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Electric field in Ns pulse and AC electric discharges in a hydrogen diffusion flame

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ABSTRACT

Time-resolved electric field is measured in ns pulse and AC sine wave dielectric barrier discharges sustained in an atmospheric pressure hydrogen diffusion flame, using picosecond second harmonic generation. Individual electric field vector components are isolated by measuring the second harmonic signals with different polarizations. Electric field measurements in a ns pulse discharge are self-calibrating, since the field follows the applied voltage until breakdown. Electric field is measured in a ns pulse discharge sustained both in the hydrogen flow below the flame and in the reaction zone of the flame. Peak electric field in the reaction zone is lower compared to that in the near-room temperature hydrogen flow, due to a significantly lower number density. In hydrogen, most of the energy is coupled to the plasma at the reduced electric field of $E/N \approx 50$–100 Td. In both cases, the electric field decreases to near zero after breakdown, due to plasma self-shielding. The time scale for the electric field reduction in the plasma is relatively long, several tens of ns, indicating that it may be controlled by a relatively slow propagation of the ionization wave over the dielectric surfaces. In the AC discharge, the electric field is put on the absolute scale by measuring a Laplacian electric field between two parallel cylinder electrodes. The measurement results demonstrate that a strong electric field in the plasma-enhanced flame is produced during the entire AC voltage period, without correlation with the random micro-discharges detected in the plasma images. The measurement results indicate consistently higher peak electric field during the negative AC half-period, as well as a significant electric field offset. Both the asymmetry and the offset of the electric field are likely responsible for the ion wind resulting in the flame distortion. The results suggest that at the present conditions the ion wind is dominated by the transport of negative ions generated in the ambient air plasma near the flame. The results demonstrate a significant potential of ps second harmonic generation diagnostics for non-intrusive measurements of the electric field in atmospheric pressure flames enhanced by electric discharge plasmas.

1. Introduction

Measurements of electric field in weakly ionized plasmas generated in reacting fuel–air mixtures and in flames are critical for quantifying the effect of strong electric fields on kinetics of excited species and radicals produced in the plasma, ignition, flameholding, and flame stability, as well as for development of plasma assisted combustion applications and combustion control methods [1–3]. In electric discharges sustained in fuel–air mixtures, the electric field waveform is well known to control the discharge input energy partition among the internal energy modes of molecules and atoms [1], which determines the rates of production of excited species and radicals by electron impact, as well as the rates of plasma chemical reactions at low temperatures [2]. In high-pressure chemically reacting plasmas, evaluating the electric field based on the applied voltage waveform, or predicting it based on a semi-empirical estimate of the space charge distribution [4] may result in a significant uncertainty. The electric field distribution may be strongly perturbed by the plasma self-shielding, which is controlled by ionization, electron-ion recombination, ion-molecule reactions, electron and ion transport, electron emission from electrodes, and surface charge accumulation on dielectric surfaces. In flames, externally applied electric field

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also generates the ion wind entraining the flow of neutral species, and affects the ion-molecule reaction chemistry. This has a strong effect on flame stability [5,6], flashback [7], soot generation [8], and flow field in the reaction zone [9–11]. Understanding kinetics of these processes and validation of high-fidelity modeling predictions require electric field measurements using accurate, non-intrusive experimental methods.

Two laser diagnostic techniques for electric field measurements in high-pressure plasmas developed over the last decade are ns/ps Four-Wave Mixing (FWM) [12–16] and fs/ps Second Harmonic Generation (SHG) [17,18]. Both of these methods can provide sub-ns temporal resolution, limited by the coherence decay time of molecules excited by the pump and probe beams (in the four-wave mixing technique, which is similar to CARS), or by the duration of the laser beam (in the second harmonic generation). Other advantages include a straightforward absolute calibration and measurement of individual components of the electric field vector with well-defined spatial resolution. Finally, the second harmonic generation is basically species independent [17] and can be used for diagnostics in different gas mixtures, while the four-wave mixing requires the use of different wavelength Stokes beams for different probe species. In both methods, the spatial resolution along the laser beams, determined by the Rayleigh range of the beams and by the coherence length, may vary from ~1 mm [17] to several cm [14]. The spatial resolution in the direction perpendicular to the laser beam is of the order of the focused beam diameter, ~100 µm.

In our previous work [16], ps four-wave mixing was used for the measurements of the electric field in ns pulse discharges in ambient air and in a hydrogen diffusion flame, using molecular nitrogen as a probe species. The results have shown that the sensitivity of this diagnostic in the flame is significantly worse compared to that in room-temperature air, ~20 kV/cm vs. 3–4 kV/cm. This occurs primarily due to the higher temperature and lower N_2 fraction in the combustion product mixture, since the signal is proportional to the number density of the probe species squared. This difficulty limits the applicability of the four-wave mixing to the electric field measurements in high-pressure flames (several atm), where plasma generation and control become more challenging. However, comparison of ps FWM and ps SHG measurements of the electric field in ambient air shows that the latter method is considerably more sensitive, generating a much higher signal at a significantly lower laser power, and suggesting that it would be more effective for diagnostics of atmospheric pressure flames. Also, the electric field induced second harmonic signal is generated in the visible part of the spectrum, instead of the IR signal obtained in the four-wave mixing (4.3 μm if molecular nitrogen is used as a probe species), such that it can be measured by photomultiplier detectors and CCD cameras.

