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Development of arc channels in propellant beds will lead to initiation of chemical reactions and possible ignition. Same initiation can take place with high-energy density plasmas generated by electrothermal plasma sources. Arc channels can be simulated via arc generators from as low as few milli-joules to several joules of energy. For electrothermal plasmas, the energy is in the range of few kilo-joules. When using electrothermal plasmas, the performance of the propellant is more governed by radiation transport and the plasma-flow-field parameters. The temperature of the propellant's bed may also play a role in the burn rates under plasma injection. In this report, a set of experiments were first conducted on the plasma-flow-field to determine the spatial and temporal distribution of the plasma temperature, pressure, number density, and velocity. The experiments revealed a decreasing plasma pressure, plasma temperature and plasma number density as plasma is leaving the capillary source and expands in air. The plasma jet velocity 2 inches from the source exit was found to be about 1300 m/s. Following characterization of the plasma-flow-field, a set of experiments were conducted on JA-2 solid propellant with controlled bed temperature. Increased burn rates were observed with increased bed. A model for the burn rate is proposed, which includes the bed temperature and has the $BR = A P^a (T/ T_{ambient})^b$.

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1. ONR PROPOSAL NUMBER: **Project ID: 00 – 0376**

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5. NAME OF INSTITUTION: **North Carolina State University Department of Nuclear Engineering.**

6. AUTHOR (S) OF REPORT: **Mohamed A. Bourham**

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

No full manuscripts during this reporting period. Only TWO presentations were displayed in the following meetings:

-17th Electric Launcher association Meeting, US Army Research Laboratory, Aberdeen Proving Ground, MD, 23-24 October 2000; presented by Brian L. Bures for NCSU team, entitled: Plasma engineering applications research at NCSU: an update on current research and future plans.

-American Nuclear Society Student Conference, Texas A&M University, March 2001, presented by Ryan Davis for NCSU Team; entitled: Temperature Sensitivity of Plasma Impacted Propellant

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

- 1- Ryan Davis:	**MNE Graduate Student (expected July/August 2001).**
2- Bradford Lambert	**PhD Graduate Student (expected 2004).**
3- Jeffrey Preston	**Undergraduate student.**

7. REPORT OF INVENTIONS (BY TITLE ONLY):

None

10. SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS:

Arc channels are characterized to explore impact on solid propellants and initiation of the chemical reactions. Also, electrothermal plasma jet in the plasma-flow-field has been characterized spatially and temporally. Experiments on JA-2 solid propellant with elevated bed temperature have shown increased burn rates with increased bed temperature. A power law is proposed to modify the burn rate equation to include bed's temperature and has the form: $BR = A\,P^{a}\,(T/T_{ambient})^{b}$.

11. TECHNOLOGY TRANSFER:

None

Initiation of Chemical Reactions in Energetic Materials Using Plasmas and Arc Channels

PROGRESS REPORT

DR. MOHAMED A. BOURHAM

May 24, 2001

U.S. NAVY OFFICE OF NAVAL RESEARCH

CONTRACT N00014-00-1-0901

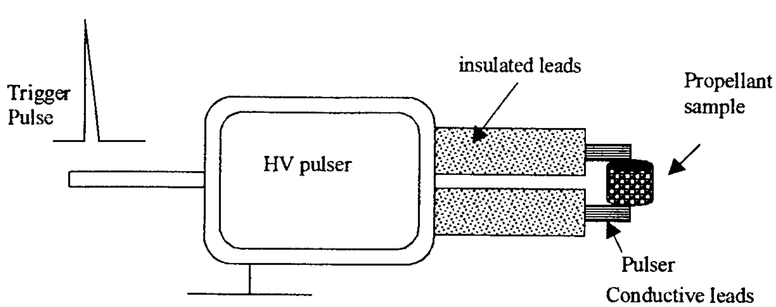
DEPARTMENT OF NUCLEAR ENGINEERING
NORTH CAROLINA STATE UNIVERSITY
RALEIGH, NC 27695-7909

