flow velocity were collected. These cases were compared and analyzed, and the effects of DC field on small-scale diffusion flame combustion characteristics were examined.

A thermocouple was used to measure the flame temperature at the flame top position, as shown in Fig. 2. The flame temperatures at different positions were measured and it was found that the highest temperature in the flame was at the top position. So the temperature at the top position was chosen to represent the flame temperature. Moreover, the measurement at the top position brought the smallest disturbance to the flame compared with other positions [28].