Enhancement of Combustion and Flame Stabilization Using Stabilized Non-Equilibrium Plasma

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The effect of a stabilized non-equilibrium gliding arc plasma discharge on the stabilization and extinction of nitrogen diluted, methane/air counterflow diffusion flames was investigated both experimentally and numerically. To quantify the effect, extinction limits and flame temperature profiles via Rayleigh scattering were measured, calculated and compared to numerical simulations using detailed chemistry. The results show that the extinction limits were significantly extended, with up to a 220 percent increase in the extinction strain rate with low levels of plasma power addition. Comparison between experimental and numerical simulations showed good agreement for low power plasma activation of the air stream, indicating that the combustion enhancement of the diffusion flame was dominated by thermal effects.

Nomenclature

\[ B \] = magnetic field
\[ C_d \] = drag coefficient
\[ d \] = distance between inner and outer electrode at largest gap
\[ F_a \] = ampere force per unit arc length
\[ F_d \] = drag force
\[ I \] = current
\[ Q \] = volumetric flow rate
\[ u \] = gas velocity
\[ \rho \] = gas density

I. Introduction

Ignition and flame stabilization are key problems that need to be addressed in order to develop an effective supersonic combustion ramjet engine. Since the flow speed is so high, there is only a short residence time from initiation to completion for a combustion reaction. Various approaches have been developed, with plasma showing much promise as a solution. This is partly due to the fact that, unlike the typical method of pre-combustion, it is not constrained by the flammability limits of a mixture. Therefore, many different plasma systems have been investigated, ranging from using nanosecond high voltage discharges\(^1\) to plasma torches,\(^2\) and yet the fundamental chemistry and mechanisms of the plasma/flame interaction are not well understood. The major reason why little knowledge has been gained on the interaction is because the ability to establish a well defined plasma/flame system for detailed experimental and numerical analysis can be extremely complicated. The design of the system is first thwarted by the complexity of the plasma geometry. It is then exacerbated by the fact that the mechanisms of non-equilibrium plasma are not completely understood. By then adding the complexity of flame geometry, the system surpasses most abilities to accurately predict, measure, and model the interaction. Specifically, what needs to be

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understood is what the effects of non-equilibrium plasma are on a flame and to what extent those effects are thermal and/or non-thermal.

Before trying to understand the plasma/flame interaction, the type of plasma to study needs to be established. Specifically, the type of plasma that was investigated here was a type of electrical discharge. Generally, electrical discharges are divided into two major branches, thermal and non-thermal. Thermal plasmas include arc discharges and radio frequency inductively coupled plasmas. They mainly ionize and dissociate thermally, leading to large amounts of Joule heating. Because of this heat addition, the gas temperature is very high (5,000K–50,000K) with energy input in all degrees of freedom. This results in poor chemical reaction selectivity. Non-thermal plasmas include low pressure glow, radio frequency, and corona discharges and have the benefit of high chemical selectivity and energy efficiency. Unfortunately, both types of these discharges lack the ability to simultaneously provide high levels of chemical reaction selectivity, high electron temperatures, and high electron densities. The ideal plasma would have an intermediate temperature, between that of a thermal and non-thermal discharge, utilizing the properties of both.

The goal of our research was to understand the fundamental interaction between non-equilibrium plasma and diffusion flames. This came from developing a new type of stabilized non-equilibrium plasma gliding arc discharge and integrating it with a counterflow diffusion flame burner. The system establishes new geometry for the plasma, which, when combined with a counterflow burner, isolates the diffusion flame from complicated fluid dynamics. This provides an ideal platform for experimental measurements and observations and numerical computations.