BRIEF OUTLINE OF RESEARCH FINDINGS

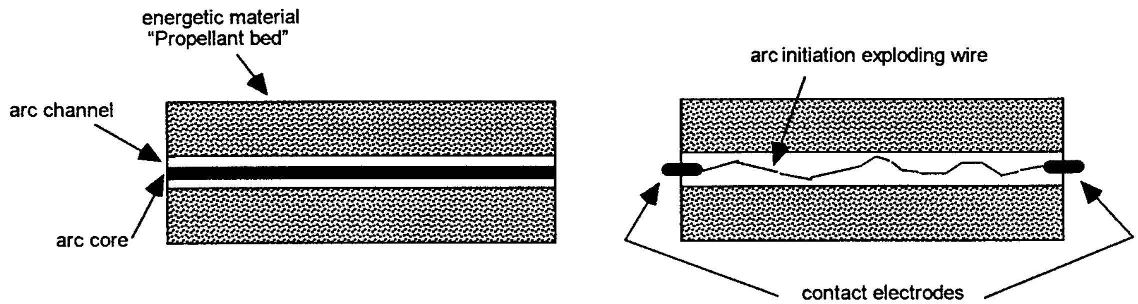
Initiation of chemical reactions in energetic materials (propellants) may take place with the development of an arc channel that has a low energy in the range of few milli-joules to several joules. Such arc channels could be developed as a consequence of stresses or friction between propellant grains at high loading densities. Also, initiation may be enforced with electrothermal plasma injected into the propellant. Such electrothermal plasma may be a low-energy density plasma of few hundreds joules to high-energy density plasma of several thousands of joules. Experiments on initiation of chemical reactions are designed to explore the low energy arc regime and the high-energy electrothermal plasma regime. Experimental study necessitates the knowledge of the arc current and voltage and how the arc radiant energy interacts with the propellant grains. When using electrothermal plasma, it is also necessary to gain the knowledge on the plasma parameters and flow regime of the plasma jet. For arc regime, A high voltage pulser of 18-30kV is used to characterize the arc within a discharge distance of 2-4 mm. For electrothermal plasma regime, an electrothermal plasma source capable of producing up to 100kA discharge current at 10kV is used. Optical emission spectroscopy and absolute pressure transducers are used as diagnostics to obtain plasma parameters. The 2-D, time dependent TITAN code has been modified to simulate low-energy arc channels with the incorporation of plasma non-ideality, which is also applicable when simulating electrothermal plasma regime. Solid granular propellant JA-2 is used as the energetic material for this research, however, other energetic materials will also be used when available. Additionally, it is important to test the sensitivity of the propellant bed to elevated temperatures. The temperature of the propellant's bed may play a role in the burn rates under plasma injection and/or arc channels. In this report, a set of experiments were first conducted on the plasma-flow-field to determine the spatial and temporal distribution of the plasma temperature, pressure, number density, and velocity. The experiments revealed a decreasing plasma pressure, plasma temperature and plasma number density as plasma is leaving the capillary source and expands in air. The plasma jet velocity 2 inches from the source exit was found to be about 1300 m/s. Following characterization of the plasma-flow-field, a set of experiments were conducted on JA-2 solid propellant with controlled bed temperature. The first set includes elevating the bed temperature from ambient temperature to 50 °C. Increased burn rates were observed with increased bed temperature, which appears to follow a power law. A model for the burn rate is proposed, which includes the bed temperature and has the $BR = A\, P^a\, (T/T_{ambient})^b$.

1. Arc Characterization for Arc Channel Experiments:

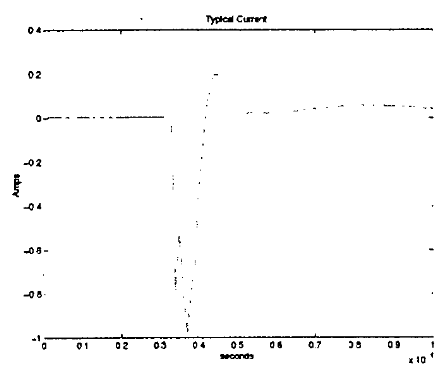
Characterization of the arc initiated by a high voltage pulsing device does not necessitate expensive or sophisticated diagnostics. Such arcs generated by HV pulsers are usually easy to generate at atmospheric conditions. The arc may take any shape from one pulse to another depending on the triggering circuitry and the atmospheric conditions during the time of measurements. However, with short arcs generated between thin electrodes at small separating distance, consistency of the arc parameters could be obtained.



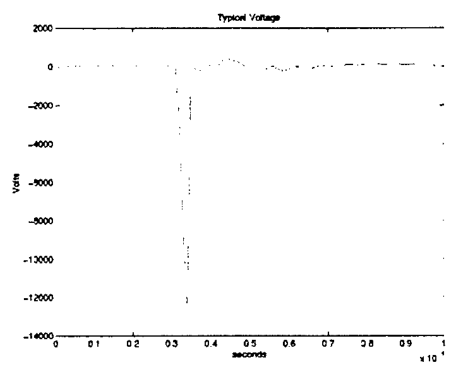
The propellant sample resides between the pulser leads such that the arc is initiated through the central perforation of the JA-2 sample. This means that the arc core is inside of the propellant as illustrated in the following figure (left drawing), where the arc core joule-heats the inner wall of the propellant. Also, an exploding wire may be inserted in the central perforation (right drawing) and connected to the pulser to initiate the arc via wire explosion.



