A Study of Plasma-Stabilized Diffusion Flames at Elevated Ambient Temperatures

Wookyung Kim, Hyungrok Do, M. Godfrey Mungal, and Mark A. Cappelli

***Abstract*—We report on a study of the use of repetitive ultrashort pulsed plasma discharges in stabilizing a lifted methane jet diffusion flame in elevated temperature (855 K–975 K) vitiated coflow. CH chemiluminescence images are used to record the flame liftoff height, which serves as a measure of the flame stability. The results show that, for the same reduced electric field (E/n), the stabilizing ability of the discharge in the investigated temperature range diminishes with increasing coflow temperature. Based on the results of a zero-dimensional transient chemistry simulation, it is conjectured that the reduced propensity for stabilization at elevated temperature is caused by the rapid depletion of H_2 and CO formed in the postplasma gas, under high ambient temperature conditions.**

***Index Terms*—Elevated temperature, flame stability, plasma-assisted augmentor, plasma-assisted diffusion flame.**

I. Introduction

THE USE of plasma discharges in combustion applications has been studied extensively during the past two decades [1]. This research has demonstrated the promising ability to achieve leaner combustion [2]–[11], reduce harmful emissions [12]–[14], and ignite and sustain flames in high speed flows [15]–[18].

This paper is aimed at further understanding the role played by nonequilibrium plasma discharges in stabilizing jet diffusion flames. In this paper, we report on the response of a jet diffusion flame to plasma activation under conditions of elevated ambient temperature. This understanding is particularly relevant to the use of plasmas to enhance bluff body flame stabilization in the after-burner augmentors of an aircraft engine [19]. In our experiments, we use a simple jet and bluff body configuration as a first step toward understanding plasma-assisted flame stabilization mechanisms in augmentors modified for reduced pressure drop. The elevated ambient temperature typical of the after-burner augmentors may impact the plasma-assisted chemistry of jet diffusion flames in ways that differ in comparison to what is seen at lower temperatures. This is partly because of the following: 1) the lower gas number density, which will affect the total number of radicals produced by the discharge; 2) the altered flow field; 3) the altered coupling of discharge power to the flow; and 4) the change in temporal evolution (lifetime) of postplasma intermediate species.

In the previous studies of nonequilibrium plasma-assisted combustion in fully premixed lean methane–air flames [20], we have provided compelling evidence that the plasma ultimately serves as a fuel reformer, producing H_2 and CO, which burns with a higher flame speed and can thus promote greater flame stabilization. Hereafter, we show that the effect of the plasma discharge in jet diffusion flame stabilization in high-temperature coflow diminishes with increasing ambient temperature. We attribute this to the accelerated depletion of these important postplasma intermediate species, namely, H_2 and CO, which persist for much longer times at room temperature. As described in the section that follows, this mechanism is supported by simple chemical kinetic studies.

II. Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 1(a). High-temperature (1300–1500 K) vitiated coflow is produced in a 210-mm-diameter premixed burner [21] located centrally in a larger 50 $\times$ 50 cm cross-sectional area vertical wind tunnel. Air is delivered by a 1.5-hp blower and mixed with methane at a location of approximately 3 m upstream of the burner exit. The volume flow rate of the mixture at room temperature is 1300 standard liters per minute, confirmed by pressure drop measurements across the top surface of the burner. The burner has 2184 1.6-mm-diameter holes on the top surface spaced such that the array of tiny flames generate a uniform temperature profile over a wide region. Since the vitiated coflow can generate a temperature higher than that needed for the purpose of simulating a typical augmentor stream, a copper grid through which cooling water passes is placed on the top of the burner for heat extraction. The resulting temperature of the cooled postcombustion gas ranges from approximately 855 to 975 K, which is typical of the augmentor temperature in an aircraft engine [22], and is controlled by adjusting the equivalence ratio of the methane/air mixture comprising the coflow from 0.62 to 0.72. The velocity of the postcombustion gas is measured by particle image velocimetry (PIV) using a 15-Hz double-exposure interlaced CCD camera (Kodak ES 1.0), a 15-Hz double-pulse second harmonic ND:YAG laser (Spectra Physics PIV-400), and an alumina particle seeding system. As demonstrated next, the speed of the postcombustion

