

Cathode-Spot Ejected Particle Imaging Velocimetry (PIV) Calculations

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Introduction

Spacecraft reentering the atmosphere at hypersonic velocities are enveloped by a layer of plasma, commonly referred to as the 'plasma sheath'. This plasma envelope is caused by a hypersonic shock and frictional heating of air as it passes around the hypersonic vehicle. The layer of plasma blocks and prevents transmission and reception of communication signals below the plasma cutoff frequency.

A method of plasma 'quenching' via fine particulate dispersal is being investigated to reduce the plasma cutoff frequency. Cathode spot plasma plumes are utilized to disperse ceramic powder into an overhead radio frequency (RF) plasma used to simulate the reentry plasma. As the ceramic particles are ejected and travel through the plasma, the particles will collect electrons as they float in the plasma floating potential, reducing the electron density.

The velocity at which these particles are ejected is of significant importance for practical implementation of this mitigation method.

Background

The dispersion relation for electromagnetic waves in a non-collisional, non-magnetized plasma is given by:

$$\omega^2 = \omega_p^2 + c^2 k^2$$

Where ω is the frequency, ω_p is the plasma frequency, c is the speed of light in vacuum, and k is the wave number. The plasma cutoff frequency can be expressed as:

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

So waves below the plasma frequency will be reflected when they reach the plasma sheath, preventing radio communication.

For spacecraft reentry, plasma sheath density varies from 10^8 to 10^{14} cm^{-3} . This results in cutoff frequencies as high as 90 GHz, well above the GPS

(1.176 GHz) and S-band communication frequencies (2.3 GHz) commonly used.

By ejecting ceramic particulate into the plasma sheath to collect electrons, the cutoff frequency can be lowered, eliminating the communications blackout period.

However, a communications 'window' region of electron depletion must be created from the spacecraft antenna, reaching all the way through the plasma sheath. Therefore, the ceramic particles must be able to reach the outer layer of the plasma sheath in order to collect electrons and allow propagation from the spacecraft antenna to ground control and vice versa.

Cathode Spots

The ceramic particles are ejected via the initiation of cathode spots. Cathode spots are an intense, vacuum arc discharge that emanates from the surface of an electrode covered with ceramic powder and biased to a large negative voltage. In this process, a violent plasma plume ejects the ceramic powder from the electrode surface into an overhead plasma used to simulate the reentry plasma.

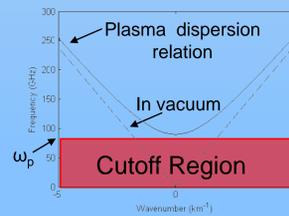


Figure 1: Plasma dispersion relation indicating the cutoff region for $n_e = 10^{14} \text{ cm}^{-3}$.



Figure 2: Cathode spot plumes eject the ceramic particulate into an overhead plasma.

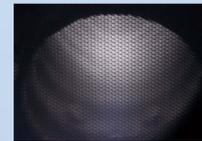


Figure 3: An inductively coupled RF plasma source creates an overhead plasma to simulate the reentry plasma sheath.

Experimental Setup

A diode laser with beam expanding optics and a high speed camera are used to view, image, and then perform particle imaging velocimetry (PIV) calculations. These calculations allow us to estimate the velocity with which the ceramic particles are ejected from the surface of the electrode.

The laser beam is expanded into a cylindrical volume. A notch filter used in conjunction with a high frame-rate camera allows primarily only laser light to pass, filtering out the plasma and cathode spot background light. The laser light scatters off of particles traversing through the cylindrical laser interrogation region, making them visible in the captured images.

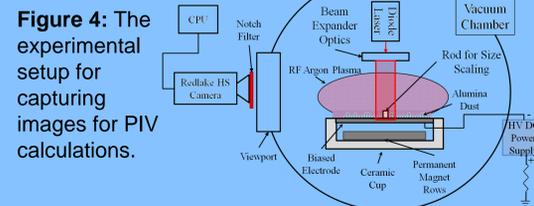


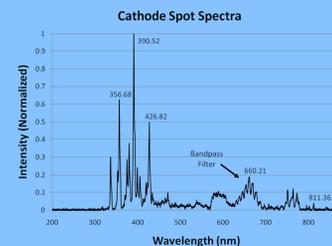
Figure 4: The experimental setup for capturing images for PIV calculations.

Plasma Measurements

A Langmuir probe was inserted to make plasma ion density measurements above the electrode. The ion density was found to be on the order of 10^8 cm^{-3} .

The floating potential of the overhead plasma was found to vary slightly between the electrode surface to 6 cm above. However, a variation of 50 mV over this distance results in a negligible electric field.

Figure 5: Spectral analysis of the cathode spots shows strong atomic lines between 300nm – 450nm as well as some molecular lines.