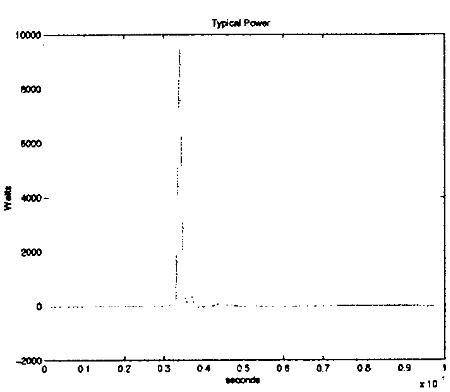
The following figures show typical arc current, voltage, electrical power and energy. The arc current peaks at 0.9-1.0 A at a peak discharge voltage of 12 kV, which provides an arc power of about 10kW. The discharge period is 1-2 μs FWHM, and hence the total energy of the arc is in the milli-joule range. The figure shows that the integrated energy of the arc is less than 120 mJ. This arc is perfect to simulate the mJ energy range of arc channels that can be developed in a propellant bed. The arc voltage can be increased up to 30kV and the arc current up to 70 A, which provides over 2 MW of power over a 1.0 μs duration, and thus the integrated arc energy can be increased to 2.0 J. Controlling the arc energy in the present pulser is via the arc voltage and thus a wide range of arc energy could be produced, from few milli-joules to several joules. The arc current, as seen from the figure, is sharp enough to closely simulate initiation of narrow arc channels at considerably short period of time.



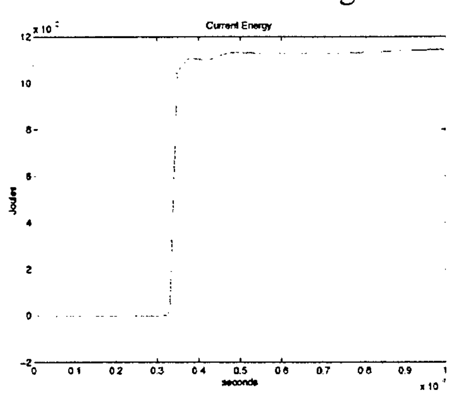
Arc current



Arc voltage



Arc power



Arc energy

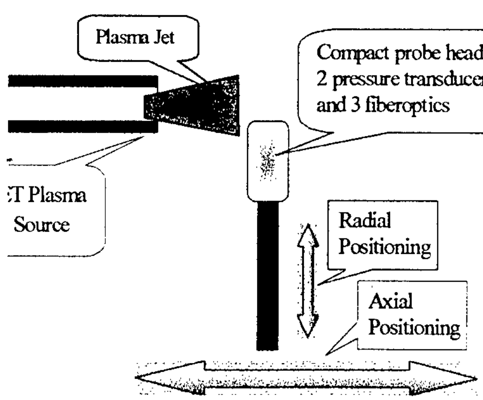
2. Plasma Flow-Field Characterization for Electrothermal Plasma Experiments:

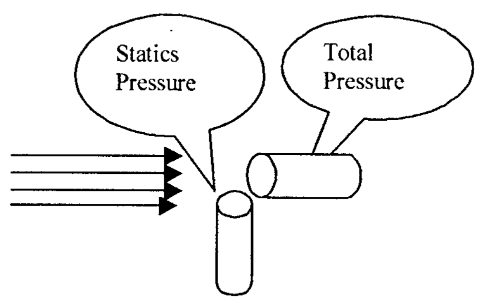
To accurately determine the effect of radiation transport and kinetic pressure on the propellant's burn rate when electrothermal plasma is injected into the propellant's bed, it is necessary to determine the plasma pressure and temperature of the plasma jet outside the electrothermal source where the propellant is situated. These measurements will determine the momentum and energy terms at any chosen location, and thus the plasma impact on the propellant bed can be expressed in terms of the plasma parameters at such location. The plasma-flow-field experiments were conducted and the pressure-temperature distribution in the flow-field were measured.

For this purpose, a compact multi-sensor measuring probe was developed, constructed, calibrated and tested. This compact measuring probe allows for spatial and temporal measurements of the total and Static plasma pressure, plasma temperature, plasma density and plasma Velocity. All measurements were conducted at atmospheric pressure by fusing the ET source with aluminum fuses. The ET plasma is thus jetting into open air inside of a cubical chamber. The plasma jet expands out of the ET source with a measured expansion angle of approximately 23° from the ET source's axis.

