Non-premixed Impinging Flames and CO Release under the Influence of an Electric Field

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1 Introduction

This research examines the use of electric fields as one mechanism for controlling combustion. In particular, it studies the use of the electrical properties of the flame to determine the combustion behavior and it then explores the use of the electric field driven ion wind to improve the burning in real time.

The current work follows from a related study of carbon monoxide (CO) release from flames near a quenching surface by Weinberg, et al. [1]. That paper provided measurements of CO released from a small diffusion flame as a quenching surface was brought into its proximity. By relating surface proximity to CO release, the study showed that electrical detection of the flame-to-surface distance could be used to predict incipient quenching and CO release. The research focused on sensing and so mainly supplied the flame with low DC voltage from batteries (37 and 56 Volts) and probed with an electrode around a partially premixed flame to observe the first ion current appearance. This prior research revealed the possibility of using a low voltage source and different probe materials as a flame proximity sensor, and by inference then incipient CO release. The study also suggested another potential investigation – active electric field control of CO release. Reference [1] also postulated that the source of CO release from impinging diffusion flames is the high concentration of partially oxidized fuel inside the flame envelope that avoids the final oxidation step. Hence, by exploiting the flame shaping capability of an ion-driven wind [2], it may be possible to control CO release from flames near a quenching surface. In particular for the current work, we measure CO emission changes when a quenching surface gradually moves close to a small diffusion flame. Then, by using strong electric fields as a mechanism for controlling combustion, we examine the changes in CO release. The research comprises primarily experimental measurements of flame shape, hydroxyl radical (OH) location, and global carbon monoxide emission.

Experimental measurement have already demonstrated that CO emission is changing under electric field influence [3], [4]. The present work helps elucidate some of the processes that might account for these CO emission results by including OH* chemiluminescence and OH planar laser induced fluorescence (PLIF) imaging [5] results, as OH is a key reactant for diffusion flames. The use of OH and OH* together has been described as marking the heat release zone and reaction zone in several publications (e.g., [6], [7]). These two pieces of information make OH PLIF and OH*

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chemiluminescence a complementary combination that can provide useful information regarding the physical extent and progress of combustion processes.

The thermal and flow characteristics of electrically actuated impinging flames are not easily assessed because any particles or probes strongly influence the electric field. The spatially-resolved non-intrusive measurement of CO is also a challenge, as it requires multi-photon approaches [5], [8], or laser absorption by tunable diode laser [9] followed by tomographic reconstruction. Consequently, in order to determine the relationship between carbon monoxide release and the electrical potential applied to a diffusion flame near surfaces, we use PLIF of OH to provide qualitative information of the two-dimensional distribution of this important reactive intermediate. We also identify the highly reactive zone using tomographic reconstructions from the chemiluminescence of excited-state OH. These two techniques help describe the relationships between the quenching surface, electric field effects, OH distribution, and CO emission from impinging diffusion flames. In addition, the research explores the possibility of detecting and changing the flame behavior electrically. The ultimate goal is to control the emission of carbon monoxide from flames near surfaces.

2 Experimental setup and electric field flames

The experiments are conducted using a coflow burner with a plate progressively lowered toward the burner surface so that it gradually quenches the flame. In order to generate a diffusion flame, a stainless steel coflow burner is used. The burner is 13 cm tall and 4 cm outer diameter sits on a Teflon mount to prevent conducting current through optical table. At the exit, the burner has a 2.13 mm inner diameter center small tube ducting fuel and, at the same time, air is provided separately through a concentric outer ring (like a donut). The air is designed to form a uniform distribution (top-hat) at the exit after it passes through a bed of beads and a honeycomb mesh (25mm in inner diameter) close to the exit. Inside the burner, the length of the tube is sufficient to ensure fully developed flow at the exit for the range of desired Reynolds numbers.

