LIF MEASUREMENTS OF SPECIES VELOCITIES IN AN ARCJET PLUME

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Velocity slip is investigated near the exit plane of a hydrogen arcjet thruster by seeding helium into the propellant flow. The axial velocities of helium and atomic hydrogen are measured using laser-induced fluorescence. The velocities are found to be the same, within the uncertainty of the measurement, indicating that slip velocities are negligible.

Introduction

Velocity slip is a phenomenon in which different species have different mean velocities. It has been studied for molecular beam nozzles and isotope separation. Significant velocity slip has been measured in the plume of low power arcjet thrusters. These measurements, obtained by mass spectrometry of a molecular beam sampling probe, were limited to locations more than 10 diameters from the exit plane.

The determination of whether this slip develops in the nozzle, near the exit plane, or in the plume expansion, is important to both modeling efforts and to the interpretation of measurements. If velocity slip develops inside the nozzle, numerical models will need to include separate momentum and energy equations for each neutral species or an appropriate model for diffusion. These additions increase the complexity of an already difficult task. Measurements of exit-plane velocity and kinetic temperature have been made by laser-induced fluorescence (LIF), a species specific technique. If significant slip exists, separate measurements need to be made for each species in order to characterize the flow field.

We have previously reported the results of LIF velocity and kinetic temperature measurements of atomic hydrogen in a hydrogen-fueled arcjet. The flow however, consists of both atomic and molecular hydrogen (along with small mole fractions of ions and electrons). The most conclusive method to investigate velocity slip would be to measure the velocity of molecular hydrogen under the same conditions for which atomic hydrogen velocity has been measured. However, absorption transitions from the ground state require vacuum-ultraviolet wavelengths, owing to the low densities of excited-state molecules, these transitions are also difficult to probe. Multiphoton excitation techniques can be used, e.g. to probe ground state populations, but they are somewhat complicated in their implementation and interpretation.

A simpler approach is to seed the flow with a species that is accessible by the same laser used to probe atomic hydrogen. Helium was chosen here as the seed species owing to its compatibility with the arcjet as well as its convenient electronic transitions in the visible wavelength region. Velocity and temperature are measured by LIF of both helium and hydrogen at the same arcjet conditions. The absence of slip between helium and atomic hydrogen would suggest that slip is not a dominant mechanism in the nozzle or exit plane vicinity.

Theory

In a flow with multiple species, where each species, i, may have its own mean velocity \( v_i \), the mean mass velocity, \( v_m \), is defined by

\[
v_m = \frac{\sum n_i m_i v_i}{\sum n_i m_i}
\]
where \( n_i \) is the number density of species \( i \) and \( m_i \) is the mass. The steady-state momentum equation for a single species in the axial direction, \( z \), can be formulated as
\[
n_i m_i \frac{\partial v_i}{\partial z} + \frac{\partial p_i}{\partial z} = n_i m_i \sum_j k_{ij} (v_j - v_i) \tag{2}
\]
where \( p_i \) is the partial pressure. The term on the right side of Eqn (2) represents the momentum transfer between species due to collisions. This assumes that the force per unit volume exerted on particles of species \( i \), due to collisions with other species, is proportional to the difference between mean velocities. The proportionality constant, \( k_{ij} \), can be considered as a collision frequency for momentum transfer which can be determined from kinetic theory.\(^7\)\(^8\) The slip velocity, \( v_{\text{slip}} \), is usually defined for a binary mixture as the difference in velocities,
\[
v_{\text{slip}} = v_j - v_i \tag{3}
\]
If the density is high such that flow is in a continuum regime, there are enough collisions to keep the different species in equilibrium. However, in an expanding flow, conditions can occur in the transition from continuum to free molecular flow, where velocity slip becomes significant. This is because \( k_{ij} \) is inversely proportional to the Knudsen number \( (Kn)^8 \)
\[
k_{ij} \propto \frac{1}{Kn} \tag{4}
\]
As the Knudsen number increases there begins to be a net transfer of momentum from one species to another. The conversion of momentum is balanced by convective and pressure forces. As the flow becomes rarefied to the extent that collisions become negligible, the slip approaches a constant value (which may be zero).

**Experiment**

The arcjet thruster used in this experiment is a 1 kW class radiatively-cooled thruster designed and built at NASA Lewis Research Center. The tungsten nozzle has a 0.64 mm diameter, 0.25 mm long constrictor and a conical (20° half angle) diverging section with a area ratio of 225 (9.53 mm exit diameter). A more complete description of the arcjet is available elsewhere.\(^9\)\(^10\) When operating on the hydrogen-helium mixture, the current and voltage are 9.5 A and 143 V corresponding to 1.36 kW arc power. The arcjet is operated in a 0.56 m diameter cylindrical stainless steel chamber 1.09 m long. The 0.5 Torr background pressure is maintained by two 1250 CFM blowers evacuating through 6 inch pipe.