II. Experiment Description

A. Stabilized Non-Equilibrium Gliding Arc Plasma Discharge

The gliding arc is a type of electrical discharge between two diverging electrodes, with a thermal equilibrium arc at initiation, a transition to a non-equilibrium arc, and then finally quenching when the arc elongates to a point where the arc cannot be maintained by the energy input. The thermal equilibrium arc relies mainly upon thermal dissociation and ionization of the molecules in the system with an electron temperature on the order of the gas temperature. The non-equilibrium arc relies mainly upon high temperature electrons accelerated by an electric field to dissociate and ionize molecules. This yields a lower gas temperature and most importantly, better chemical selectivity. Unfortunately in a gliding arc system, the non-equilibrium regime exists only for a short time in the arc evolution process. Recently it was found that during the gliding arc process, the plasma arc was stable much past the transition from the equilibrium to the non-equilibrium regime before extinction. This allowed for stabilization of the arc near extinction, in the non-equilibrium regime. This is significant because the process would not have to be cyclic, like a traditional gliding arc, in order to observe the benefits for a small non-equilibrium portion of the process of each cycle.

Due to this newfound stability, the plasma arc could be stabilized near extinction in the non-equilibrium regime for an indefinite amount of time creating a plasma disk. The new system utilizes this special type of gliding arc discharge. It is comprised of an inner electrode (cathode) with a coiled wire that spirals progressively closer to the outer electrode (anode as well as the ground). The cathode wire is separated from the outer anode by 2 mm at the smallest gap (point (a) in Fig. 1). The electrodes and spiral wire are made of stainless steel. In addition, there is a magnetic field in the discharge region produced by an external donut shaped permanent ferrite magnet. The direction of the magnetic field determines the direction of the rotation of the arc (in this case counterclockwise when looking down upon the system as in Fig. 1) and the field strength determines the frequency of rotation.

B. Counterflow Diffusion Flame Burner

The stabilized non-equilibrium gliding arc plasma discharge system was integrated with a counterflow diffusion flame burner. A schematic of the system is shown in Fig. 2. It consisted of two converging nozzles of 15 mm in diameter, separated by 13 mm. The upper nozzle was cooled. The feedstock for the plasma device, upstream of the lower nozzle, was air, while for the upper nozzle of the burner, methane diluted with nitrogen. To isolate the jets
emanating from the nozzles from the ambient air, a nitrogen curtain was used. The nitrogen curtain passed through a 0.75 mm annular slit around the circumference of each nozzle exit. The velocity of the curtain was maintained at or below the exit speed of the nozzle to minimize diffusion into the stream. The flame was established on the upstream air side of the stagnation plane. This counterflow burner system provided a simplified flame configuration to examine the effects of stretch on the quenching limit of the flame as a function of the flow velocity gradient for different levels of plasma power addition. The flow rates of the individual gases were controlled with sonic nozzles that were calibrated with a DryCal dry piston flow meter (1% error). The methane and nitrogen were then mixed in a hollow mixing cylinder (for minimal back pressure). To ensure that the mixture input to the flame was held constant while the velocity was increased through the nozzles, a bypass system was used. Here the methane/nitrogen mixture, as well as the air, was teed off before the respective nozzles. The flow rate could then be increased or decreased through the nozzles by closing or opening the valves of the bypasses respectively. By then measuring the flow through the bypass using the DryCal flow meter, the nozzle exit velocities could be calculated.

To find the extinction limits, the flame was first established with the bypass fully open, and hence the lowest flow rate through the nozzles. Then each bypass was slowly closed, while maintaining the flame at a fixed position. During this process the flame moved closer to the stagnation plane between the two nozzles which decreased the residence mixing time as well as increased the strain rate until extinction was reached.

C. Rayleigh Scattering

To measure the temperature profiles of the diffusion flame between the two nozzles, a Rayleigh scattering system was utilized. A frequency-doubled, injection-seeded Nd:YAG laser (Quanta-Ray GCR-4) with an output of approximately 450 mJ per pulse at a wavelength of 532 nm was used. The beam energy was measured and recorded for each image taken by directing a small portion of the beam to a photodiode (or Molectron Joulemeter). A laser sheet was formed using two lenses. These consisted of a plano-concave cylindrical lens (-300 mm focal length) to spread the beam in the vertical direction and a plano-convex spherical lens (1 mm focal length) to focus the beam in the horizontal direction and also collimate the beam in the vertical direction. The laser sheet was then directed between the two nozzles of the counterflow diffusion flame burner. To clearly define the laser sheet and minimize any stray scattering in the vertical direction, absorptive filters were used to clip the sheet. The scattering was imaged with a Princeton Instruments PIMAX intensified CCD camera (photocathode optimized for the visible spectrum) with a 105 mm, f/2.8 macro lens. The camera employed a 512 by 512 pixel array that was binned to improve the framing rate.

