Electrical Aspects of Impinging Flames

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This research studies the potential of controlling the release of carbon monoxide from impinging flames by using electric fields. Carbon monoxide results from incomplete combustion. In some syngas processes the carbon monoxide is desirable but usually it is a dangerous emission from forest fires, gas heaters, gas stoves, or furnaces where the insufficient oxygen available in the core reaction does not fully oxidize the fuel to carbon dioxide and water. Electrical aspects of flames, specifically, the production of chemi-ions in hydrocarbon flames have been investigated in a wide range of applications. Despite this fairly comprehensive effort to study electrical aspects of combustion, relatively little research has focused on electrical phenomena near flame extinguishment. This research examines the use of electric fields as one mechanism for controlling combustion as flames are partially extinguished when impinging on nearby surfaces. In particular, we study the use of the electrical properties of the flame to determine the combustion behavior and we then explore the use of the electric field driven ion wind to improve the burning in real time.

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 the use of the electric field driven ion wind to improve the burning in real time.

CO poisoning is mostly seen in incomplete combustion situations, such as forest fires, building fires, gas stoves, or gas heaters, where there is insufficient oxygen available in the core reaction zone to fully oxidize the fuel. Because CO is colorless, tasteless and odorless, people need detectors to monitor the amount of CO in the surroundings as an alert to its dangerous presence. As a result CO emission generally occurs when a non-premixed or fuel rich premixed flame source burns near, or impinges on, a surface which can create conditions near extinction (quenching) of the fire [1].

Inside a hydrocarbon flame, positive ions and negative charge carriers (generally electrons) appear in the reaction zone. H3O+ is the most important ion for near stoichiometric mixture combustion, having a much higher concentration than other ions such as C2H3O+, C3H3+ and HCO+. Prager, et al. [2] found H3O+ dominant in lean flames. The fundamentals of chemi-ion production and the transport of these ions is well-documented in the references already cited so a complete repeat of this topic is not necessary [3]. A general finding in all cases is that the weak plasma naturally occurring inside flames is not essential for heat release reactions [4].

Proper application of electric fields can act on the charge carriers in flames and modify combustion behavior. The use of electrical aspects of flames has been explored for many years, with continuing investigations in microgravity and zero gravity combustion [5], [6], [7]. Recent work also demonstrates the direct current electric field effect on thermoacoustic behavior of flat premixed flames where the ion-driven wind has been used to suppress

thermo-acoustic oscillations [8]. Emissions such as carbon monoxide and NOx can be minimized with electric fields, even when they are weakly applied [9], [10], and these effects are also seen in turbulent premixed flames at high pressure [11]. Optically based experiments, such as particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF), have been used to study how the shape of premixed fuel/air flames responds to high electric fields [12], [13], [14]. These past studies have helped demonstrate several different experimental methods for measuring the ions generated in flames and their influence [3] but they have not been used in the context of flames near surfaces.

Despite the fairly comprehensive effort to study electrical aspects of combustion, the only published study on electrical phenomenon related to CO release near flame extinguishment was presented at the 2012 International Symposium on Combustion by Weinberg et al. [15]. The paper included measurements of carbon monoxide concentration with respect to each location of a diffusion flame to evaluate the possibility of developing a sensor for surface proximity by detecting electrical currents in the flame. 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. The experiment was also conducted with different electrode materials. The results showed that aluminum is chemically and catalytically active, with the generation of CO near quenching, while brass, copper or steel are catalytically inactive materials. The electrical structure of quenching flames was also studied under small (<10V/mm) electric fields, and the current detection area was compared with the quenching regime where CO release was maximum. The catalytic effects are significant since they can lead to erroneous interpretations of the carbon monoxide formed by the flame directly as compared to that produced during interaction with the quenching surface. This prior research revealed the possibility of using a low voltage source with different probe materials as a CO detecting sensor, and also opened another field to investigate – electric field control of CO release. To begin exploring the effects associated with impinging flames interacting with an electric field as an active control mechanism, this paper investigates high voltage electric field effects on CO release near a quenching surface.

The basic objective of this study is to understand the fundamental electrical aspects of flame behavior near quenching. The study involves determining the relationship between carbon monoxide production and the electrical signal generated by the flame under different conditions near surfaces. In addition, the research involves exploring 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. The research comprises primarily experimental measurements of flame shape and global carbon monoxide emission.

2   Experimental

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 has a 4 cm outer diameter. It sits on a Teflon mount to prevent conducting current through the optical table that supports it. At the exit, the burner has a 2.13 mm inner diameter center tube carrying fuel and air is provided separately through a concentric outer ring. The air is designed to form a uniform distribution 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 stainless steel with 2 mm thickness. It is indirectly connected onto a vertically moving slide. The slide can be adjusted in the range up to 40 mm from the burner exit surface. An L-shaped connection fastens the plate (with insulation) to the slide. The plate is screwed through two cylindrical ceramic threaded posts for electrical insulation. The diffusion flame in this research has flow rates equivalent to a constant nominal speed of 20 cm/s for both methane and air at the burner exit.