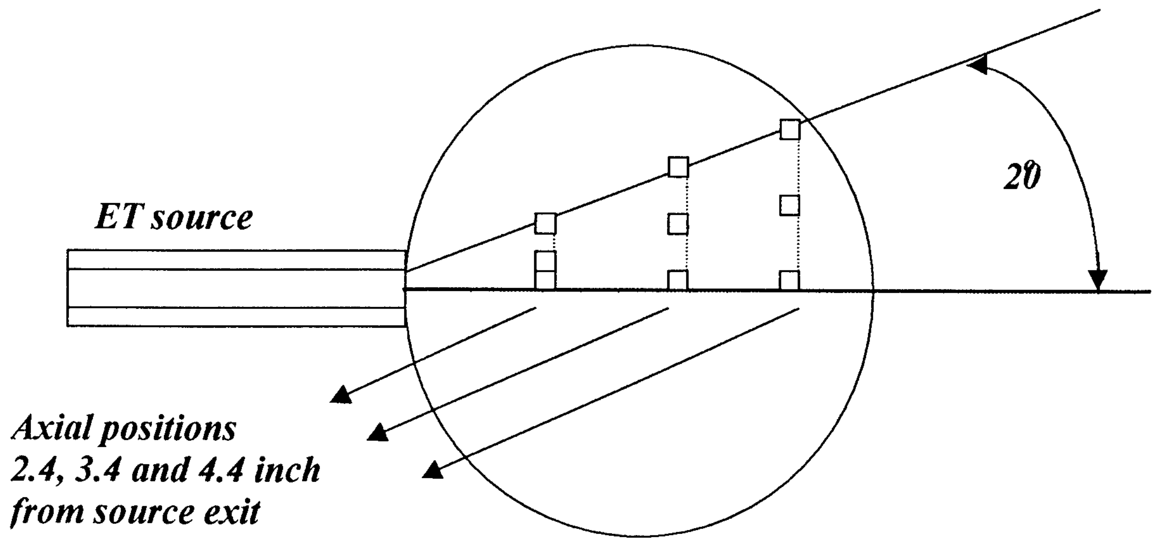
2.1 The Compact Multi-Sensor Probe:

The compact multi-sensor probe, as shown in the figure below, has two absolute pressure transducers (Kistler Model 601B) and three fiber optic cables. The sensor head is arranged such that the two pressure transducers are close to eachother with one pointing towards incoming plasma flow to measure total pressure, and one situated upright to measure the static pressure.



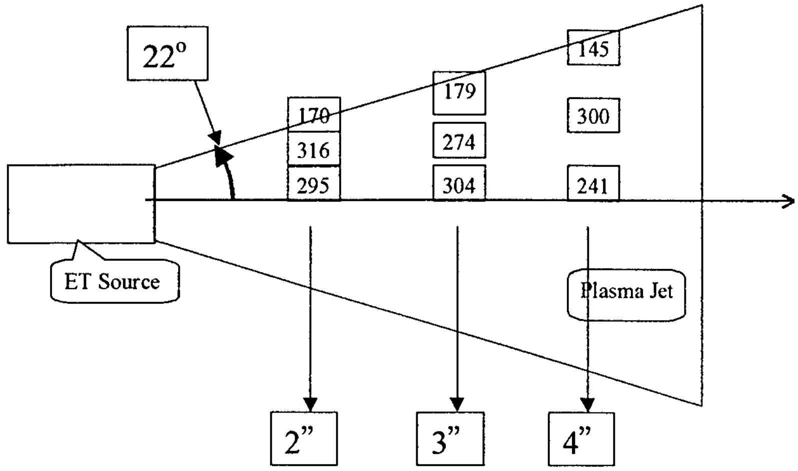


An in-house built shock tube was used to calibrate the pressure transducers. It consists of a high pressure chamber and a barrel section, separated by a burst disc. Pressure signals are recorder on a LeCroy 9310 digital storage oscilloscope. It was determined that the relation between the true pressure versus measured pressure is linear and is expressed by $P_{true} = 1.03\ P_{measured} - 0.46$. the three fiberoptic cables are arranged as a bundle, with one fiber optic interfaced to an optical multichannel analyzer for time-integrated opticalemission spectra measurements, and two other fiberoptics each is interfaced to a monochromator and a photomultiplier for time-resolved spectral measurements. Monochromators were adjusted to 521.82 nm and 570.02 nm wavelengths (copper lines). Optical emission spectroscopy was used to measure the plasma temperature, assuming plasma is at LTE, and plasma density from line broadening. Three axial locations were chosen for measurements, 2.4, 3.4 and 4.4 inch from source exit. At each axial location, three radial locations are defined to measure distributions within the diverging plasma jet. The following drawing shows the source exit and the locations of compact multi-sensor probe measuring positions.