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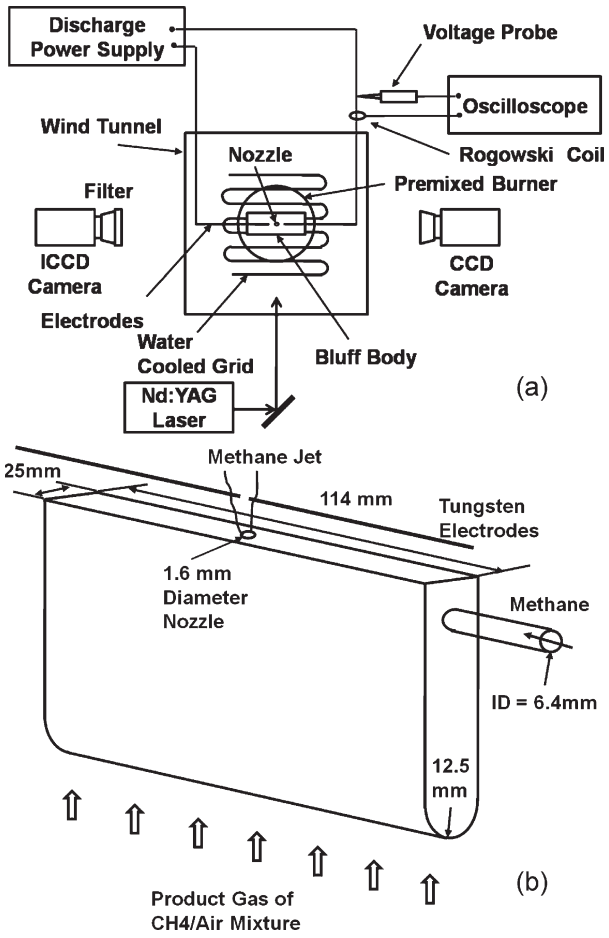

Fig. 1. (a) Overall schematic of the experimental setup. (b) Detailed schematic of the bluff body and injector.

gas is found to be 3.4–4.6 m/s, which is dependent slightly on the gas temperature, but this small speed dependence is not likely to affect the broader conclusions about the kinetics.

Important issues in streamline-shaped bluff body flame holder design include the geometrical shape and dimensions, and the appropriate selection of materials that are able to survive the high-temperature environments. Following the design considerations discussed in Lovett *et al.* [22], we selected a basic geometry consisting of a 114-mm-long by 25-mm-thick rectangular body with a 12.5-mm radius rounded forebody shape, as shown in Fig. 1(b). A porous ceramic (fused silica, 63% nominal porosity) was selected for construction because of its superior high-temperature properties. This ceramic is machinable, has good resistance to thermal crack propagation, and can withstand temperatures of up to 2000 K, eliminating the need for complex cooling. The pure methane jet for afterburning studies is delivered from a 1.6-mm-diameter centrally located fuel injection nozzle (on the base of the bluff body) branched from a single 6.4-mm-diameter fuel delivery pipe located within the ceramic body. The initial jet velocity at the nozzle exit is $\sim$7 m/s.

An ultrashort pulsed repetitive plasma discharge is produced by a pulse generator (FID Technology SU-20) that provides pulses (typically) of 10-kV peak voltage with 15-ns pulsewidths, at a 50-kHz pulse repetition rate. Two 0.8-mm-diameter opposed blunted electrodes made of thoriated tungsten are placed along the base of the bluff body, where the flow speed in the vicinity of plasma location is $\sim$1 m/s, as determined by PIV (see next). The height of the resulting discharge above the jet nozzle is approximately 25 mm ($\sim$16d, where d is jet nozzle diameter) and is located 30 cm from the top surface of the burner. The electrode separation is adjusted, from $\sim$0.8 mm (at 300 K) to $\sim$2.6 mm (at 975 K), to maintain the nominal reduced electric field (E/n) of approximately 500 Td. The discharge voltage and current are monitored at a location of approximately 1 m from the electrode with a 1000 : 1 high voltage probe (Tektronics P6015A) and Rogowski coil (Pearson Electronics, model 2877), respectively. For the range of conditions studied, the typical average power deposited into the flow is approximately 10 W. The temperature of the vitiated coflow is measured at the discharge location, with the bluff body in place (but discharge inactivated), using an R-type thermocouple.