The carbon monoxide emission is measured with a portable combustion analyzer which aspirates the exhaust gas inside the chamber at a slow and fixed flow rate. The generated CO from quenching fills the chamber with the existing air to yield a gradually increasing natural release from the chamber. Once this product no longer increases, based on the reading of the concentration, steady-state complete capture is confirmed. The decay rate of carbon monoxide release from the chamber as well as the generation rate has been considered and analyzed [16]. The acrylic chamber was designed to create a steady environment for the experiment and to diminish the external influence of air currents on the small flame. The entire schematic of the system and setup is shown in Figure 1.
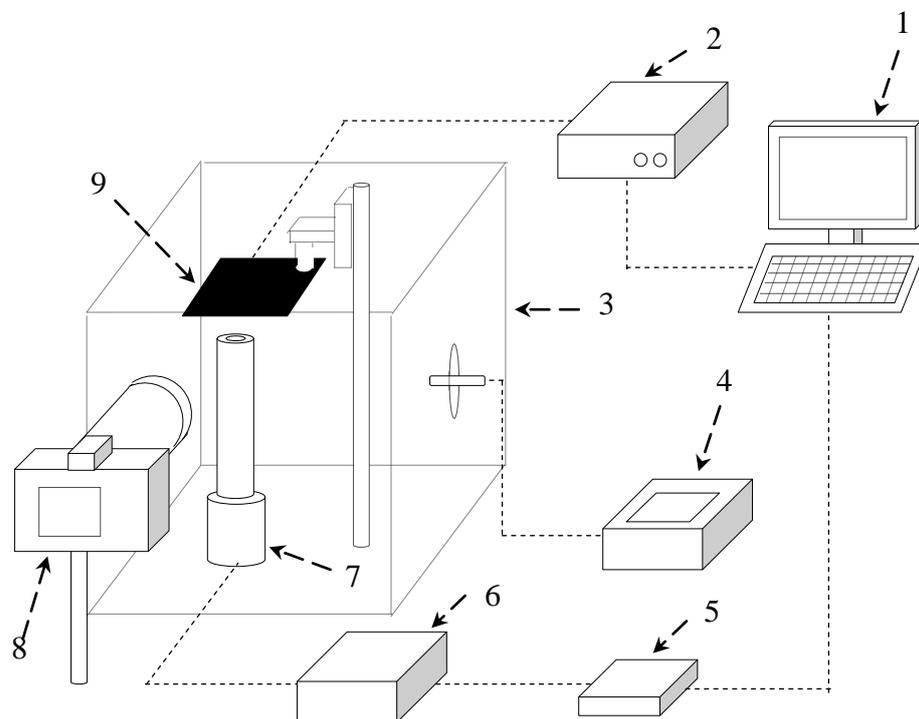
Figure 1. The measurement system schematic diagram. (1) PC (2) High voltage power supply (TREK) (3) Acrylic chamber (4) Emission meter (5) Data acquisition (DAQ) box (6) Shunt current system (7) UCI coflow burner (8) Digital camera (9) Movable quenching plate

3   Quenching and CO

Figure 2 shows characteristic photos of flame shape changes as the plate progressively moves toward the burner exit; where 3 mm is the limit distance that still allows a stable flame. At 9 to 8 mm, the luminous portion of the flame tip starts opening. For plate to burner spacing between 7 and 3 mm, the flow begins to strongly stagnate at the plate, with a clear transverse flow toward the outside edge.
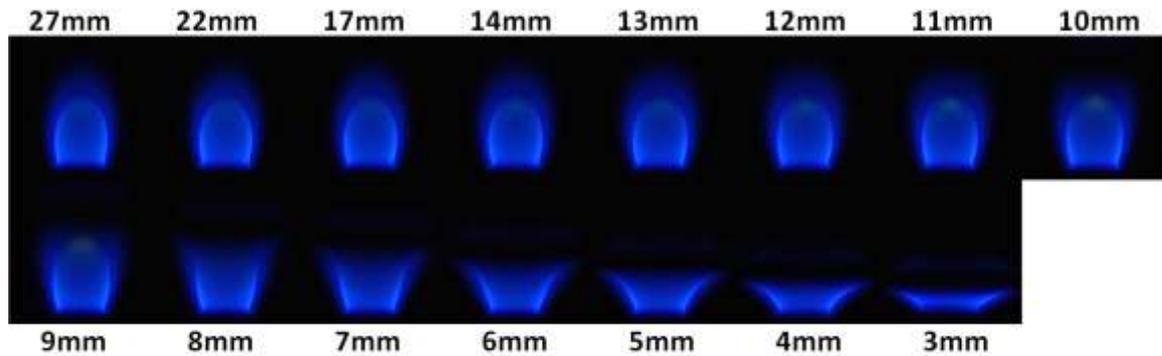
Figure 2. A small diffusion flame changes with a plate progressively approaching it. As a size reference, the flame base is approximately 3 mm in diameter.

