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ADP012130

TITLE: Experimental Investigation of the Interaction of Electrothermal Plasmas with Solid Propellants

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TITLE: Army Research Office and Air Force Office of Scientific Research. Contractors' Meeting in Chemical Propulsion [2001] Held in the University of Southern California on June 18-19, 2001

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EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF ELECTROTHERMAL PLASMAS WITH SOLID PROPELLANTS

Grant/Contract Number: DAAD19-00-1-0420

Philip L. Varghese and Noel T. Clemens

Center for Aeromechanics Research
Department of Aerospace Engineering and Engineering Mechanics
The University of Texas at Austin
Austin, TX 78712

SUMMARY/OVERVIEW:

The primary focus of the proposed work is a detailed experimental study of the plasma and its interaction with representative solid propellants. The objective of the work is to develop an extensive experimental database of species concentrations both during the plasma-propellant interaction and immediately thereafter. Such a data base is vital to develop a correct thermochemical model of mechanisms that lead to rapid, repeatable ignition and which permit temperature compensation of the gun charge. This knowledge is essential if the Army is to field plasma initiators.

TECHNICAL DISCUSSION

ARL studies of propellant charges ignited by plasma discharges have shown that this technique has significant advantages over conventional (primer) ignition. Ignition delay and jitter were substantially reduced, and temperature compensation achieved with a plasma energy input that was substantially smaller than the energy required to heat the propellant bed to the reference condition. However, the mechanism of the interaction is unknown. The plasma could function merely as an improved thermal source since it has a very high temperature compared to conventional combustion products. It could function as a radiant source that distributes the energy into the propellant bed more uniformly and rapidly than simple flame spread. Additionally, the plasma could provide a source of highly reactive species, not present in flames, which promote rapid and reliable ignition. Plasma jets issuing into the propellant beds may penetrate more effectively than combustion products from a primer, and thus give a more distributed ignition. It is also possible that the blast wave accompanying the plasma discharge causes microfractures in the propellant grains that increases the burning surface area sufficiently to provide temperature compensation, though it seems hard to reconcile the observed repeatability of the process with known mechanisms of microfracture.

A combination of several of these mechanisms might also contribute to the observed performance improvement. An improved fundamental understanding of the interaction will help the Army design better initiators that tailor the plasma to the propellant thus reducing energy required or enhancing gun performance. For example, it may be possible to achieve the observed temperature compensation with a much smaller energy input than is currently needed, which would reduce the size of the power source required. A fundamental understanding is also needed to reduce risk. Because of the current lack of understanding, one cannot rule out the possibility that the plasma is interacting with only a minor component of the propellant charge, and thus plasma igniters could fail because of minor changes in propellant composition.

Owing to the complexity of the physical processes involved in plasma-induced ignition, achieving an understanding of the fundamental physics will likely be achieved only through computational/theoretical approaches aided by experimental data. To date, however, there is insufficient experimental data on the plasma-propellant interaction to properly develop and validate chemical models. Therefore, the primary goal of this project is to use advanced laser diagnostic techniques to develop a unique database that can be used to aid in the modeling efforts being undertaken at ARL and elsewhere.

We concentrate on studying the interaction of the plasma with solid propellants at atmospheric pressure. These conditions are representative of the ignition and initial stages of combustion before the gun chamber pressure rises. The reason for limiting this study to atmospheric pressure conditions is because of the difficulty of making meaningful measurements at high pressures especially with the intense background luminosity of the plasma.

The primary objective of this work is to generate as complete a picture as possible of the plasma-propellant interaction and subsequent ignition, by measuring a range of species that provide information on the distribution of the plasma or are important combustion intermediates. As a general philosophy, we try to make time resolved, simultaneous multi-point measurements whenever possible so as to build up an extensive database. The multi-point measurements will be supplemented with line of sight averages and single-point measurements when necessary.

The plasma-propellant flow field is a very challenging environment in which to make measurements because of the high temperatures and densities, complex chemistry and the transient nature of the interaction. Transient reacting flows are best studied by non-intrusive optical techniques that do not perturb the system. The high plasma luminosity presents the biggest challenge for laser-based studies of propellant ignition when interacting with a plasma, but we believe that a number of optical diagnostic techniques can be used effectively to study the plasma ignition process. However, we recognize that any single technique may not work as well as anticipated in such a severe environment. Thus we plan to employ a number of different techniques for studying different aspects of the problem.