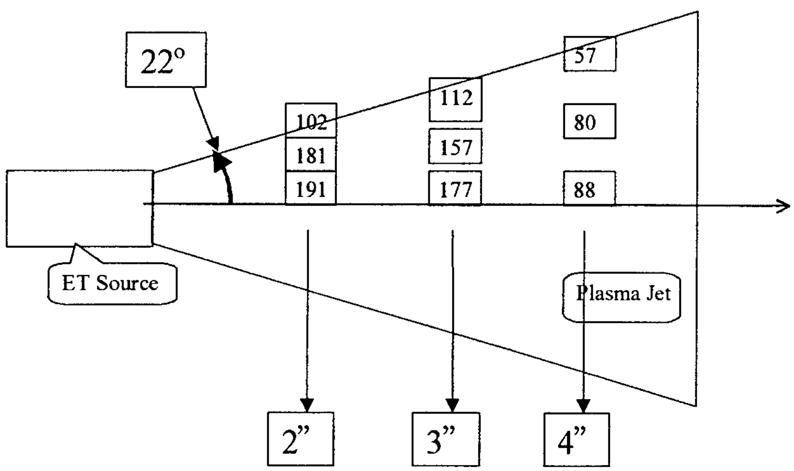
2.2 Plasma-Flow-Field Distribution:

Preliminary measurements of the plasma parameters at 2.4, 3.4 and 4.4 inches from the source exit, at 3 radial locations for each axial position are shown in the following figures. The following two figures show the pressure distribution from the source exit. The top figure is for the peak total pressure, showing that the axial profile is approximately flat for all radial locations, while the radial profiles are of a top-hat distribution. The measurements imply that for axial locations between 2 and 4 inches, the plasma jet undergoes an essentially isentropic expansion, while the edge of the jet is subjected to mixing process with the surrounding gas. The bottom figure, is for the distribution of the peak static pressure, where the general trend indicates a decrease in the static pressure as the jet expands. Of course the largest static pressure is at the location closest to the source exit.



Spatial distribution of peak total pressure (psig) of the plasma jet as measured from the source exit

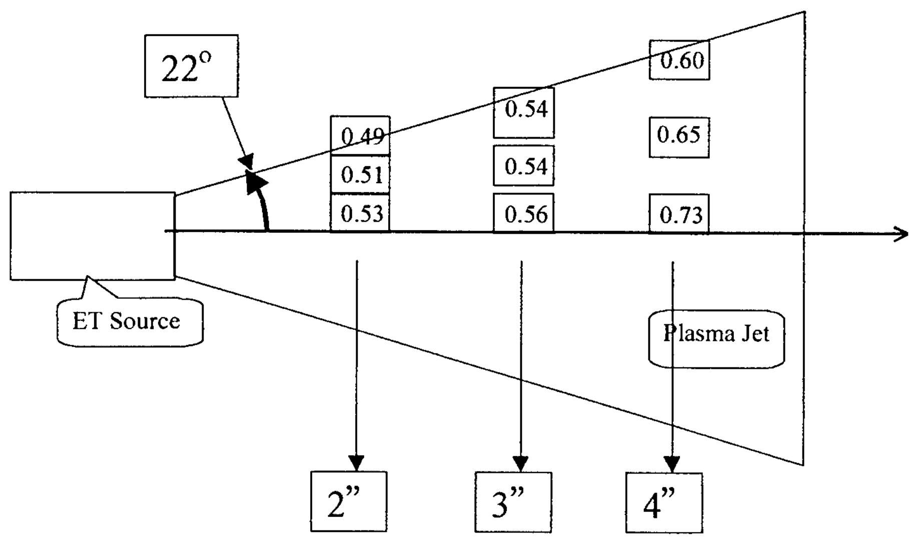
Peak Total Pressure



Spatial distribution of the peak static pressure (psig) of the plasma jet as measured from the source exit

Peak Static Pressure

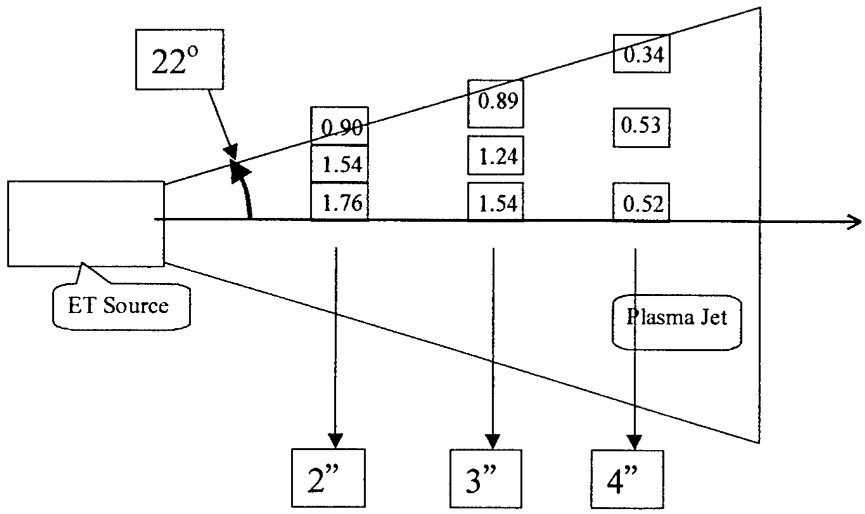
Of importance is the distribution of the plasma temperature and density. Below is the spatial distribution of the plasma temperature. These temperatures were obtained from time-integrated optical emission spectroscopy using copper lines. The plasma temperature drops quickly from 2.1 eV right at the source exit (axial distance = 0) to approximately 0.5 eV at 2 inches down stream. Further into the stream, one may observe that the plasma jet is approximately isothermal. With additional data from time-resolved spectral measurements of copper lines, it was obvious that the plasma temperature inside the jet is 0.4 +/- 0.16 eV. A slight increase in the plasma temperature was observed at 4.4 inches from the source exit. Such temperature increase is attributed to the expansion of the plasma jet.