The amount of carbon monoxide is measured at the heights from Figure 2. Figure 3 shows that when the plate progressively moves toward the burner, carbon monoxide generation increases. Because of quenching, the CO concentration grows as the distance drops. Two sets of data are presented in Figure 3; the first set is measured at two minutes after the plate moves to its new position and the other set is after the CO concentration reading becomes fully steady. The time required for the reading to reach an unchanging level differs for each case. Therefore, having a well-defined time scale for recording carbon monoxide concentration at different plate heights is useful to ensure the precision of the measurement.
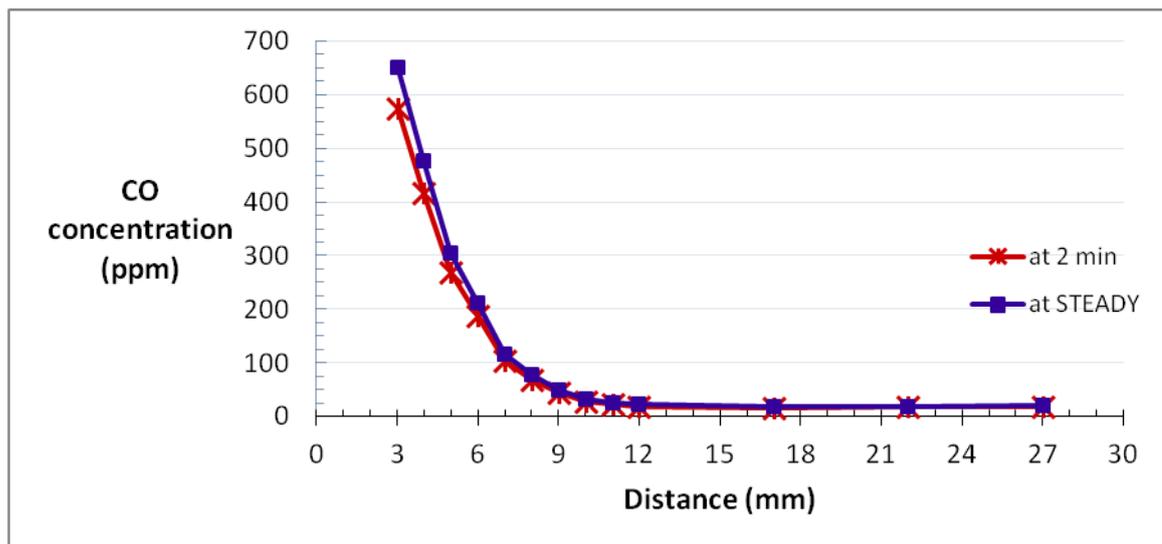
Figure 3. CO concentration changing with the height of plate

4   Voltage control

The high voltage is applied onto the quenching plate electrode from a high voltage power supply that can produce from -10,000 volts to +10,000 volts. A computer is connected to the supply, which sends an output request for the desired high voltage. Figure 4 shows the flame shape with various electric fields applied. The arrow represents the direction of the electric field. One of the confusing aspects of the literature is that several definitions about the

direction of the field are used in different research articles. To be clear, in this research all of the definitions of positive or negative electric field are based on the polarity of the burner relative to the downstream plate electrode. At 9 mm, Figure 4(a), the plate is very close to touching the outer dim luminous region of the zero-field flame but it does not reach the brightest flame front tip. For this plate location on the positive field side, 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. The luminous zone at the flame front is brighter presumably because the ion drift wind (also called Chattock wind [17]) has entrained more oxidizer and shifted the reaction zone. When the flame is in positive field strength 6kV/0.9cm, the flame quenches. On the negative field side, the flame is pushed down gradually as the negative field strength grows. The downward ion wind spreads the flame and opens it. As in the case of the positive field, the flame quenches at approximately 6kV for the negative field but the extinguishment process is different. For the negative field, an arc develops between the plate and burner, and the arc disrupts the flame sufficiently to quench it. Similar phenomena can be seen when the plate is located at 5 mm, Figure 4(b), except that the flame is already open with zero field. The flame opens wider with increasing negative field strength, with the bottom rim of the flame close to the burner exit. This opening behavior results from downward directed positive ions producing a downward blowing wind when the burner is negatively charged.

   To determine the effects of surface flame quenching on the electrical properties, the downstream plate is moved to different heights above the burner as the voltage is varied. At each different height of the plate above the burner, the range of electric field that is able to operate on the flame without extinguishing it or without generating an arc varies. The limits of the electric field become narrower as the gap between the plate and the burner decreases.

