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Effect of a uniform electric field on soot in laminar premixed ethylene/air flames

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ABSTRACT

The effect of a nominally uniform electric field on the initially uniform distribution of soot has been assessed for laminar premixed ethylene/air flames from a McKenna burner. An electrophoretic influence on charged soot particles was measured through changes to the deposition rate of soot on the McKenna plug, using laser extinction (LE). Soot volume fraction was measured in situ using laser-induced incandescence (LII). Particle size and morphologies were assessed through ex situ transmission electron microscopy (TEM) using thermophoretic sampling particle diagnostics (TSPD). The results show that the majority of these soot particles are positively charged. The presence of a negatively charged plug was found to decrease the particle residence times in the flame and to influence the formation and oxidation progress. A positively charged plug has the opposite effect. The effect on soot volume fraction, particles size and morphology with electric field strength is also reported. Flame stability was also found to be affected by the presence of the electric field, with the balance of the electrophoretic force and drag force controlling the transition to unstable flame flicker. The presence of charged species generated by the flame was found to reduce the dielectric field strength to one seventh that of air.

1. Introduction

The effects of an electric field on a flame have been studied extensively for many years [1]. Malinowski [2] discovered that a flame can be extinguished by a sufficiently strong electric field. Hu et al. [3] examined experimentally the effect of a uniform electric field on the visible shape of a candle-type flame. Katzer et al. [4] proved experimentally that different electrodes, such as needle-type and plate-type and different applied voltages can result in different flame shapes at extinction. Electric fields also have a noticeable effect on primary particle size, agglomerate size, and the crystallinity of nanoparticles [5–7]. Hardesty and Weinberg [8] demonstrated an influence on the size of primary particles in silica agglomerates caused by the presence of an electric field applied coincident to the gas-stream line. They showed that the primary particle size of SiO_2 powders is reduced by a factor of 3 by a 1.5 kV/cm potential. This was attributed to decreased particle residence time. Katz and Hung [9,10] investigated an H_2/O_2 counterflow diffusion flame with an electric field. They found, in contrast, that particle size is increased with an applied electric field of 1.2 kV/cm. Despite this and other previous research on the subject for over a century, the influence of an electric field on soot remains incompletely understood.

Weinberg et al. [11–15] demonstrated that the growth of soot particles in a flame is related to the species charge and can be influenced by means of an electric field. In the case of DC coronas, the effect of aeration due to the corona wind becomes dominant and reduces the emission of soot. Payne et al. [16] experimentally found that when a negative voltage of sufficient magnitude is applied to a plate electrode, the length of a laminar Bunsen flame decreases and its width at the flame tip increases. While a positive voltage is applied, it exhibits the opposite trend. Ohisa et al. [17] studied the effect of an AC corona discharge applied to the lower part of a flame. They confirmed that it results in soot suppression. They also identified a limit in the magnitude of current at which an arc occurs and with it, an abrupt decrease in the discharge voltage. Also it has previously been reported that most negatively charged species are found in the flame root, while positively charged species including soot particles are predominantly found at higher positions in the flame [18–20]. However, no information on which type of charge in soot particles is prevalent has been reported. The recent advent of modern techniques such as LII, LE and TSPD offer potential to provide new understanding from classical experiments, such as those pioneered by Weinberg and co-workers [11-13] using techniques not available at the time.

To meet these needs, the overall aim at the present research is to investigate the effects of a uniform electric field on a series of one dimensional laminar premixed ethylene/air flames. The first specific aim is to assess whether positively or negatively charged soot particles dominate in a flame. This was addressed by laser

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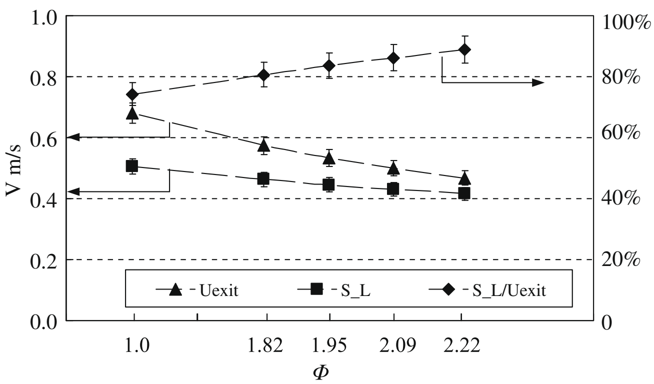

Fig. 1. Burner exit velocity and flame speed calculated based on simplified-theory and global one-step reaction mechanism with $\Phi = 1.00$; 1.82; 1.95; 2.09 and 2.22.