Spectral analysis of the cathode spots shows atomic lines corresponding to iron and other steel alloying elements. This is further evidence that the cathode spot plumes are composed of vaporized and ionized electrode material. It is also evident that the cathode spots act to further excite and ionize background neutral argon atoms, as seen from the spectral peak at 811nm in the cathode spot spectra.

Witness Plate

Experiments were performed with a witness plate placed directly above the powder-covered electrode. Double-sided carbon tape was applied to the bottom of this plate:

Figure 6: Regions of electrode powder removal correspond to areas of powder collection.

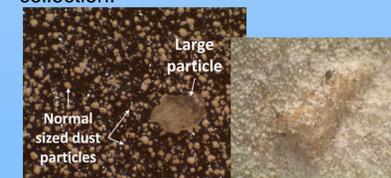
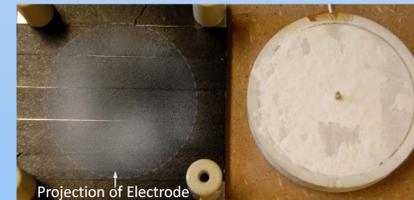


Figure 7: Large, possibly melted alumina particles were found on the witness plate and the electrode.

Captured Images

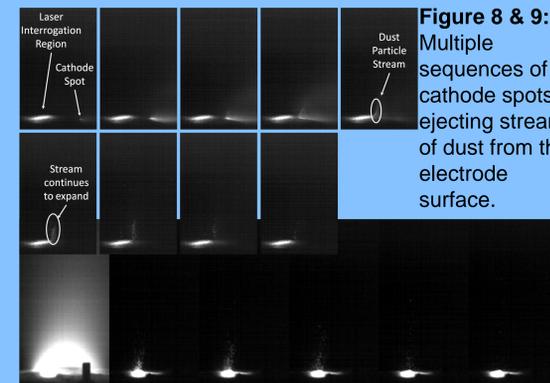


Figure 8 & 9: Multiple sequences of cathode spots ejecting streams of dust from the electrode surface.

Equations of Motion

- Air drag, ion drag, and electric field forces are small compared to the force of gravity and can be neglected
- Using simple conservation of energy equations, we can derive the equations of motion to determine the particle velocity at the time of ejection

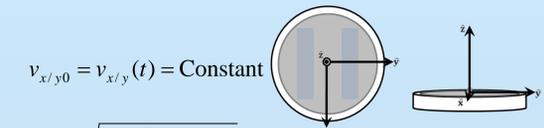
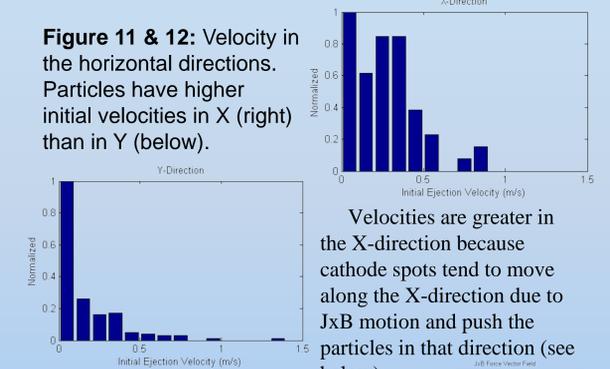


Figure 10: The electrode with the axes as indicated. The vertical direction is the z-axis.

Particle Velocity Distributions

Figure 11 & 12: Velocity in the horizontal directions. Particles have higher initial velocities in X (right) than in Y (below).



Velocities are greater in the X-direction because cathode spots tend to move along the X-direction due to JxB motion and push the particles in that direction (see below).

The velocity is greatest in the vertical direction (Z), as would be expected, since it is the primary ejection direction. The total velocity in 2 dimensions is between 0.2 and 1.5 m/s, with the most probable velocity being around 0.5 m/s.

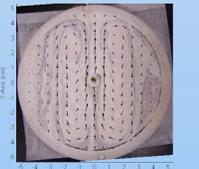


Figure 13: Cathode spots move in JxB direction.

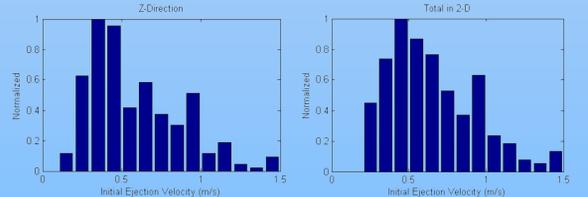


Figure 14 & 15: The distribution of velocities in the vertical direction (left) and the total velocity in 2D (right).

Future Work

- Measure time-resolved electron density with electrostatic probes, microwave interferometry, and/or microwave cutoff measurements
- Vary overhead plasma conditions and electrode parameters to investigate effects on plasma depletion

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Acknowledgements

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For further reading:

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