The temperature and velocity measurements were made using LIF. A CW ring dye laser scans across the atomic transition. Since the laser bandwidth is much smaller than the spectral feature, the fluorescence excitation spectrum accurately depicts the broadening mechanisms of the probed species. The velocity is determined from the Doppler shift while the temperature is inferred from the shape of the fluorescence excitation spectrum using a Doppler-broadened lineshape model. Since Doppler broadening arises from the velocity distribution of the species, this diagnostic technique determines the kinetic or translational temperature which may differ from the electronic temperature or rotational and vibrational temperatures of the molecular species in the flow.\(^11\)\(^12\) Details of the implementation and analysis have been previously published; the only difference in this experiment is the use of optogalvanic detection in a DC discharge for the reference (unshifted) signal. The optogalvanic cell provided a reference for helium with a high signal-to-noise ratio. The signal for hydrogen was much weaker but the reference calibration is in agreement with calibrations using fluorescence and absorption in a microwave discharge.

The atomic hydrogen transition probed is the Balmer \( \alpha \) transition at 656 nm (15233 cm\(^{-1}\)), an electronic transition between the first and second excited states. This transition actually consists of the overlap of several fine structure components. Since the separation of these components is the same magnitude as the broadening, they must be accounted for when analyzing the lineshape. The helium transition probed is the 2\(^1\)P \( \leftrightarrow 3\)1D at 668 nm (14,970 cm\(^{-1}\)).

Helium's high excitation energy makes probing the excited states difficult. The first excited state is 166,278 cm\(^{-1}\) (20.6 eV) from the ground state. In order to obtain a strong enough fluorescence signal (relative to the noise), a high helium flow rate of 6.2 SLPM was necessary. This is significant when compared to the 9.0 SLPM of hydrogen. The addition of helium to the propellant increases the arc voltage and reduces the velocities. The voltage increase of less than 3 Volts can be explained by a combination of the increased flow due to the helium addition and helium's higher ionization energy. The 30% velocity decrease (at the centerline) can be attributed to helium's higher atomic mass and the reduced specific power. Also, the peak temperature drops 20% from 5000 K to 4000 K. While the addition of the helium modifies the flow parameters,
the conditions that allow slip to occur are expected to be within the same magnitude of the unseeded arcjet.

**Results and Conclusions**

The raw data from the helium and hydrogen fluorescence are shown in Figures 1 and 2 respectively. The Doppler shifts correspond to axial velocities of 10.4 km/s for helium and 10.3 km/s for hydrogen. The velocities are the same within the 0.2 km/s uncertainty of the measurement. This indicates that the slip velocity is less than the uncertainty of the measurement. Thus, the uncertainty determines the upper limit of the slip velocity to be 2% of either species' velocity.

The inferred temperature for helium and hydrogen are 3991 K and 4259 K respectively. The 6% difference is less than the 20% uncertainty of the measurement. This indicates that temperature slip is also negligible compared to the experimental uncertainty. Thus, all species share a common kinetic temperature. Note that due to higher sensitivity to noise, the uncertainties of the temperature are higher than the uncertainties of the velocity.

The results indicate that the velocity of any single species, as measured in the vicinity of the exit plane, represents the mean mass velocity (within the uncertainty of the measurement). This is significant because it implies that species specific velocity-measurement techniques such as LIF need only be applied to a single species. In a hydrogen-fueled arcjet, it is much easier to probe the atomic hydrogen than the molecular hydrogen.

To further investigate the effect of collisions, it would be interesting to extend these slip measurements further along the axis of the plume to see where slip develops. This, however, should be conducted in a test chamber capable of maintaining high vacuum back pressures that would simulate the thruster environment appropriately.

To measure the slip velocity with higher accuracy would require a higher resolution velocity measurement. The technique used for this work uses a wavemeter to measure absolute laser frequencies. An alternative technique uses a Fabry-Perot interferometer to measure relative laser frequency. While this would reduce the uncertainty and improve the resolution, it requires laser scanning techniques not available for this experiment.

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**References**


2. For example, see a number of papers from Rarefied Gas Dynamics Volume II; ed Hakuro Oguchi; University of Tokyo Press; 1984; Pp 645-720.


Figure 1. The Doppler-shifted fluorescence excitation spectrum of helium is presented along with the unshifted reference signal used to calibrate the wavemeter. The probe volume is centered in the plume, 0.5 mm from the exit plane.

Figure 2. The Doppler shift of atomic hydrogen is measured relative to its calibration. The measurement location is the same as the helium data. Note that the smaller atomic mass leads to broader linewidths eventhough the temperature is the same.