To calibrate the Rayleigh scattering signal, images of the scattering intensity were taken of clean, particle-free air (at a known temperature) that was directed through the lower nozzle. Even though great care was taken to minimize the background scattering, some still existed. To account for this, high purity helium was passed through the nozzles of the burner system, allowing the background to be measured. Helium was used for this purpose because its scattering cross section is very small compared to that of air (less than 1.5%). Also to account for any variations in the system (and minimize error) as the experiments were conducted, such as shifts in the laser sheet, the air-reference and background scattering were checked periodically.

D. Spectroscopy

There was a noticeable difference in the visible luminosity of the flame between when the stabilized gliding arc plasma discharge was on and off. Visually, the flame appeared to be thicker, with more white and a hint of orange.
To measure the spectrum between 180 nm and 880 nm, an Ocean Optics USB 2000 miniature fiber optic spectrometer was used. The fiber optic cable was used with a high temperature probe for close access to the flame to allow for measurements of the luminescent spectrum. The spectral measurements gave a general qualitative measurement of the difference in the luminescent species present with the plasma on and off.

III. Results and Discussion

A. Experiment

1. Plasma Disk

As the high voltage (10kV) was applied to the plasma device, there was an initial breakdown and a thermal plasma was established at the smallest gap. The arc then rotated in the magnetic field and increased in length as the distance between the spiraled wire and the outer electrode increased (as seen in Fig. 1 from point (a) to (b) to (c)). The increased length of the arc resulted in a transition to a non-thermal/non-equilibrium plasma leading to more rapid cooling and intermediate temperatures (2000 K – 3000 K) as well as an increased electric field and electron temperature (> 1 eV). Once the arc reached the cylindrical inner electrode (point (d) in Fig. 1), there was a stable rotating intermediate temperature arc in the gas flow; a plasma disk. A top view of the plasma disk can be seen in Fig. 3. The plasma arc rotation frequency ranged from approximately 20Hz - 50Hz and only decreased by a few percent when the flow rate was increased (Fig. 4). The increased rotation frequency came from the higher current input (and hence, higher power addition), forcing the arc to rotate faster in the magnetic field. Since the frequency of rotation of the arc was fast when compared to the gas velocity, there was quasi uniform activation of the flow. When the ratio between the magnetic field strength and the gas flow velocity was high enough, after the arc reached the cylindrical inner electrode (meaning it reached a constant length) and started rotation at a fixed axial position, it was possible to decrease the arc current. This meant that the arc propagated through the ionized media, but not through the initial non-ionized gas. This also meant that the electric discharge did not extinguish completely between two appearances of the arc at the same place.

To show that the plasma disk uniformly activated the flow, calculations were performed to find what flow rate, $Q$, of air can be uniformly activated by the gliding arc. The system had a distance of 10 mm at the largest gap (38 mm outer electrode diameter, 18 mm inner electrode diameter) where the plasma disk was located and a magnetic field, $B = 0.15$ Tesla (a typical value that is possible to obtain with permanent ferrite magnets). The low current, high voltage gliding arc operation would have an electric field strength, $E$, for the case of the gliding arc propagation through non-ionized air of about 1 kV/cm. This would lead to a gliding arc voltage drop of 1 kV for the given length of the gap. The ampere force per unit of arc length that would rotate the gliding arc would be $F_a = IB$, and in equilibrium conditions it would be equal to the drag force $F_d$. It was possible to estimate the drag force per unit length from the assumption that the arc was not “transparent” to the gas. Therefore, all of the gas was flowing around the hot cylinder of the arc. The drag force on the cylinder can be calculated as $F_d = 0.5 C_d \rho d V^2$, where $\rho$ was the gas density, $d$ the cylinder diameter, and $C_d$ the drag coefficient. The limits for $C_d$, for a very wide range of Reynolds numbers (from $10^2$ to $2\cdot10^6$) would be $1.3 < C_d < 0.9$. The solution to the equation is