Spatial distribution of the plasma jet temperature (eV)

Plasma Temperature

The plasma density is another important parameter. It was calculated from the peak static pressure and the time-integrated plasma temperature. The figure below shows the plasma density at spatial locations of measured pressure and temperature. The density decreases with increased axial length as well as increased radial position. This is expected for an expanding plasma jet from an electrothermal source. It is obvious that the plasma density follows the static pressure distribution, especially that the temperature is almost same inside the jet and thus the density profile follows the static pressure profile.



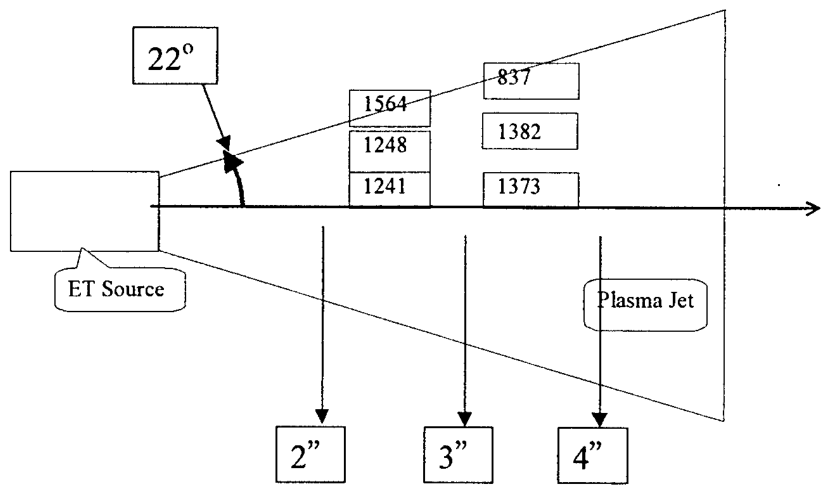
Spatial distribution of plasma density (x $10^{25}/m^3$)

Plasma Density Distribution

The distribution of the average speed of the plasma jet was obtained from the plasma arrival time to the sensors at the chosen measuring locations. The speed of the jet is approximately constant and close to 1300 m/s on axis. The slowing of the plasma near the jet boundary is attributed to the mixing processes with the surrounding air. For a 0.5 eV idea gas, the sound speed is 3100 m/s, and thus the measured speed indicates that the jet flow is sub-sonic with a Mach number of about 0.4. The time-resolved spectral measurements were also used to calculate the plasma precursor, from which the precursor plasma velocity is found to be about 3000 m/s.

The obtained parameters are important in deciding where to place the propellant for a given experiment, and what to be expected in terms of plasma parameters, at any selected location.

Further measurements of the plasma electron number density, based on spectral analysis, will be conducted to obtain a complete ‘picture’ of the plasma jet as it opens into air at atmospheric conditions.



Spatial distribution of the plasma jet average speed (meter/sec)

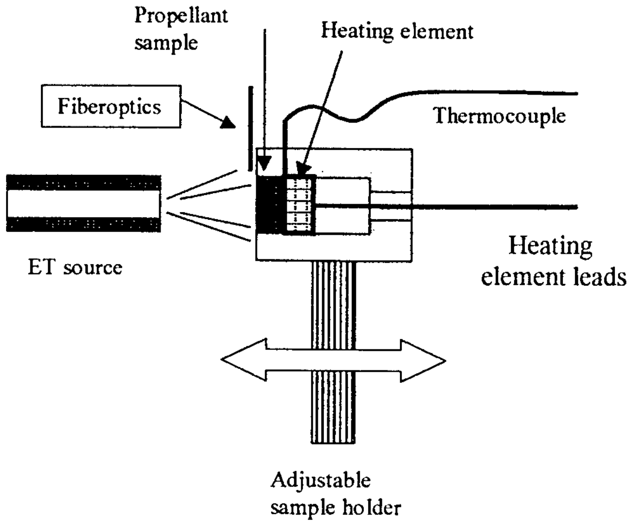
Average plasma jet speed

3. Temperature Sensitivity Studies

Temperature sensitivity of the propellant bed may alter the burn rates under plasma injection. When the bed's temperature is elevated, it is expected that the burn rates would increase as a result of increased in-depth heating of the bed. Also, the plasticizer may migrate causing alterations in the burn rates. A temperature-control unit is designed such that the bed's temperature prior to plasma injection is maintained constant, and the chosen range of the bed's temperature is temperature from -40°C to +40°C.