In this paper, we use the mean value of the flame liftoff height as a criterion to characterize flame stability. To measure this liftoff height, we collect and ensemble an average of 100 images of CH chemiluminescence using an intensified camera (Princeton Instrument, PI-MAX) with a gate width of 100 μs. A 10-nm-wide spectral bandpass filter centered at 430 nm (in the vicinity of the $A^2\Delta - X^2\Pi$ transition of CH) is used to isolate the CH emission. This intensified imaging is also necessary to determine the instantaneous detailed characterization of the structure of the flame base, namely, its location and fluctuation behavior.

III. Results

The representative instantaneous CH chemiluminescence images of two (from a number of) cases examined for this discharge-stabilized afterburner-simulated methane jet in coflow are shown in Fig. 2. These particular images were acquired under discharge conditions of 10-kV peak voltage and 50-kHz repetition rate, and the coflow conditions of room-temperature (300 K) air [Fig. 2(a)] and high-temperature (940 K) vitiated air [Fig. 2(b)] with flow velocities of 4 and 4.2 m/s, respectively. The equivalence ratio of the lean high-temperature vitiated coflow stream is 0.69. In each image, the bright red feature (with a superimposed blue dot for identification) is strong emission from the CH radicals produced by the pulsed discharge. The white dashed line is intended to highlight the location of the flame base. We see that, under room-temperature conditions [Fig. 2(a)], the instantaneous flame base is anchored very near the discharge. However, under high-temperature conditions in the vitiated coflow stream, the flame base is located approximately 4 cm downstream of the discharge. It is noteworthy that, in the absence of the discharge, the room-temperature case does not produce a stable flame, whereas the high-temperature case is marginally stable. The presence of a discharge in both cases stabilizes the flame, but at high temperature, it is lifted and stabilized at a distance that is distinctly and substantially downstream of the discharge, unlike the room-temperature condition case.

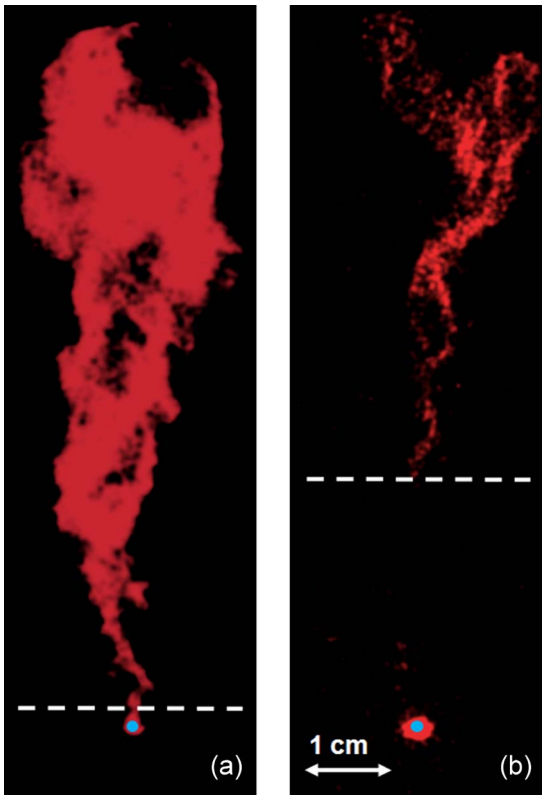

Fig. 2. Instantaneous CH chemiluminescence image: At (a) 300 K and (b) 940 K ambient temperatures. The discharge conditions are 10-kV peak voltage and 50-kHz repetition rate, and the discharges are located in the region identified by blue dots. The flow speeds are (a) 4 and (b) 4.2 m/s. The white dashed lines represent the flame base location.