In the present work, ps second harmonic generation is used for the electric field measurements in dielectric barrier discharges (DBD) sustained by ns pulse and AC sine wave waveforms in an atmospheric pressure hydrogen diffusion flame. The use of two different voltage waveforms makes possible isolating two different effects of the applied electric field on the flame, (i) radical species generation in a ns pulse DBD plasma, and (ii) ion wind generated in an AC DBD plasma. It is well known that the ion wind effect on the flame in a ns pulse discharge is minimal, since it requires a significant impulse of the Coulomb force, typical for AC and DC fields. On the other hand, ns duration voltage pulses can produce a significantly higher peak electric field during breakdown, compared to DC or AC voltage waveforms [15]. The objective of this work is to provide insight into ns pulse breakdown kinetics in reacting hydrogen–air mixtures, which controls the discharge energy coupling and energy partition, and to quantify charge transport processes in AC plasmas generating the ion wind in the flame.

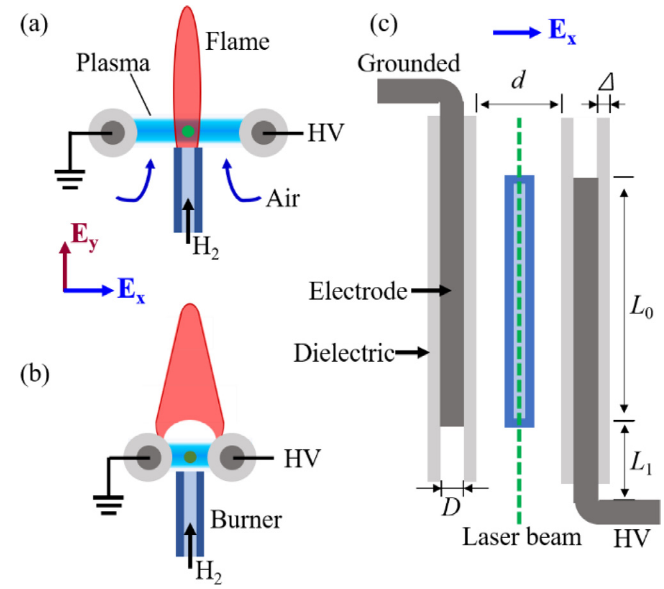

Fig. 1. Schematic of the burner, double dielectric barrier discharge electrode assembly, and the laser beam (a–c). Flame spreader dimensions 0.5 mm × 45 mm, diameter of brass electrode rods $D = 3.2$ mm, electrode overlap $L_0 = 45$ mm, non-overlapping electrode length $L_1 = 5$–20 mm, alumina ceramic tube thickness $\Delta = 1.6$ mm, electrode gap $d = 12$–15 mm (a) or $d = 4$–5 mm (b). Both the electrode plane and the laser beam are 2 mm above the flame spreader exit.

2. Experimental

Figure 1 shows a schematic of the burner, the flame, the double dielectric barrier discharge electrode assembly, and the location of the laser beam. The burner used in the present work is a Bunsen burner, in which the barrel with the air intake slots has been removed and replaced by a custom-made flame spreader made of quartz, with the rectangular exit slot dimensions of 0.5 mm × 45 mm. The quartz wall thickness at the flame spreader exit is 1.25 mm. Hydrogen flows through the burner at the flow rate of 1–2 slm, maintaining a diffusion flame ≈ 50 mm long above the flame spreader. The flame spreader provides ample access for the discharge electrodes applying the electric field across the flame, in a simple rectangular geometry. Two parallel cylinder brass electrodes, inside alumina ceramic tubes, are placed parallel to the flame spreader. The electrodes are located slightly above the burner, as shown in Fig. 1, such that their horizontal plane of symmetry is 2 mm above the flame spreader exit. The laser beam is directed parallel to the electrodes, in the horizontal plane of symmetry and halfway between the electrodes (see Fig. 1).

The rectangular geometry of the flame and of the electrodes, rather than the axisymmetric geometry used in Ref. [11], is employed because of the relative simplicity of the data interpretation at the conditions when the electric field vector is not expected to change direction over the Rayleigh range of the lens focusing the laser beam. The diameter of the brass electrode rods is $D = 3.2$ mm, the alumina ceramic tube wall thickness is $\Delta = 1.6$ mm, the overlapping electrode length is $L_0 = 45$ mm, and the gap between the electrodes is varied from $d = 4$ mm to $d = 15$ mm. For large electrode gaps, $d = 12$–15 mm, the flame is attached to the flame spreader, while for smaller gaps, $d = 4$-5 mm, it is attached to the top of the ceramic tubes, as shown schematically in Fig. 1. The electrodes are powered by a custom-made high-voltage pulse generator producing alternating polarity pulses with peak voltage of up to $U_{peak} = 16$ kV and pulse repetition rate of 20 Hz, or by a Trek Model 20/20A high-voltage AC amplifier driven by a sine wave function generator, at peak voltages of up to $U_{peak} = 14$ kV and frequencies of $f = 1$–10 kHz. The discharge voltage and current