3.1 Experimental Arrangement:

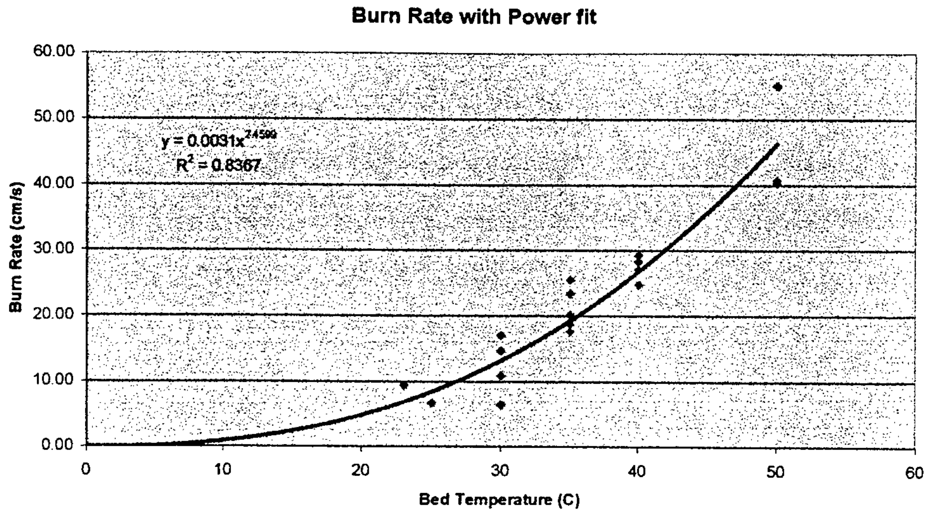
Preliminary experiments on the control unit have shown the necessity of long time circulation of the fluid in order to maintain temperature stability. A modified design using heating elements allowed for a faster temperature setting prior to plasma injection. The following figure shows the experimental arrangement using heating elements to fulfill a study on the temperature sensitivity with elevated temperatures between 20 to 50°C. This set is to be followed by a set at temperatures bellow 0°C to cover the range up to –40°C.



The sample holder is tube-shaped and has a seat for the propellant sample, which resides on the heating element. The temperature of the back surface of the propellant is monitored via a thermocouple. The sample is thin, about 1-2mm and the sample temperature is kept stable to the desired temperature via the heating element controller. The holder has a fiberoptic cable to view the plasma at the plasma-propellant interface. The entire holder is adjustable and can be placed at any location on the axis of the plasma source. Experiments are conducted at a base pressure of 20 Torr for extinguished burn (interrupted burn) such that the burn is only during the plasma pulse length (100 μs discharge). The initial and final weights of the propellant sample are recorded, as well as the initial and final weights of the plasma source's liner. For each shot, the discharge current is fed to our TITAN 2-D code to calculate the plasma exit parameters. Plasma temperature at the plasma-propellant interface is calculated from optical emission spectroscopy measurements using copper lines.

3.2 Preliminary Temperature Sensitivity results

Preliminary results on the propellant bed's temperature sensitivity have shown an increasing burn rates with increased bed temperature. For the variation of bed temperature between 23 to 50°C, the best fit is showing a power law of the form: Burn rate BR = $0.0031\ T^{2.4559}$, where the burn rate is measured by dividing the interrupted erosive thickness by the plasma impact time (FWHM). Here in this equation, T is the bed temperature in °C. This equation can be introduced to the burn rate equation such that the burn rate, including bed temperature, may be expressed by: $BR = A\ P^a\ T^b$, where the first term (P^a) represents the conventional equation for the burn rate without introducing the bed's temperature. A more general equation may be introduced as: $BR = A\ P^a\ (T/\ T_{ambient})^b$, and thus for $T = T_{ambient}$, the burn rate falls to the known equation. Bearing in mind that the pressure exponent 'a' with plasma ignition is much higher than its value for conventional ignition. The following graph shows the experimental results for elevated temperature regime with the propellant situated 2 inches from the source exit. When the propellant is closer to the source exit, it is expected that the burn rate will be much higher because of the pressure effect (momentum effect) on the burn rate.