$$0.5 \cdot C_d \cdot \rho \cdot V^2 = IB$$

Therefore, the arc, that was at least 2 mm in diameter, moved relative to the gas flow along a spiral trajectory, and if the gas velocity $u < d/\tau$, then all the gas flow would be uniformly treated by the arc. For the plasma system, this corresponded to $u < 12$ cm/s and $Q < 905$ cm³/s. In addition to the direct treatment by the rotating gliding arc, all of the gas flow would pass through the ionized disk that the gliding arc left behind.
To produce this gliding arc discharge a power supply was specifically created to efficiently supply the needs of the gliding arc system stabilized by the magnetic field. It was designed to produce a magnetically stabilized arc with minimum current while maintaining smooth current regulation. This was accomplished by minimizing the active energy losses by using a reactive capacitive resistance that imitated the resistive voltage and current characteristics. To minimize the output electric capacity and to provide the voltage-current characteristic of the power supply (which is close to the resistive voltage-current characteristics), changing the frequency of the high voltage converter allowed variation of the virtual resistance. After the output rectifier there was unidirectional voltage and current with a very high frequency of the residual pulsation. The plasma arc behavior was then the same as that for the plasma arc at a constant current and voltage because of the inertia of the gliding arc.

2. Extinction Measurements

The extinction limits for the counterflow diffusion flame were found with and without plasma power addition. When the bypass valves were closed, the nozzle exit velocities increased, pushing the flame closer to the stagnation plane. As the flame approached the stagnation plane, the strain rate increased. The flame lost more heat and had less residence time for reaction completion until finally it extinguished. If energy was added to the flame region via heat or radicals, the extinction limit could be extended to a higher rate of strain. To show this effect, three different nitrogen diluted methane mixtures were used and the extinction limits are plotted in Fig. 5. The extinction limits with no plasma power addition agreed fairly well with both Bundy et al.7 and Puri and Seshadri.8 These results showed that by using a stabilized gliding arc plasma discharge, there was a significant limit enhancement with up to a three fold increase in the extinction strain rate with only 78 Watts of plasma power addition at approximately 9 lpm of flow.

3. Temperature Profiles

Rayleigh scattering was performed on the counterflow diffusion flame for various strain rates. The laser sheet was passed through the diameter of the disk shaped diffusion flame between the nozzles of the burner. Two sample images can be seen in Fig. 6. where image a.) is with no plasma power addition and image b.) is with approximately 33 Watts of plasma power addition. The background has been subtracted and the air-reference was divided into each image. The gray scale for the can be seen below the images. The darkest is for the least scattering and the highest temperature, and the lighter for the most scattering and the lowest temperature. Therefore the flame is located in the darkest region of these images just above the middle of the picture, spanning the width. The methane diluted jet is from the top of the images and the air jet from the bottom of the images. When comparing the two images, notice that the region below the flame in the right image (plasma on) is darker than the left image (plasma off) below the flame. This indicates less scattering and hence a higher temperature. To quantify the images with actual temperatures, ten profiles were taken from each image and averaged to yield the best temperature distribution between the nozzles. These results were then compared with numerical simulations and are presented later in this paper.
4. Luminescent Spectrum Measurements