The capillary plasma source is driven by a pulse forming network (PFN), consisting of a 251 μF capacitor charged to a maximum of 5.0 kV (3.1 kJ) and a 26 μH inductor. The discharge is initiated by closing an Ignitron switch that connects the capacitor to the capillary electrodes. The capillary is 3 mm in diameter by 30 mm long and is open at one end only. The wall material is polycarbonate (Lexan, $C_{16}H_{14}O_3$). To help initiate the discharge a thin copper fuse wire (64 μm) – which explodes when the Ignitron is closed – is inserted inside the capillary between the electrodes. Ablation and ionization of material from the capillary surface then sustains the discharge. The resulting plasma expands rapidly from the open end of the capillary and issues into room air. In order to reduce erosion, the electrodes were constructed with inserts made of copper-tungsten alloy (30% Cu, 70% W). The peak current through the plasma is approximately 4.6 kA for a discharge energy of 5 kV (3.1 kJ), and the discharge duration is approximately 250 μs. Figure 1 is a close-up of the present experimental layout showing the camera systems being used to study the flowfield via emission.

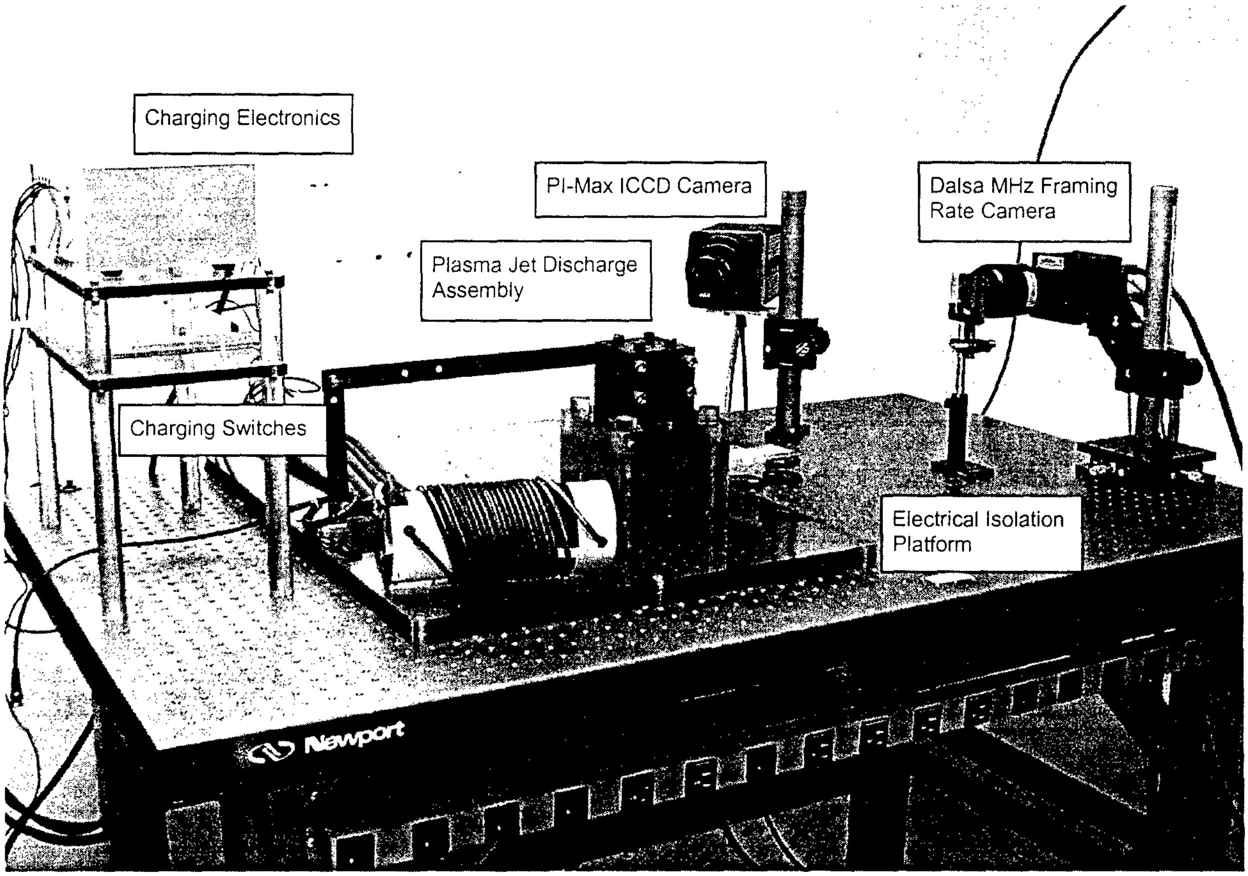

Figure 1. Close-up view of experimental set-up

The characterization of the pulsed plasma jet is accomplished using a variety of optical diagnostics. A gated-intensified CCD camera is used to capture images of visible emission and Schlieren images. Figure 2 shows a representative emission image in false color. This image was obtained for an initial charging voltage of 3 *kV* (1.1 *kJ*) and was captured 160 *μs* after the initiation of the discharge. The gate-width (exposure time) used was 85 *ns* which was sufficiently small to freeze the flow. The barrel shock, Mach disk, contact surface and luminous bore-exit flow are clearly seen in the emission image. (Animations of the emission and Schlieren images showing the evolution of the plasma jet flow field can be found on the web page http://www.ae.utexas.edu/research/FloImLab/plasma.html.)