4. Next Phase Studies:

Next phase studies will be to initiate arc channel at milli-joule to few joules energy levels into the central perforation of the propellant at atmospheric pressure. A second step is to initiate the arc using a metalized fuse in the same perforation. The third set is initiation in grooved beds with same energy input to the arc channels. The fourth step is initiation with electrothermal plasma at several kilo-joules of energy.

The will be a continuation of the elevated temperature regimes to obtain a complete evaluation of temperature sensitivity by taking measurements down stream at 1 inch and 3 inches from the source exit. This will determine the effect of increased/reduced burn rates as a result of increased/reduced momentum transfer. Actually, when the propellant sample is farther away from the source exit, the effect of radiative heating of the propellant is dominant compared to momentum effects.

Following completion of the hot regime, the cold temperature regime will be experimented between –40 to 0°C. In the cold regime, again, the distance from the source exit to the propellant will be varied between 1 to 3 inches. The cold regime will further determine if the power law holds, as proposed in this report.

Scanning Electron Microscopy (SEM) and high-resolution optical microscopy will be conducted to evaluate the samples' surface changes and EDXA will provide surface elemental composition.

17th Electric Launcher Association Meeting, 23-24 October 2000
US Army Research Laboratory, Aberdeen Proving Ground, MD

Plasma Engineering Applications Research at NCSU
"An Update on Current Research and Future Plans"

Presented by: Brian L. Bures

For

NCSU Plasma Engineering Applications Team

Dr. Mohamed Bourham, Dr. Orlando Hankins, Dr. Mofreh Zaghloul, Christopher Hobbs, Brad Lambert, Brian Bures, Chad Boyer, Ryan Davis, Joseph Wagner and Jeff Preston
North Carolina State University, Department of Nuclear Engineering, Raleigh, NC 27695-7909

Electrothermal plasma discharges are being investigated for use in a variety of applications, ranging from production of DLC films in a pulsed mode using high-energy density plasmas, to studies on plasma-enhanced burn-rates of solid propellants for ETC guns application. In order to optimize the electrothermal plasma for each application, an understanding of the basic physics is required. At NCSU, joint efforts in computational modeling and experimental measurements overlap to develop an understanding of the physics with these chemically complex plasmas. In parallel to the ET-ETC launch experiments, EM launch experiments are currently underway to re-evaluate some of the basic scaling laws for rail guns, and re-evaluation of plasma armature dynamics. The re-evaluation of these laws comes from a new derivation of the average electron-ion momentum transport cross-section for nonideal plasmas. In addition to development of experimental and computational models for such plasmas, experiments on the biological effects of the electric pulse from these devices is currently underway. Also, a strong effort in using atmospheric plasmas is ongoing, in collaboration with NCSU School of Textile, to provide enhanced features and better dry finishing process for textile materials. Details of research efforts will be presented and discussed.

Work supported by the US Army ARL-ARO Contract DAAD19-00-1-0555, the US Navy ONR Contract N0001400-1-0901 and the National Textile Center (NTC) Project C99-S09.

Poster Abstract

The American Nuclear Society Student Conference
Texas A&M University, March 2001

Category: Future Technologies

Temperature Sensitivity of Plasma Impacted Propellant

Ryan Davis, Jeff Preston and Mohamed Bourham
North Carolina State University, Department of Nuclear Engineering
Raleigh, NC 27695-7909

Presented by: Ryan Davis

It has been shown in the past that plasma ignited propellant burn is substantially higher than conventional (black powder) means. This is due to the high pressure impact of the plasma and the burn rate's pressure dependence. These experiments were performed on Electrothermal Chemical (ETC) plasma guns, which generate a capillary discharge plasma that impacts a propellant sample, at ambient pressure. What had not been done was testing the temperature sensitivity of the propellant bed with the plasma impact.

This work represents the first set of experiments designed to determine what the dependence of burn rate is with respect to a raised propellant temperature. The NCSU ETC gun PIPE was used as the plasma source for propellant impact. The propellant bed was heated to a predetermined temperature (on the range of 30-50 °C) and then subjected to the plasma impact at two inches away from the barrel under vacuum conditions (20 Torr). This resulted in an extinguished burn of the propellant. The burn rate was calculated for each shot and plotted as a function of propellant temperature to determine the functional dependence. The current data set shows an increasing burn rate with temperature, but is inconclusive in that both a power and an exponential dependence on temperature fit the data statistically and physically. A second set of experiments at one inch from the barrel is under way to determine the true dependence, but is not complete and not represented in this work.

Work supported by the US Army ARL-ARO Contract DAAD19-00-1-0555, the US Navy ONR Contract N00014-00-1-0901 and the National Textile Center (NTC) Project C99-S09.

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