Fig. 3 shows the average flame base locations (liftoff height) for a range of coflow ambient temperatures, as measured with and without the discharge. As mentioned earlier, due to the change in the ambient temperature, the free-stream flow velocity does vary somewhat over the high-temperature range studied, from 3.4 to 4.6 m/s for the 855–975 K range, respectively. Fig. 3 also shows, as a reference, the room-temperature pure air coflow case with a 4-m/s free-stream velocity. The discharge conditions for the data presented in Fig. 3 are identical to those of Fig. 2. However, the electrode separation is adjusted from 0.8 mm (at 300 K) to 2.6 mm (at 975 K) so that the nominal reduced electric field is kept approximately constant (500 Td).

We see from the results shown in Fig. 3 that the flame stability, characterized by the average liftoff height, is improved substantially by the presence of the discharge. In the absence of the discharge, no autoignited/sustainable flame is obtained until the ambient temperature reaches approximately 940 K. Once a sustainable flame is autoignited, the liftoff height of the flame is seen to *decrease* with increasing ambient temperature (from 150 mm at 940 K to 110 mm at 975 K). This decrease in the liftoff height with increased ambient temperature is attributed to faster chemistry at higher temperature, which increases flame speed and hence flame stability. In contrast, in the presence of a pulsed nonequilibrium discharge, the flame liftoff height is seen to *increase* from 8 mm at 855 K to 70 mm at 975 K. In all cases studied, the flame was stabilized by the discharge, and for temperatures where a stable flame was obtained without a

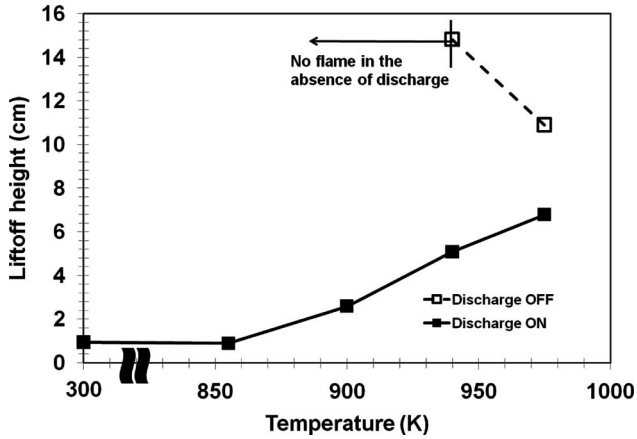

Fig. 3. Liftoff heights as a function of ambient temperature. Discharge conditions are the same as those in Fig. 2. Flow speeds are 4 m/s (300 K), 3.4 m/s (855 K), 3.8 m/s (900 K), 4.2 m/s (940 K), and 4.6 m/s (975 K).

discharge, the flame liftoff height was significantly reduced in the presence of a discharge. This result shows the benefit that a pulsed nonequilibrium discharge plays, even at high coflow temperature, and further suggests that such discharges may have been beneficial in improving flame stability in augmentor applications. An interesting question is why, in the presence of a discharge, the liftoff height increases with increasing temperature, in contrast to the trend seen when the discharge is turned off. Clearly, the discharge plays a lesser role at higher temperatures, and we presume that the two curves will merge together at temperatures of approximately 1000 K, where the discharge may afford little or no benefit. At this time, we cannot confirm this because of experimental limitations at the higher temperature.

As discussed hereafter, we attribute this diminishing effect of the discharge on stability, with increasing temperature to the increased depletion with temperature, of postplasma intermediate species, namely, H_2 and CO, that are found to enhance combustion.

IV. Discussion

In a previous study [20], we showed that an important process in nonequilibrium discharge-plasma-enhanced flame stability is the production of stable intermediate species such as H_2 and CO. These species are formed from various dissociated molecular fragments that are produced directly within the discharge and can survive for much longer time than the radicals themselves. As a consequence, a long range interaction can exist, between the flame base and the discharge, evidenced in some cases by the persistence of weak chemiluminescence, which we have attributed to the presence of a cool flame in previous plasma-assisted premixed combustion experiments [20]. We believe that a similar process is responsible for anchoring these jet diffusion flames in high-temperature coflows.

