The Use of Pulsed Electron Beam Fluorescence for Arcjet Plume Diagnostics

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Abstract

A new method of making ground-state point density measurements in the plume of an arcjet is introduced. By using a pulsed, high-current electron beam, the limitation of conventional electron beam fluorescence to extremely low-density flows is overcome. It is determined that the fluorescence produced by pulsed electron excitation will be linearly dependent on ground-state density in an arcjet plume. Furthermore, the combination of high beam current and moderate flow density results in a self-focusing effect which assures good spatial resolution. The paper gives a description of the planned application of this technique to a 1-kw helium arcjet, and discusses the issues involved in applying PEBF to arcjets using hydrogen propellant.

Introduction

This paper introduces a new diagnostic technique which promises to increase understanding of nozzle and plume flow in arcjet thrusters by providing point density measurements of any desired species in the plume. Previous studies of arcjet plume flows have used optical techniques (LIF and emission spectroscopy) which are limited to examining excited state populations. Thus, while the velocity and temperature profiles of arcjet plumes are reasonably well understood, the ground-state density is not. As the bulk of the flow consists of ground-state atoms and molecules, it is difficult to determine key parameters, such as momentum flux, using current techniques.

At present, only limited inroads are being made into the problem of plume density measurement. Two approaches are extreme-ultraviolet (XUV) absorption spectroscopy\(^{(1)}\) and mass-velocity analysis.\(^{(2)}\) XUV spectroscopy requires considerable equipment, and is fundamentally difficult due to the need for a separate light source for each absorption feature and the formidable problem of data inversion in the presence of an unknown absorption lineshape. Mass-velocity analysis has produced good results in the far field of a 1-kW arcjet plume, but this approach has several limitations: data cannot be obtained in or near the engine nozzle; few vacuum facilities can achieve the low pressure required\((10^4 \text{ torr})\) required while still maintaining the propellant flow; and finally, plumes from high-power arcjets would melt the analyzer.

Therefore, we propose the use of pulsed electron beam fluorescence (PEBF) to measure total species density in the plume. As electron impact can excite any atom, molecule, or ion in any state, an electron beam fluorescence technique can measure the density of a species independent of state. Until recently, the use of electron beams for diagnostic purposes\(^{(3)}\) has employed low-current\((-1-10\text{mA})\) dc beams, limiting it to extremely low densities by collisional quenching and beam scattering effects, and has therefore been of little use for arcjet studies.
However, the recent development of simple devices for generating pulsed, high-current electron beams promises to overcome both of these limitations and allow the application of electron-beam diagnostics to arcjet plume flows.

We expect that the use of PEBF will produce accurate species-specific ground state density measurements in arcjet plumes, with spatial resolution of approximately one millimeter. Such measurements will allow the determination of momentum flux distribution in the plume, which is critical to understanding flow nonuniformity loss and boundary layer effects. In conjunction with optical techniques for determining excited state populations, this will enable us to measure the ratio of excited to ground state population at any point in the plume, and therefore increase understanding of frozen-flow losses in the nozzle.

In this work we will describe the background and theory of the pulsed electron beam fluorescence technique, along with the application of the technique to arcjet plume flows. We will also discuss our recently-begun construction of a facility for conducting PEBF studies on a 1-kw helium arcjet and the possible future application of the technique to high-power arcjets and different propellants. The use of helium propellant for our initial study was motivated by the relative ease of calibration when only a single atomic species exists in the flow, but there are no major obstacles to using PEBF in molecular or multicomponent flows.

Background

The electron beam fluorescence technique has been used in extremely low-density flows for almost thirty years. Traditionally, as, low-current dc beam of electrons is used to excite atoms and molecules in the flow and the resulting fluorescent emission is collected and analyzed. A schematic of a typical EBF experiment is shown in figure 1. At densities of greater than \(10^{-14}\) cm\(^3\) collisional quenching causes the signal to lose density dependence. Moreover, beam divergence causes a significant loss of spatial resolution at such densities.