(a)

(b)
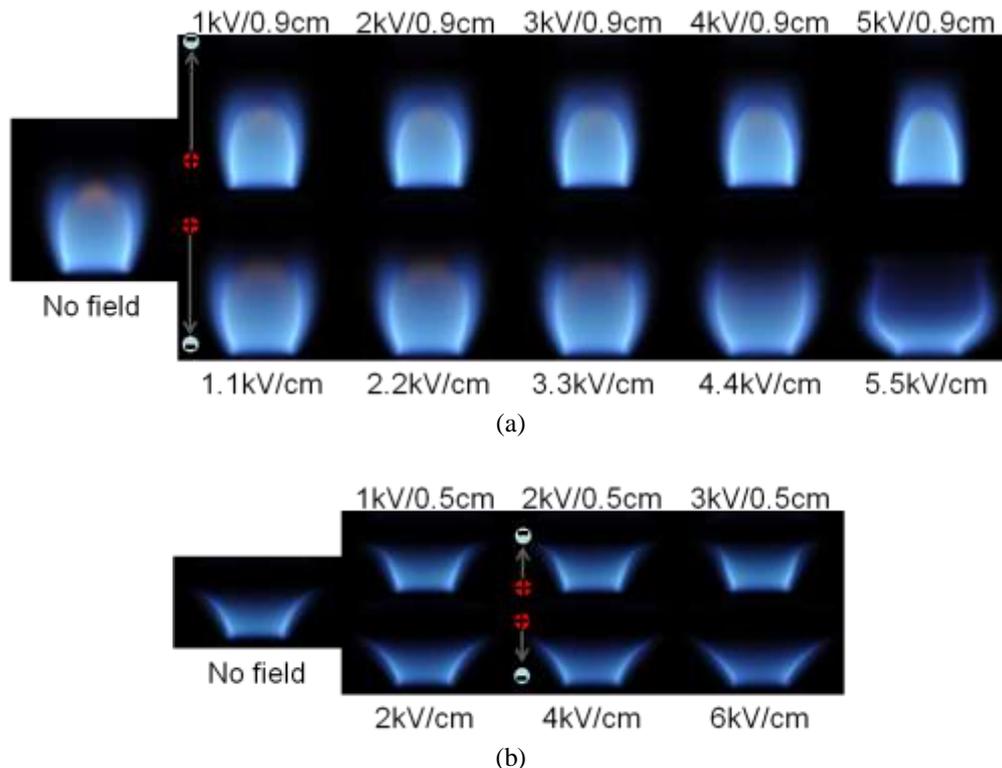
Figure 4. Electric effect flame near quenching with different height of the plate position (a) 9 mm (b) 5 mm.

5 Ion current detection

The electric potential driving the ion current of the flame is formed between two electrodes, the plate and the burner. Therefore, the flame itself can be imagined as variable electrical resistance. The ion current of the flame is measured by a shunt current system that leads ion current to pass around a lower resistance path. The circuitry of the shunt current system is protected with diodes and also includes a slow discharge circuit to prevent electric shock. A National Instruments data acquisition card connects the shunt current system and a computer together. Both the high voltage request from computer and the data acquisition from the DAQ card into the computer are programmed with the MATLAB computational package and Data Acquisition toolbox. A voltage monitor port from the high voltage power supply is also recorded for reference. Ohm's law is used in the MATLAB program for computing the ion current from the potential drop across the shunt resistance.

The experiment is conducted with plate heights from 25 millimeters to 3 millimeters with different field strength limits. Figure 5(a) shows the ion current changes with different electric fields. In Figure 5(a), the ion current response to the electric field shows three distinct regions: sub-saturation, saturation and enhanced saturation (also referred to as secondary ionization or super saturation) [5].

The ion current curve at each height shows good agreement with past studies and shows that the field strength at saturation is nearly constant but that the onset of enhanced ionization varies. As the plate moves closer to the burner, the saturation ion current limit becomes smaller. The ion current response in the enhanced saturation region shows approximately parabolic behavior until an arc appears as the field strength increases beyond breakdown. The steep vertical lines in the 25 mm case are an artifact of the voltage limit of the power supply.

Figure 5(b) shows a closer view of the transition from the sub-saturation to the saturation region. The capability to contain ions decreases as the distance between the plate and burner decreases. In the far field flow cases (i.e., from 25 to 12 mm plate distance) the plate has not reached the visible flame zone so the saturation ion current changes only a small amount due to a slight temperature effect from the plate. As the plate moves down into the visible flame from 11mm, the saturation ion a current drop consistently. The decrease appears to result from the wider opening flame tip, which decreases the flame temperature and reaction volume thereby decreasing the ion production. More detailed study is needed to confirm this explanation, however.