At elevated ambient temperature, we might expect that the range of influence of these important intermediate species (H_2 and CO) will be reduced due to the accelerated oxidization processes, i.e., as represented by the overall reactions: $H_2 + 1/2O_2 \rightarrow H_2O$, and $CO + 1/2O_2 \rightarrow CO_2$. To support this

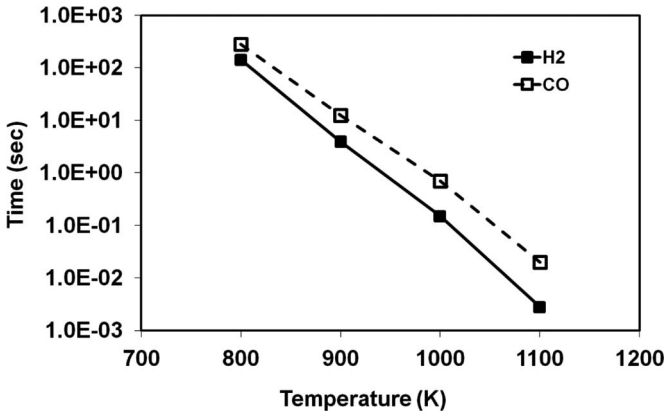

Fig. 4. 90% concentration decay time of H_2 and CO in a postcombustion mixture whose original equivalence ratio is 0.67. Initial concentrations of H_2 and CO are 5000 ppm each. CHEMKIN with GRI MECH 3.0 was used for this simulation.

hypothesis, we performed zero-dimensional kinetic simulations using the chemical kinetic software package CHEMKIN [23], along with the embedded GRI MECH 3.0 combustion mechanism [24], which is a mechanism optimized for methane combustion. The initial species concentrations (mole fractions) for this calculation are determined from the equilibrium combustion products of a 0.67 equivalence ratio methane/air mixture with major product assumptions, and it is then assumed that 0.5 vol.% of water vapor and carbon dioxide is dissociated by the discharge to produce 5000 ppm of H_2 and CO, respectively. This level of 5000 ppm is approximately that which we calculated as typical concentrations of these species in our previous study of plasma-assisted combustion in lean premixed methane and air [20]. We might expect that, with increasing temperature, the chemical reactions will shift to partially destroy (oxidize) the H_2 and CO introduced in the simulations. This is indeed what is seen in the simulations, with trends that are qualitatively consistent with the experimental variation in flame liftoff height.

Fig. 4 shows the variation with ambient temperature for the 90% concentration decay times of the initial 5000 ppm H_2 and CO in the postcombustion mixture. While we see that the H_2 and CO persist for over 100 s at 800-K ambient temperature, we also find that the decay time decreases strongly with increasing temperature. At 1000 K, the 90% decay of H_2 is approximately 0.1 s, which implies a characteristic survival distance of approximately 10 cm for a flow speed of 1 m/s. It is apparent then that, near the higher temperature of the range studied here experimentally, these intermediate stable species are being rapidly oxidized, and the flame stability is compromised, resulting in a liftoff height that is comparable to that seen in the absence of a discharge. One can thus attribute the significantly nonlinear phenomena of flame liftoff height, i.e., the observation of a similar liftoff height at temperatures of 300 K and 855 K, but an abrupt increase in a very narrow temperature range (855–975 K), to the highly nonlinear characteristics of H_2 and CO oxidization chemistry.

It is worthwhile to question the possible role played by other experimental factors, in the observed temperature dependence in the flame liftoff height. As noted, we expect a variation in the molecular number density with the variation in ambient temperature. This change in density results in a variation in the reduced electric field E/n, which in turn affects the evolution in the electron energy distribution function within the discharge. The electron energy distribution controls the inelastic electron-impact dissociation processes, and the initial production of radicals, which leads to the production of H_2 and CO by subsequent recombination reactions. To account for this possible sensitivity, the expected increase in E/n with increasing ambient temperature was compensated for by increasing the electrode separation. Attempting to maintain E/n based on the ambient temperature does not fully guarantee the preservation of the local electron energy distribution within the pulsed discharge, since the local gas heating and power coupling within the discharge kernel may still vary with increasing ambient temperature. However, as we discuss further in the following sections, we do not see significant evidence for strong variations in coupled power. Furthermore, calculations based on an initial product yield using the method of Penetrante *et al.* [25] for the conditions of our experiments do not show an initial yield that is strongly sensitive to any additional variation in the temperature (density) due to possible gas heating by the discharge. We believe that the experimental trend seen for the liftoff height with increasing temperature is too nonlinear to be explained by local variations in E/n.