![Figure 1 - Generic Electron Beam Fluorescence Experiment](image)

However, by using a high-current, pulsed electron beam in conjunction with a fast gated detector it is possible to use electron beam fluorescence at much higher densities. Quenching will still cause the emitted signal to take on a Stern-Vollmer form, with time-integrated emission sublinearly dependent on density. However, if the pulse length is small compared to the quenching timescale, the peak emission will be unaffected by quenching and will retain full density dependence. Also, at high currents and moderate to high gas pressures, an electrostatic self-focussing effect has been observed which maintains beam collimation despite scattering effects.

Until recently, it was not practical to generate pulsed electron beams of sufficient energy or current for diagnostic use. However, the recent development of pseudospark discharge switches has provided a simple and compact means of generating electron beams with electron energies of 20-50kV, currents of several hundred amps, pulse length of order 10ns, and beam diameter of about 1mm. We have explored the use of such devices for diagnostic purposes for several years, and are currently developing a facility for applying PEBF diagnostics to low-power arcjet plumes.
PEBF Capabilities

The plume of a low-power helium arcjet consists primarily of ground-state helium atoms at a density of order $10^{14}$ cm$^{-3}$, with a small population of excited-state atoms, ions, and free electrons. When an electron beam passes through the plume, it will excite atoms and ions by inelastic collisions regardless of initial state. For diagnostic purposes, it is convenient to excite the N=3 state and observe the 3-2 transition at 5015.7 Å.

The population of atoms excited to state i by a pulsed beam is given by the following equation:

$$N_i = I_b T_b L N_0 Q_a$$

where $I_b$ and $T_b$ are beam current and duration, L is probe volume length, $N_0$ is ground state number density and $Q_a$ is the cross section for electron impact ionization to state i.

For ground-state helium excited to the N=3 state by 30kV electrons, this cross section is 4.2x10$^{-19}$ cm$^2$.

Assuming a beam current of 100A and 10ns duration, a probe volume of 1mm$^3$, and a local density of 10$^{14}$ cm$^{-3}$, we expect a population of 2.6x10$^7$ N=3 atoms in the probe volume. For comparison, with a local temperature of 10,000K and electron density of 10$^{14}$ the Saha equation gives a much lower background N=3 population of 1.3x10$^7$ cm$^{-3}$.

The cross-section for collisional quenching of the N=3 state in helium is approximately 1.5x10$^{-15}$ cm$^2$ (11). The quenching rate is given by:

$$\Delta_{\text{in}} = 2 N_0 Q_{\text{in}} (2kT/\pi M_e)^{1/2}$$

At the temperature and density expected in the plume, this corresponds to a quenching timescale of 300ns, much longer than the pulse length or the signal collection time. Therefore, the time-dependent signal will be directly proportional to the local number density. Given the spontaneous emission coefficients $A_{31}$ and $A_{32}$ for helium (5.66x10$^4$ and 0.13x10$^4$, respectively), the anticipated signal for a local density of 10$^{14}$ cm$^{-3}$ is 6.0x10$^7$ photons at 5015.7Å emitted during the ten nanoseconds immediately following excitation. Additional photons may be created by secondary electrons and by resonant scattering of radiation from the 3-1 transition, but these photons will be time-delayed and will probably not be observed by a fast gated detector.

The magnitude of this signal, along with its linear density dependence, is the primary motivation behind the PEBF technique. As the signal is several orders of magnitude greater than the background emission of the plume, it is easy to detect and isolate. After calibration of the experiment with a static gas of known density, it is straightforward to extract the number density in the probe volume. Furthermore, this signal is strong enough to be easily detectable even if densities are an order of magnitude more than expected, and fast enough to overcome quenching at densities an order of magnitude larger than expected.

Application to Multicomponent Flows

The above analysis assumes that the flow field being probed consists only of ground-state helium atoms. In fact, a small portion of the flow field will consist of excited state atoms, ions, and free electrons. Also, it may be desirable to use the technique to examine flows consisting of molecular species in a state of partial dissociation. We will therefore consider the effects of these complications of the PEBF technique.