Luminescent spectrum measurements were taken for the nitrogen diluted methane/air diffusion flame because of the noticeable difference observed in the visible spectrum when the plasma was on. The strain rate was fixed at 83.28 s^{-1} and measurements were taken with no plasma power addition and also with approximately 60 Watts of plasma power addition. The two flames and their respective spectrums can be seen in Fig. 7. The integration time was different for each measurement, with 5 s for no plasma and 2.5 s for 60 Watts. Therefore the spectrums were not quantitatively compared, but rather their general shape and peaks compared for qualitative analysis. For both spectrums it can be seen that there are three common peaks around 309 nm, 431 nm, and 517 nm. These can be associated with mostly OH and some HCO around 309 nm, CH around 431 nm, and C_2 around 517 nm. These peaks are common for a methane/air flame. The flame with plasma power addition had additional peaks around 336 nm, 359 nm, and 388 nm, and broadband emission between approximately 477 nm and 850 nm. The 336 nm peak can be associated with NH, HCO and O_2 band emission, the 359 nm mostly with HCO and some O_2, and the 388 nm mostly with CN and some CH band emission. It is not fully understood why there is such a significant difference in the luminescent spectral output of the flame when the plasma is on.

B. Numerical Computation

To quantify whether the enhancement seen by using the plasma was from a thermal or a non-thermal effect, numerical simulations were performed. A slightly modified version of the Oppdiff program was used with plug flow for comparison to the experimental conditions and results. For a numerical simulation of the counterflow diffusion flame system, the computation was performed using inputs of nozzle exit velocities and temperatures found using a thermocouple. These results were then used to compare to the extinction limits found experimentally and to derive temperature from the Rayleigh scattering measurements.
1. Extinction Limits

The numerical computation of the velocities at the extinction limits were calculated and compared to the experimental results in Fig. 8. The computation remained consistently slightly lower than the experimental measurements for both the plasma on and off. Take note though that the numerical result was derived assuming that the major input into the system was heat (measured with a thermocouple), and that there was no independent non-thermal effect. Regardless of the fact, the plot clearly shows that both the numerical and computation results have similar trends. Therefore the extension of the extinction limits at these power levels and flow rates was dominated by thermal effects because the numerical computation with only a temperature input agrees with the measurements taken experimentally.

2. Rayleigh Scattering Temperature Profiles

Since temperature was only an input to the computation, the measured temperature profiles found via Rayleigh
scattering could be compared and any difference could be seen as a non-thermal effect. The species concentrations changed between the nozzles because the scattering cross sections changed due to the presence of the flame. The scattering cross section needed to be known at each point along the profile as a reference to derive the temperature. Therefore the species concentrations associated with specific temperatures and axial positions from the numerical computation were used as a base. The scattering cross sections for species in molar concentrations of tenths of a percent and larger were calculated using refractory data from Gardiner et al. This accounted for the variation in scattering cross section and gave accurate temperature profiles from the Rayleigh scattering. The temperature profiles derived from the Rayleigh scattering were then compared to the results of the numerical computation at the same input temperature and flow conditions. Figure 9 shows two temperature profile comparisons between the experimental results via Rayleigh scattering and the numerical computation using both the C1 mechanism (18 species and a 58-step chemical mechanism) and the GRI-3.0 mechanism (53 species and a 325-step chemical mechanism). The plots are in good qualitative and quantitative agreement with little variation seen between using the two different mechanisms. Figure 10 shows similar comparisons between the experimental results and the numerical computation using the C1 mechanism, except with the addition of plasma power. Once again, the temperature profiles are all in good qualitative and quantitative agreement. Take notice that on the air side, the right side of the plots, is where the elevated temperature inputs were, mimicking the plasma. The temperature was found experimentally by placing a thermocouple in the hot air stream and then given as the only input to the numerical computation. Since the temperature profiles agree, the effect of the plasma can be seen as predominately thermal for the cases investigated.

IV. Conclusions

A new non-equilibrium plasma/flame system was developed to provide an ideal platform for experimental and numerical studies. The experimental results of extinction limits and temperature profiles qualitatively and quantitatively agreed with the numerical computation, where it was assumed only input air temperature changed. These results suggest that for power levels below 78 Watts in the laminar flow regime, the stabilized gliding arc plasma discharge interaction with the diffusion flame was dominated by thermal effects. In the future, to further understand the chemical effect due to the interaction of a stabilized non-equilibrium gliding arc plasma discharge with a flame, ignition behavior and higher power levels will be investigated on premixed and partially premixed flames.

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