Initial concerns were raised above the possible effect that the variation in temperature may have on the velocity field and its subsequent effect on the flame liftoff. We performed PIV measurements just downstream of the bluff body base in the absence of the discharge to investigate the flow pattern variation with temperature. Representative results obtained at ambient flow temperatures of 300 K (air), 855 K, and 975 K are shown in Fig. 5. The corresponding free-stream flow speeds are 4, 3.4, and 4.6 m/s, respectively, all within approximately 17% of each other. Some difference is seen between the cold flow and the two elevated temperature flow cases. At room temperature, the recirculation region appears to be larger, and the stagnation point (which is about 40 mm above the base) is higher in comparison to the high-temperature coflow cases (24 mm at 855 K and 29 mm at 975 K). Less of a difference is seen between the two high-temperature cases, with little or no noticeable flow pattern variation other than the difference in the free-stream flow speed. We conclude that, while the flow may have an impact on the differences seen in flame stability between the room- and high-temperature cases, the subtle change in flow field at high temperature is not likely to be the cause for the rapid change in liftoff height which is seen to occur between 855 K and 975 K.

Finally, we also discount possible variations in discharge energy coupling in explaining the variations seen in liftoff height at high temperature. Sample oscilloscope traces of the measured discharge voltage and current are shown in Fig. 6. Comparisons between voltage pulse histories [Fig. 6(a)] and current histories [Fig. 6(b)] between the 855 K and 975 K cases show that the differences are also very subtle (and indistinguishable for the main portion of the pulse) and not likely to be responsible for the strong variation seen in flame stability. While the traces measured at a 1-m distance from the

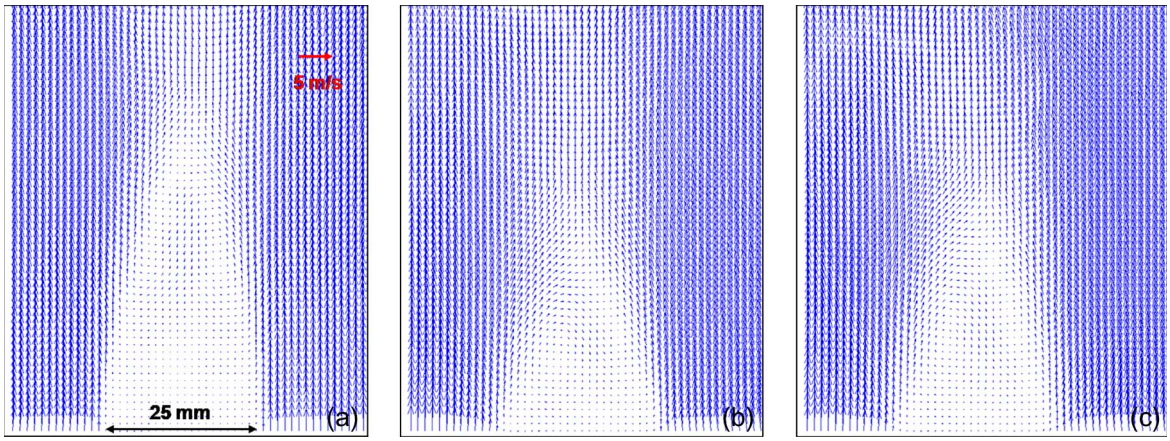

Fig. 5. 100 ensemble averaged PIV images downstream of the bluff body base: At (a) 300 K, (b) 855 K, and (c) 975 K ambient temperatures. The location of the base is represented by the black arrow in (a), while the blue arrows represent velocity vectors at the corresponding locations. Free-stream speeds are (a) 4, (b) 3.4, and (c) 4.6 m/s.