It is interesting to see that the ion current saturates faster (in electric field strength terms) on the positive side than on the negative side according to the contributions of the ion driven wind. The sub-saturation region increases as the plate gets closer in the positive field domain while the saturation region reduces as the plate moves closer to the burner. Therefore, the quenching plate plays an important role by affecting the flame shape, flow direction, reaction condition, and ion distribution with respect to electric field.

Parabolic curves occur in the enhanced saturation region. One hypothesis for enhanced ionizaton is that a small corona discharge occurs between the plate and burner at high field strengths; however, another measurement with a hydrogen diffusion flame has shown no ion current, which suggests that the effect is instead due to collision induced secondary ionization.
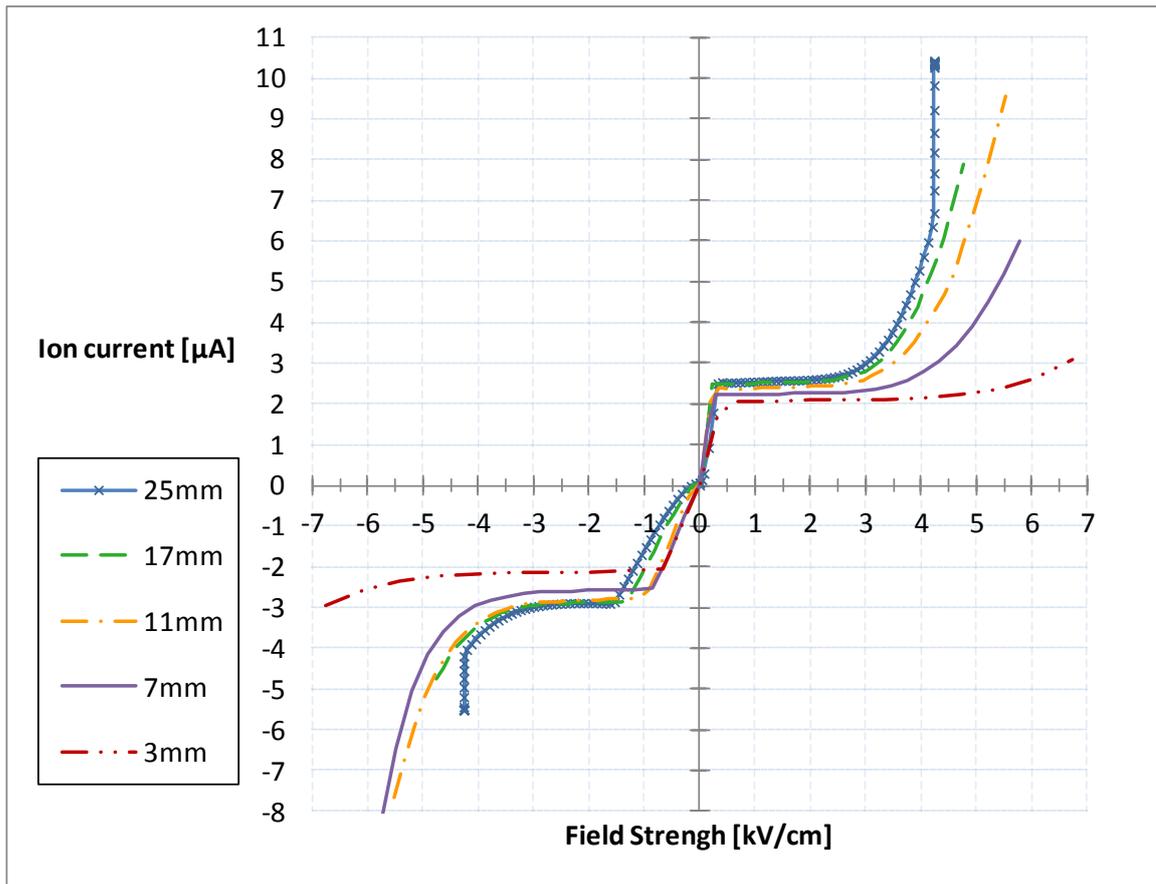
(a)
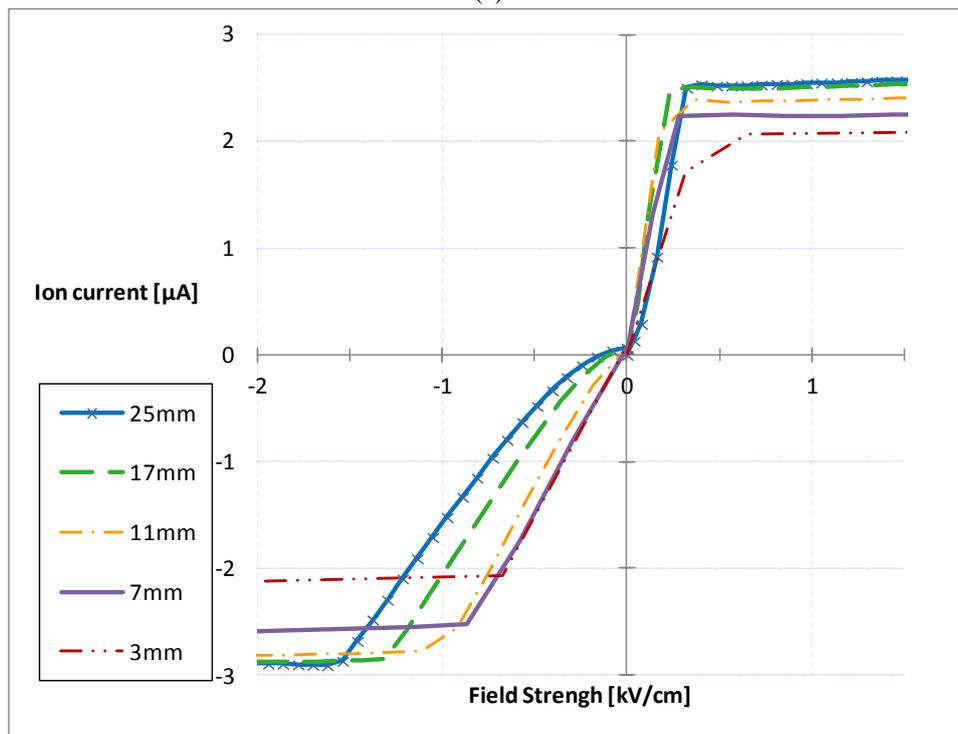
(b)