The presence of a preexisting excited state will produce a background signal which can easily be subtracted from the measured signal. However, in many cases the excitation cross section of excited states will differ from that of the ground state, and equation 1 will require modification. If the excited state population is large, the $Q_{\text{in}}$ term must be replaced by an average cross section $Q_i$ determined by summation over all states existing in the flow.

$$Q_i = \sum_{n=0}^{j} Q_n (N/N)$$

This has the obvious disadvantage of requiring prior knowledge of the excited state distribution in the flow. However, the effect of this should be small for typical plume excitation where we do not expect atomic excited state populations to be more than a few percent of the ground state population.

It may be possible to use optical techniques such as LIF to measure excited state populations and subtract the expected fluorescence signal due to the PEBF signal, thus measuring only ground-state populations with PEBF. Alternately, the fact that high-energy electrons will excite only optically-allowed transitions suggests that it may be possible to observe a fluorescence signal from an
excited state accessible only from the ground state but not from low-lying excited states. This is not feasible with helium, as the $N=1$ and $N=2$ states have similar quantum numbers ($1S$ and $2S$), but may be possible with other species.

If the flow consists of more than one species, it is necessary to isolate the signal produced by the species of interest. This can usually be accomplished by using narrow-band filters to limit detection to a spectral line unique to the species. An additional complication arises if the two species are different forms of the same element (e.g. $\text{He}$ and $\text{He}^+$, or $\text{H}_2$ and $\text{H}$). In such cases, the electron beam may cause ionization or dissociative excitation of the parent species and thus exaggerate the population of the radical or ion being observed.

For $\text{H}_2$, the cross-section for dissociative excitation to the $N=3$ state is approximately one order of magnitude lower than the cross-section for excitation of the $\text{H}$ atom ground state to $N=3^{1+}$. Therefore, the observed population of $N=3$ atoms will be due primarily to excitation of $\text{H}$ atoms and not dissociation of $\text{H}_2$ molecules except in cases where the $\text{H}_2$ population is much larger than the $\text{H}$ atom population, which is clearly not the case in arcjet plumes. Similar effects may prevent the accurate measurement of the small $\text{He}^+$ population in the plume of a helium arcjet, but the $\text{He}^+$ population in a helium arcjet plume is very close to the electron density, and is thus accessible by other means.

One final difficulty with multicomponent flow is that of calibration. A PEBF system can easily be calibrated by filling the entire test area with a static gas of known density and composition, and measuring the resulting fluorescence signals. However, if the species in question is an ion or radical, such as atomic hydrogen, this becomes much more difficult. Although it may be possible to calibrate using a gas discharge of known characteristics, or on the basis of cross-section calculations, it is probably easier to use helium for initial tests.

**Electron Beam Generation**

The success of the PEBF technique depend on the availability of a practical means of generating pulsed, high-current electron beams. This is provided by the development of the pseudospark discharge device, shown in figure 2. Two planar electrodes are maintained at a constant separation of several millimeters, with holes of a few mm diameter on the centerline. The discharge chamber is pressurized to about 100 microns of helium, and the electrodes charged to a voltage of 20-50kV.

![Figure 2 - Electron Gun Design](image)

The device operates on the left-hand side of the Paschen curve, and the spacing of the electrodes and design of the support structure prevents any short-path or surface discharges. The device can be triggered by a secondary electrode (as shown) or by photoemission from the cathode surface using a UV flashlamp. Either method produces a long-path discharge through the axial holes, where the initial electrons are accelerated to the electrode voltage and proceed ballistically to the test area.

Since 20-50kV electrons are not energetic enough to pass through a foil window, there must be a hole for the beam to pass between the gun and the test area. This allows the possibility of contamination of the discharge chamber by gas from the test area. As the pseudospark discharge is extremely sensitive to gas pressure and composition, this must be avoided. Therefore a vacuum isolation section must be installed between the gun and the test chamber. So long as the pressure in the test area is not greater than 1 torr, maintaining isolation is not difficult even with moderate pumping (~100cfm) of the isolation section.
It is also important to provide a current diagnostic of the electron beam. As the beam current and duration of the beam may vary from pulse to pulse, it is necessary to normalize the fluorescence signal by the integrated pulse current. A shielded Rogowski coil at the entrance to the test area provides this measurement. Earlier experiments with such a device indicate a beam duration of approximately 10ns with a peak current of several hundred amps at 30kV.