The quenching plate is 2 inches by 2 inches square thin stainless steel with 2mm thickness. It is indirectly connected onto a vertically moving slide. The slide can be adjusted in the range up to 40 mm maximum. An upside down L-shaped connection bridges between the plate (with insulation) and the slide. The plate is screwed through two cylindrical ceramic threaded posts for electrical insulation, which are connected onto the adjustable mount. The diffusion flame in this research is stabilized with a constant average flow speed of 20 cm/s for both methane and air at the burner exit.

An overall integrated flames image at various burner-to-plate spacings and different electric field strengths is shown in Figure 1; H/D denotes the ratio of plate height to the diameter of the center fuel tube. The detailed electric field flame behavior is described and presented in previous work [3]. Before doing further exploration of electric field effects on quenching flames it is important to clarify the direction of the field interacting with the combustion zone.

In Figure 1, the right-hand side represents the positive field in which the electric field drives positive ions and the ion wind toward the plate so that the flame is pulled up and the top of the flame narrows. In this way, the upward electric field direction represents positive field strength while the downward arrow indicates a negative field, which at the same time refers to the direction that the ion wind blows. The flame quenches when a field is applied above the maximum limit in both field directions. It is clearer to represent the field strength, ion wind direction, and flame behavior/shape all at once by solely field direction. With this qualitative understanding of how the flame shape changes under the influence of the plate and the electric field it is now possible to examine linkages to the possible release of carbon monoxide.

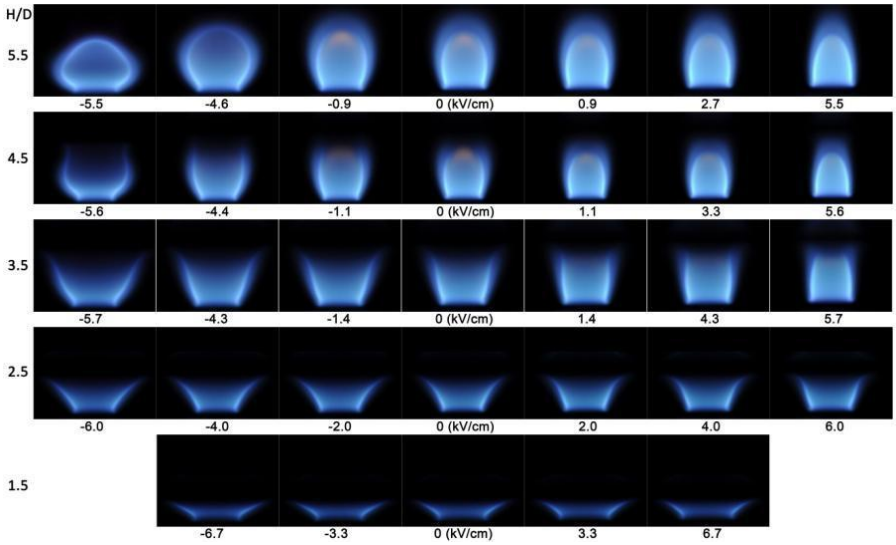

Figure 1. Overall electric field flames with a plate impinging at different burner-to-plate spacing H/D.

3 OH PLIF

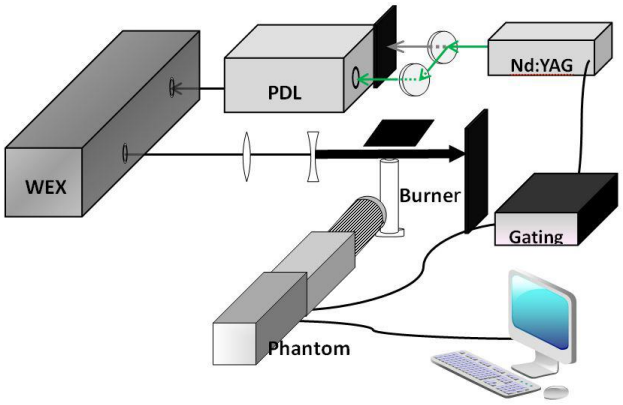

Figure 2. PLIF experimental setup, including Nd:YAG pump laser, pulsed dye laser (PDL), wavelength extender (WEX), one convex UV lens, one concave UV lens, high speed camera with intensifier, gating system and control computer.