Figure 5. Ion current changing with field strength applied in different heights of the plate above burner. (a)
Whole region (b) detailed.

6   CO detection with high voltage control

Measurement of CO released from the flame with an electric field applied at different heights between the burner and the plate provides an indication of the potential for CO emission control of quenching flames.   For each case of carbon monoxide emission measurement, the chamber is first flushed with air.   The flame is then operated for 4 minutes before the CO measurement is taken; this not only ensures that all of the measurements are recorded at the same time but also avoids a long wait on a small concentration variation.   As shown in the earlier transient evaluation, 2 minutes is generally sufficient to reach steady conditions.

The experiments are conducted for plate spacing from 3mm to 7mm, where the amount of CO generated is over one hundred ppm. The results show that CO concentration is affected significantly by the plate to burner quenching distance. Interestingly, CO concentration also varies with electric field. Figure 6 demonstrates a normalized picture of this effect at each height with each value divided by the appropriate zero-field CO concentration.   As the negative field grows, the CO level rises. In the positive field side, CO does not show a significant change but it still grows slightly just before falling near the breakdown or extinguishment limit.
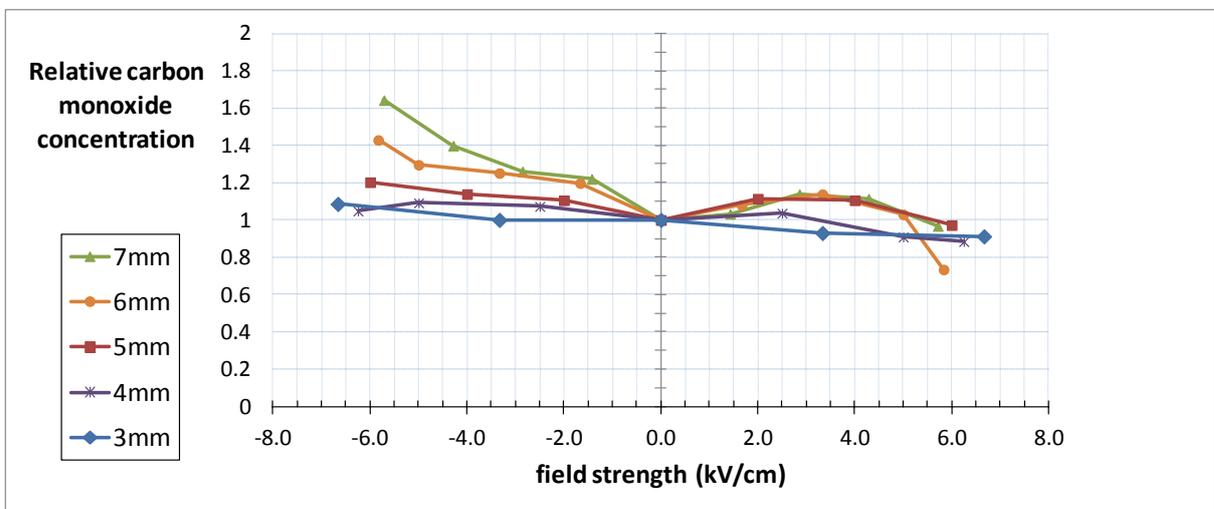
Figure 6. CO concentration at each different height with electric fields.