Electron Beam Propagation

An electron beam will tend to disperse by two methods: scattering (prevalent at high gas densities) and space-charge repulsion (at high currents and low energies). This would limit the utility of electron-beam fluorescence were it not for the fortuitous occurrence of a self-focusing effect. If a high-current beam passes through a relatively high-density gas flow, it will produce a significant degree of ionization. The positive ions will not move noticeably during a 10-ns pulse, but even 1eV secondary electrons will move several millimeters during this period, and therefore probably leave the beam path. This results in a narrow core of positive charge surrounded by a negative sheath, and tends to confine the electron beam.

If the positive ion density in the beam path is comparable to the electron density in the beam, this self-focusing will largely prevent beam divergence due to space-charge repulsion. At higher plume densities, the self-focusing should be sufficient to overcome the effects of small-angle scattering. The electron density in the beam is given by:

\[
N_e = I_e A_{ls}^{-1} (M_e / 2E)^{1/2}
\]

At 100A and 35kV, this gives an electron density of \(6.2 \times 10^{12}\) cm\(^{-3}\). Calculating ion density in the beam path is a more difficult problem, as it depends on both primary and secondary ionization processes. Experimental measurements indicate that the total production of He\(^+\) ions by 30kV electrons is 165 per cm per electron for He at standard temperature and pressure. With a 100A, 10ns beam the necessary number of ions (\(6.2 \times 10^{12}\) cm\(^{-3}\)) will be produced at a density of \(10^{13}\) cm\(^{-3}\) or greater. This corresponds quite well with our experience. Since the expected plume density is of order \(10^{14}\) cm\(^{-3}\), and recent work suggests that arcjet operation and plume flow is not adversely affected by background pressures of up to \(5 \times 10^{15}\) cm\(^{-3}\), we can be confident that the local density will always be sufficient to maintain focusing.

The upper limit for beam propagation in high-density flows is the attenuation of the beam due to large-angle scattering. This cannot be overcome by the self-focusing process described above. For 30kV electrons and He atoms, the cross-section for large-angle (>5 degree) scattering is approximately \(10^{-18}\) cm\(^2\). The characteristic penetration length in a gas of \(10^{16}\) cm\(^{-3}\) density is of order one meter. Thus, beam attenuation due to large-angle scattering is not a factor at the densities involved in arcjet studies.

Proposed Experiment

We currently have a 1-kW hydrogen arcjet designed by NASA-Lewis, along with associated power supply and propellant feed system. We plan to use the PEBF technique to measure particle density in the plumes of this arcjet. The experiment is illustrated in figures 3 and 4. The arcjet will be installed in a steel chamber of 1-meter diameter, with a 6000 cfm vacuum system to maintain background pressure within acceptable limits during operation.
Conclusion

The inability to make point density measurements in the plume of an arcjet has been a major barrier to understanding of momentum flux and boundary layer losses in arcjets. The use of pulsed, high current electron beams as a flow diagnostic technique offers the ability to make such measurements for the first time. The broadband excitation produced by an electron beam enables the observation of any species in any electronic state, and the use of a pulsed, rather than continuous, beam allows the use of the technique at high densities despite the effects of collisional quenching.

Analysis indicates that the PEBF technique can easily be applied to a low-power helium arcjet. The expected signal is large enough to be easily detected and analyzed, and will retain a linear density dependence throughout the range of interest. Furthermore, the beam will self-focus and will not be significantly attenuated or dispersed in the test area. It is also possible to use the technique to measure species-specific densities in arcjets using hydrogen or ammonia propellant, although there are minor difficulties in calibration and data analysis in multicomponent flows.

A test facility with a 1-kW arcjet is currently under construction. This facility will be able to make point density measurements with a spatial resolution of 1mm anywhere in the plume, and will ultimately provide a density map of the entire plume.

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References