The OH PLIF technique has provided valuable information from flames for many years [5], [10]. Our PLIF measurements follow generally recommended practice [5], [11] except that they are conducted by pumping OH at 282.0 nm in the *A*-*X*(1,0) band and detecting fluorescence in the *A*-*X*(0,0), (1,1) band. The system is composed of a Nd:YAG laser (YAG) and a pulsed dye laser (PDL) with a wavelength extender (WEX), shown in Figure 2. The Nd:YAG laser generates 1064nm light that then is frequency-doubled to 532 nm and passed through dichroic mirrors to reflect only 532 nm into the PDL. The PDL dye (Rhodamine 590 dye in methanol) fluoresces at around 564 nm. The laser light then travels into the WEX where doubling crystals generate 282 nm light. A prism guides the residual light to a beam block. The pump beam is directed through UV sheet forming optics coated from 270 nm to 350nm to focus on the flame. Being a legacy laser system, it is not automated and the experiment requires manual tweaking of the crystals to find and maintain good performance. The requirement for continuous adjustment makes precise quantification difficult but, as shown by the results, the manual effort produces very clear evidence of OH distributions in the impinging diffusion flames (recent measurements from a colleague using a new PLIF system have confirmed the quality of

the images presented in this paper[12]). The sheet forming optics are a spherical lens plus a cylindrical lens, forming a sheet with a height of 8 mm; both lenses have long focal length to accomplish a thinner and more homogeneous sheet in the flame. The pulse energy was kept below 1 mJ to stay in the linear regime of the fluorescence. A high speed Phantom camera (v4.3) and a HiCaTT intensifier equipped with a P24 phosphor collected the images. A band pass filter centered at 320 nm was used (Semrock FF01-320/40-25) which offers 70% transmissivity to collect the light from the A-X(0,0) transition. The camera plus intensifier setup is not optimal for 10 Hz PLIF because of the loss of resolution inherent in a system that has the capability of achieving imaging up to 10 kHz. Nevertheless, the performance was adequate at 10 Hz. The images were taken using a gate of 100-150 ns to suppress background light from the flame. Detection at A-X(0,0) was selected to avoid Rayleigh scattering interferences.

As mentioned above, accurate scans were difficult due to required manual adjustment of the doubling crystal for each output wavelength from the dye laser. To evaluate the system, we simulated an excitation LIF scan with LIFBASE [13] from 281.7 nm to 283.0 nm. This range of wavelengths corresponds to the A-X(1,0) band; the linewidth of the exciting pulse was estimated from similar PLIF set ups at 0.8 cm^{-1}[7]. The main peaks that are found suitable for PLIF imaging are the stronger ones that start at 282.0 with the Q1(1) transition followed by the Q1(2), Q1(3). Most other PLIF work has been done around Q1(8) because the rotational population associated with that transition varies less than 10% for typical reaction zone temperatures between 1400-2200 K. For our particular experimental configuration we found, however, that the transition with the strongest signal was Q1(1) due to the combination of the laser power profile, the LIF cross-section, and the fact that the Q21(1) and the R2(3) lines are very close by and can contribute to the signal.

4 OH* chemiluminescence and tomography

OH* chemiluminescence represents the hot region of the flame or the reaction zone. It is important to identify and locate where the reaction takes place within the flame. The chemiluminescence images in the band from 300 nm to 340 nm (using the same filter as for PLIF) are recorded with a gate of 10 microseconds on the camera. Because the image is taken from the side of the flame, the OH* distribution is integrated along the line of sight. In order to retrieve the actual OH*, the images are processed through an Abel transform to reveal tomographically reconstructed local distributions [14], as shown in Figure 3a and 3b. The reconstructed image is after averaging 200 pictures taken at a rate of 100Hz and after filtering with its background. The transformed image shows a clear region of the hot zone.