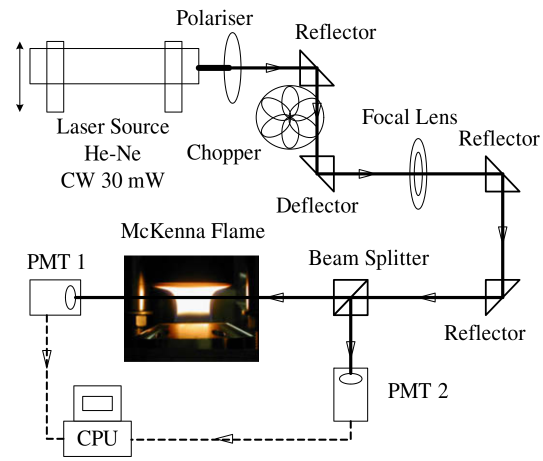

Fig. 3. Optical arrangement for laser extinction measurement.

extinction, used to measure the variation of soot volume fraction due to the deposition under an electric field. The second aim is to measure the variation of soot volume fractions and particle morphology with change in the residence time induced by an electric field. Laser-induced incandescence and thermophoretic sampling particle diagnostics were used for this. The third aim is to assess the effect on flame flicker of an applied electric field as a function of equivalence ratio. This was examined by determining the flickering and the discharge points.

2. Experimental arrangement

All of the measurements were performed in the TEC lab of the University of Adelaide. A series of rich premixed ethylene/air flames were produced with a McKenna burner. The burner consisted of a water-cooled stainless steel porous plug of 25 mm diameter with a stainless steel main body. An external shroud of nitrogen was supplied around the plug to shield the flame from atmospheric air. To stabilize the flames, a 60 mm diameter solid iron plug was placed 23 mm above the burner surface. The ethylene gas flowrate was kept to 2.1 mg/s to keep the total mass flux of carbon constant in all flames. This allows deposition rates on the plug to be compared. The burner was mounted to a 3-aixs traverse to enable it to be positioned within the optical measurement system.

Fig. 1 compares the effect on flame speed by varying stoichiometry at either constant fuel flow rate or total flow rate. Simplified-theory and global one-step reaction mechanism were used to calculate the ethylene–air premixed flame speed [21]. It is evident that keeping fuel flow rate constant causes both the nozzle exit velocity U_{exit} and flame velocity S_L to decrease by 31% and 18% respectively, so that the ratio S_L/U_{exit} increase by 19%. This relatively small change in S_L/U_{exit} is considered to constitute a good compromise, since it is not possible to maintain constant all parameters while varying Φ.

The burner was electrically grounded. A negative electric field was used to refer to the cases where a negative voltage was applied to the plug, and a positive electric field to a positive voltage. A DC power supply with maximum voltage of 30 kV was used. Maxwell software was used to calculate the electric field distribution and determine the conditions for which the field between the burner and the plug is uniform for the case without a flame. The results are shown in Fig. 2. The simulation revealed that a uniform electric field can be provided with a sufficiently large plug diameter and small gap. For the present conditions, the field was calculated to be uniform to within 2% over the central 60 mm of the flame.

The measurements were based on both intrusive sampling probes and non-intrusive laser diagnostics techniques. These include laser extinction (LE), laser-induced incandescence (LII) and thermophoretic sampling/transmission electron microscopy (TEM). The laser extinction measurements were performed using a He–Ne CW polarized laser beam with power of 2 mW at $\lambda = 632.8$ nm as shown in Fig. 3. The He–Ne beam was focused into the flame using a biconvex lens with a focal length of 1000 mm to provide a beam diameter of less than 2 mm. The beam was split by a beam splitter, and the intensity of the transmitted beam and deflected beams was measured by two photodiodes with sensitive surface diameter of 8 mm. The laser beam was modulated by means of a mechanical chopper working at 300 Hz. The measurements of LE were performed at heights above the burner (HAB) from 5 mm to 17 mm in 2 mm increments. The LE signals were coupled to an analog-to-digital converter, MacLab/4, AD Instruments, and then transferred to a PC for further analysis.

The line-of-sight absolute value of soot volume fraction was calculated using the following equation [22]:

$$f_{v,los} = \frac{\ln(I_0/I)\cdot\lambda}{6\pi E(m)l}, \qquad (1)$$

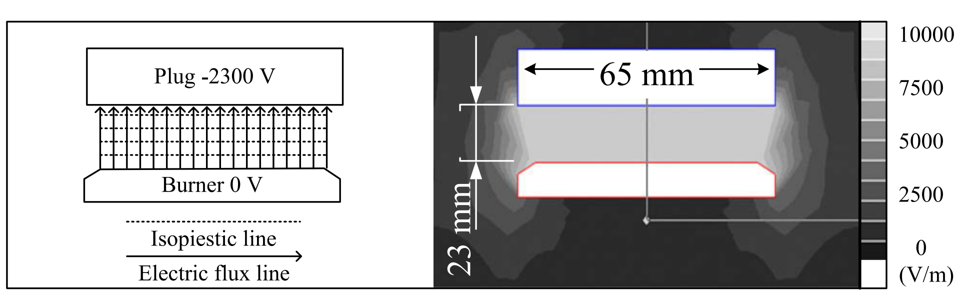

Fig. 2. The calculated electric field for the 65 mm plug with a 23 mm gap without a flame.