The normalized results show a consistent trend that can possibly relate to unsteady fluctuations in the combustion driven by the electric field. With the plate progressively quenching, it is possible to estimate that the average CO concentration rises at larger negative field strength compared to the no-field case. There still exist mysteries on the effects of positive electric field strength to uncover any feasibility for CO control, but these preliminary findings suggest that electric field control near a quenching plate will have relatively minor positive influence on CO reduction.

7   Temperature measurement – FLIR camera

Temperature and species concentration measurements in flames that have an electric field applied have been a challenge for exploring local property distribution because probes of any kind disrupt the electric field significantly.   Non-intrusive measurement therefore is the only choice, and in this work, an infrared camera is surveyed to understand how the

temperature distributes across the quenching plate as a function of the electric field application on the flame. The camera (FLIR SC620) measures radiative emission in the range from 7.5 to 13 microns, and it is situated directly above the quenching plate at normal incidence (to avoid complications associated with Lambert's cosine law). The camera is controlled by its native commercial software (ExaminIR, Figure 7). The quenching plate is painted with black paint and is considered a blackbody object. This assumption has been confirmed as reasonable using thermocouple temperature comparisons at a few spot locations.
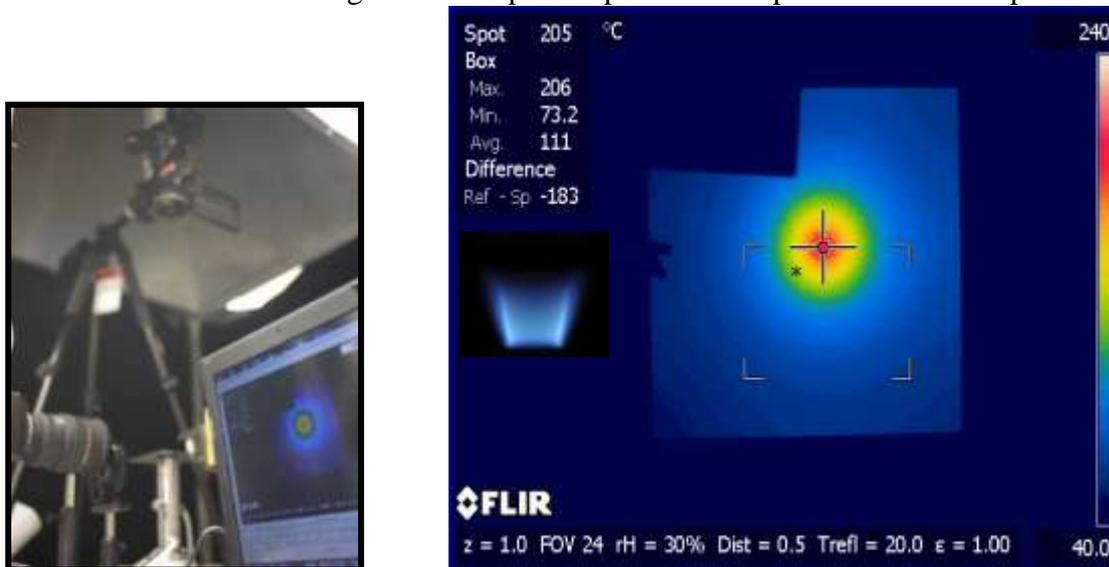
Figure 7. (a) An infrared camera for the temperature measurement. (b) IR image.

The RGB image taken at thermal equilibrium shows a well-distributed temperature change on the plate, a typical example of which is shown in Figure 7b. The temperature shown in the image does not represent a local temperature of the plate or the flame temperature. It is measuring the temperature of a thin layer of the heat resistant spray paint. The overall heat transfer includes forced convection of hot flame products onto the bottom surface of the plate, conduction through the plate, and then to the paint, the heat convection out of the surface into the air, and radiation from the surface, as the system reaches thermal equilibrium [18]. Based on straightforward heat transfer analysis it is easy to conclude that the radiation from the paint provides a reliable measure of the impinging heat from the flame on the backside of the plate. It feasible, therefore, to use the FLIR camera to characterize a quenching flame and to acquire a temperature distribution using 2-D image technology. The acquired thermal map is shown as Figure 7(b). The measurement was recorded 60 seconds after changing the electric field by which time the temperature is steady. The pressure drop during the experiment can affect the flow rate as a result of the small jet impinging on the plate, and the different flow rate affects slightly the temperature measured from the infrared camera, showing that about 1 ml/min change in the maximum plate temperature $2^{o}C$ [16]. Therefore all experiments conducted with IR imaging experiment use a fuel flow rate of 37.7ml/min (which is 20m/s) ± 0.6ml.