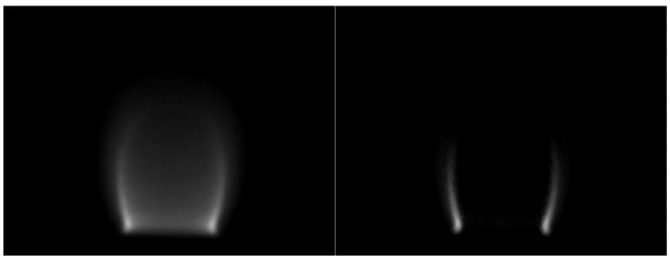

Figure. 3 OH* chemiluminescence images before (left) and after (right) tomographic reconstruction.

5 Two line OH temperature

Two-line thermometry measurement is conducted with a similar setup to that used for the PLIF. The experiment is steady so that the probing of the two lines can be done sequentially rather than simultaneously. In order to increase the measurement sensitivity, the difference of ground-state energy between two transitions is selected taking into account a large energy difference in the ground state and the smallest contribution from neighboring transitions[15]. Based on the LIFBASE dataset[13],

$R_1(3)$ and $R_1(10)$ are the two transitions captured with the PI-MAX4 ICCD camera in the experiment. For each measurement, the camera is calibrated with its background internally. The laser intensity variation is corrected. The detailed diagnostic measurements and how to compute temperature is contained in another paper also submitted to this conference; "Two-line OH PLIF temperature measurements of flames near a quenching plate."

6 Schlieren imaging

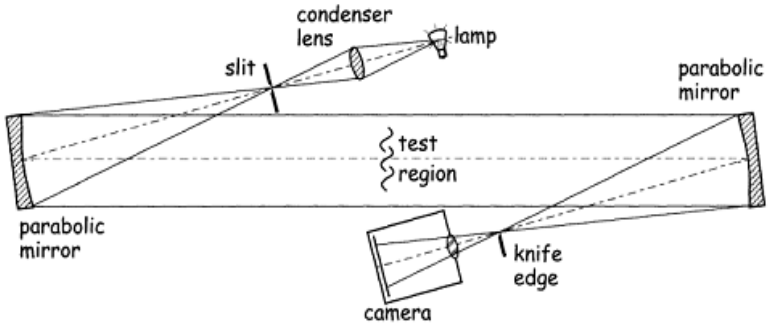

Figure 4 An example of the Z-type Schlieren setup schematic, from Settles[16].

Schlieren is an imaging technique to observe the flow field by imaging density change (and thereby refractive index change), and there are different types of setups with advantages and disadvantages. We are using the so-called "Z-type" Schlieren (Figure 4) with two 6 inch diameter parabolic mirrors, which reduced spherical aberration as compared to equal sized lenses. An arc lamp provides white light as a bright but not tightly constrained source, and this light is then focused by a convex lens. An optical fiber collects the focused light and acts as a point light source at the focal point of the the first parabolic mirror. The reflected light from the mirror travels parallel and across the test zone to the second mirror situated at its focal distance of 45 inches. A knife edge is placed at the refocused light from the second mirror to partially block the light that has been deviated by the refractive index gradients in the test section. The generated Schlieren image is then projected onto a glass screen by an achromatic lens. Figure 5a shows the point light source from the exit of the optical fiber (left), the flame (yellow) and the inverted projected Schlieren image on the glass screen.

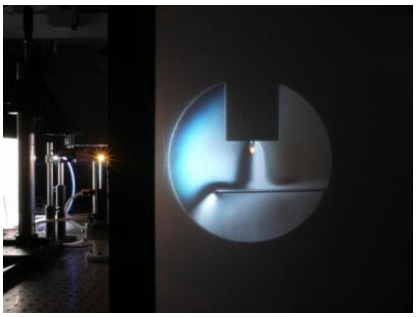

Figure 5 Photograph of the Z-type Schlieren experimental setup on an optical table

The full paper includes all of the images and results described above, including evidence that the impingement plate and the electric field can adjust the location of the OH cloud relative to the reaction zone, and that this adjustment correlates to the release of carbon monoxide..

Acknowledgement

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