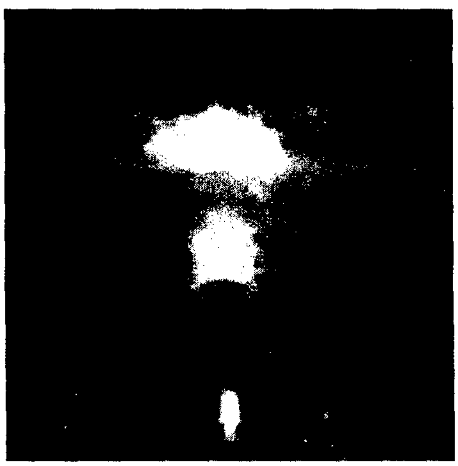

Figure 2. Image of the plasma emission 160 μs after discharge initiation. Initial capacitor voltage 3kV, 85 ns gate width.

In addition to the imaging studies, we obtain instantaneous emission spectra at several axial positions within the jet and at different delay-times (measured from the initiation of the discharge). The emission spectra are used to investigate evolution of the excitation temperature and electron density fields. Using Boltzmann plots, the spectra are used to generate axial profiles of the excitation temperature in the plasma jet at different times. We define the nondimensional axial distance, $\zeta_t = x/x_m(t)$, where $x_m(t)$ is the axial distance from the bore exit to the Mach disk at time t. In experiments to date we observe that two temperatures (upstream and downstream of the Mach disk) can essentially characterize the entire axial profile, i.e. T_{exc} = 14,000 K for $\zeta_t < 1$ and T_{exc} = 25,000 K for $\zeta_t > 1$ for discharge energies of 3.1kJ. Electron number density profiles are inferred from the linewidths of observed H_α lines. The profiles at different times are seen to be very similar when plotted *vs* ζ_t, with an abrupt increase in electron density near $\zeta_t = 1$. For a discharge energy of 3.1 kJ the measured electron number density ranges from 1.7×10^{17} cm^{-3} to 5.5×10^{17} cm^{-3} upstream of the Mach disk to 10^{18} cm^{-3} to 2.5×10^{18} cm^{-3} downstream of the Mach disk.

Figure 3 demonstrates the use of PLIF in this challenging flow-field. This preliminary PLIF image of atomic copper was obtained by pumping the $^2P_{3/2} \leftarrow {}^2S_{1/2}$ line at 327 nm and detected the fluorescence from the $^2P_{3/2} \rightarrow {}^2D_{5/2}$ line at 578 nm. The intense copper signal in the outer flow comes from the exploding wire used to initiate the discharge, whereas the smaller copper signal in the expanding jet comes from copper eroding from the Cu-W electrode during the discharge. The image was obtained by subtracting two 17 shot averages in order to remove the intense background emission from the plasma. We have purchased a second ICCD camera in order to obtain single-shot background corrected PLIF images. Over the next year we plan to use the system to obtain PLIF images of molecular species such as OH and NO when the plasma is impinging on a propellant sample.

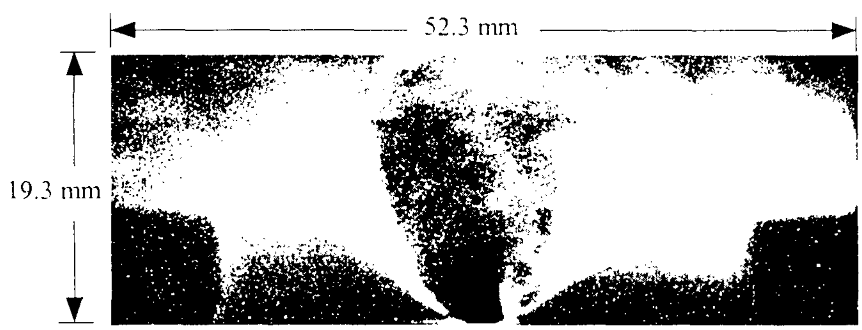

Figure 3. Grey scale image of Cu atoms detected by PLIF. 17 PLIF images were averaged, and background subtracted using a 17 shot average of plasma emission only. The excitation laser beam is passing from left to right and is retroreflected.