Measurement at various heights (3, 5, 7, 9, 11 mm) show that temperature decreases with the field strength (Figure 8). Maximum temperature of each condition at each height and field strength is recorded, and Figure 8 plots the relative maximum temperature at zero electric field at each distance between the plate and the burner. On the positive field strength side, the maximum temperature increases quickly in the beginning at 2kV/cm and keeps rising with the field strength applied. The reaction zone is narrowed due to the ion wind and the

flame's hot gas is being pulled up toward the plate. Both of these effects produce an increased local heat flux. On the negative field strength side, the reaction zone of the flame is shifted wider with the increasing of the field strength. Therefore, the maximum temperature decreases. The curve shows that the reducing trend initially decreases with similar slope until -3kV/cm, and then drops more rapidly with more negative field applied. As the plate reaches 3mm, the lowest limit of its position, the electric field effect on the maximum temperature of the plate does not vary as dramatically as for plate positions that permit more electric field influence on the flame. This is because the plate is so close to the flame that the reaction zone of the flame has already opened widely. That is, the jet momentum modification caused by the proximity of the quenching plate is more substantial that the momentum modification caused by the ion driven wind. Since we have seen that the ion-driven wind effects decrease with decreasing plate height and the physical effects of the plate increase with decreasing plate height it is clear that there will be a trade-off between these two influences. These results need more evidence and a theory to explain how the electric field is able to control and manipulate the flame's heat flux to the plate.
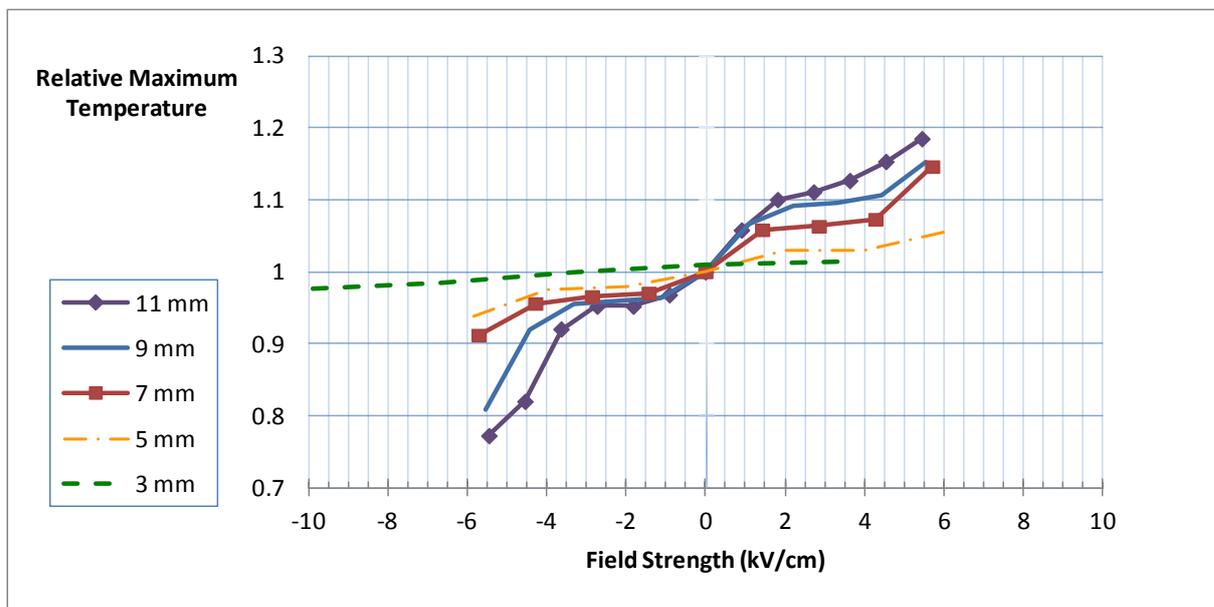
Figure 8. maximum plate temperature with electric fields

Conclusion

How an electric field changes flame behavior near a quenching surface, and how the amount of CO release changes as the impinging surface progressively approaches the flame is the subject of this paper. In particular, the work shows how heat flux from the impinging flame to the quenching surface can be related to its CO release and ion current generation. This information provides evidence for the feasibility of reaching the desirable goal of manipulating carbon monoxide release from impinging flames. More importantly, there is evidence that the electric field is capable of controlling CO concentration by affecting the tip opening of the flame. Unfortunately, it also appears that electric fields are capable of increasing CO emission as effectively as they are capable of decreasing it. While these results offer a promising approach of active control of carbon monoxide generation, further

exploration is required to understand the relationship between electric field control of the flame and the heat flux effect from the surface, and ultimately how this changes the release of CO.

Acknowledgement

Disclaimer

Product names and models are provided only for clarification and are in no way an endorsement on the part of NASA or the federal government.

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