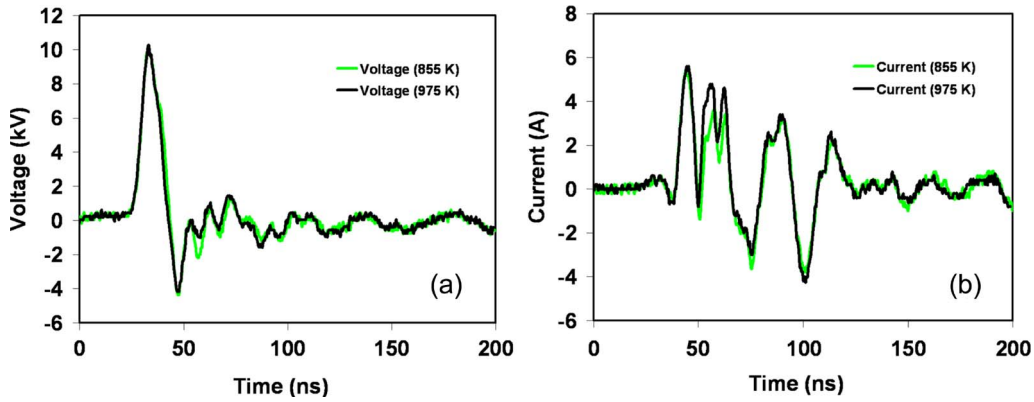

Fig. 6. (a) Voltage and (b) current traces of 10-kV-peak-voltage 50-kHz-repetition-rate discharges at 855-K and 975-K ambient temperatures.

discharge are not a full indicator of the net energy coupling at the discharge, we believe that they are qualitative indicators of substantially comparable energy coupling over the range of high temperatures studied and that coupling differences are not a primary reason of the diminishing effect of the discharge in flame stabilization at the elevated temperatures.

V. Summary

This paper has reported on experiments aimed at understanding the effect of a nonequilibrium ultrashort pulsed repetitive discharge on the stability of a lifted methane jet diffusion flame in an elevated temperature/vitiated coflow. The flame stability was characterized by flame liftoff height determined through ensemble averaging of CH chemiluminescence images. Overall, we have found that flame stability was greatly improved by the application of the discharge, extending the stability limit to temperatures well below 940 K, where there is no flame in the absence of a discharge. At high temperatures, the flame liftoff height is seen to increase with increasing temperature, in contrast to what is seen above 940 K in the absence of a discharge. The liftoff height in an 855-K vitiated air coflow was approximately 10 mm and was comparable to that seen in coflow air at 300 K. The experiments suggest that, for our discharge conditions investigated, the effect of the plasma may diminish completely at temperatures approaching ~1000 K.

We suggest that the primary reason for the diminishing effect of the discharge on flame stability with increasing temperature is the rapid depletion of the molecular hydrogen and carbon monoxide that are produced by the discharge, which are responsible for increasing the flame speed. Kinetic simulations indicate that the characteristic decay time of these critical species due to oxidation in the entrained coflow is on the order of 0.1 s at temperatures in excess of 1000 K. For a 1-m/s characteristic flow speed, the intermediate H_2 and CO species produced in a postdischarge region survive a mere 10 cm. This simple analysis is consistent with the trend in flame liftoff heights seen in the experiments, particularly at the higher range of temperatures examined, although the experimental flow field is complicated by the presence of a recirculation region (wake). Other possible effects that may vary over the range of ambient temperatures studied, such as variations in the reduced electric field within the discharge, the jet-coflow velocity field, and the discharge energy coupling, are not likely to play a significant role in the variation of the liftoff heights observed with ambient temperature.

These experiments further confirm the hypothesis presented in our studies of nonequilibrium plasma-assisted premixed combustion that the discharge ultimately serves as a reformer of

the fuel, converting a fraction of the fuel to H_2 and CO. In the diffusion flame studied in this paper, this reforming is occurring in the diluted region of the flow, where the jet has partially mixed with entrained vitiated air. The mixing is facilitated by the bluff body wake, in a configuration similar to what is seen in jet engine afterburners. This paper was motivated by the potential use of plasma enhancement in afterburner augmentors, and the results suggest that, at moderate temperatures (e.g., below ~1000 K for the conditions studied), nonequilibrium plasmas can greatly enhance flame stability by reducing flame liftoff.

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