

High-speed imaging of atomic oxygen emission in the HyMETS arcjet tunnel

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Bandpass-filtered imaging of electronically excited atomic oxygen emission at 777 nm was performed at a frame rate of 300 kHz in the NASA Langley Hypersonic Materials Environmental Test System (HyMETS) arc-heated wind tunnel. The facility was operated with a fixed working-gas composition of 95% argon and 5% oxygen. A continuous tunnel run was partitioned into test cases corresponding to arc-currents of 150, 175, and 200 A—each with and without the insertion of a cylindrical silicon-carbide (SiC) test sample oriented with the axis parallel to the streamwise flow direction. Image sequences were analyzed to extract qualitative information from time-averaged spatial distributions, temporally resolved quantitative spatial metrics such as standoff distances, and frequency content of both freestream and shock-layer emission. Emission intensity increased with arc-current in both flow regions, with shock-layer intensities approximately an order of magnitude higher than those of the freestream. The freestream emission exhibited a parabolic radial profile, with a core diameter expanding from 55 to 65 mm over an axial distance of 21.5 mm within the camera’s field of view. Shock standoff distances were consistently measured at 11 ± 1 mm upstream of the cylindrical sample across all arc-current conditions, with temporal fluctuations dominated by frequencies near 60, 180, and 360 Hz. The point of highest emission was located 2.0–2.4 mm from the front face of the cylindrical sample, decreasing with increasing arc-current, and exhibited the same frequency-specific oscillations as the shock front. These distinct frequency signatures were also observed in the freestream emission and appear to be independent of arc-current.

I. Introduction

Thermal protection systems (TPS) have, and continue to be, a critical technology for enabling the success of hypersonic vehicles. The extreme aerothermal heating experienced during hypersonic flight requires the use of these materials to protect the integrity of the vehicle structure and internal systems. The design and development of TPS materials is a complex process that requires extensive ground testing to evaluate material performance under relevant conditions. High-enthalpy arc-heated wind tunnels, or arcjets, have been the main tool in this process, as they are one of the only technologies that can produce the high temperatures and appropriate pressures necessary to simulate the aerothermal environment of hypersonic flight [1]. To generate these extreme conditions, arcjets utilize an electric arc discharge to heat a working gas to temperatures as high as 8500 K, which then produces a high-enthalpy plasma flow that can be accelerated to hypersonic velocities [2]. Unfortunately, as a result of this process, the working gas is driven far from thermochemical equilibrium, which can lead to significant uncertainties in the flow properties. This nonequilibrium state of the flow can complicate the interpretation of TPS material performance, since the material response is highly dependent on the local flow conditions. Therefore, it is critical to develop a better understanding of the flow properties in these facilities to improve the accuracy of TPS material testing and development.

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Characterizing arcjet flows has long been pursued through a combination of computational modeling and experimental diagnostics. However, the complex nature of the plasma flow and the harsh testing environment have made it difficult to obtain accurate and reliable data. Traditional intrusive probes, such as pitot tubes and thermocouples, are limited because they cannot resolve real-gas effects such as dissociation, ionization, vibrational and electronic excitation, or thermochemical nonequilibrium. Since these processes strongly influence TPS response, nonintrusive optical diagnostics have become increasingly important, offering the ability to probe thermochemical states without disturbing the flowfield.

Spectroscopic diagnostics, in particular, provide powerful tools to quantify nonequilibrium phenomena in high-speed, high-enthalpy environments [3]. By targeting atomic and molecular spectral features, these methods enable the characterization of rotational, vibrational, and electronic populations through emission or absorption, thereby yielding insights into the local thermodynamic state. Techniques successfully applied in arcjet facilities include Optical Emission Spectroscopy (OES) [4, 5], Tunable-Diode Laser Absorption Spectroscopy (TDLAS) [6–9], Planar Laser-Induced Fluorescence (PLIF) [10, 11], and Two-Photon Absorption Laser-Induced Fluorescence (TALIF) [12–14]. These diagnostics have been used to measure species concentrations, temperatures, pressures, and velocities. Nevertheless, their implementation in arcjet facilities is challenging, as strong background radiation, limited optical access, and mechanical vibrations often hinder high-quality measurements. Recent advances in laser technology and diagnostic techniques, however, continue to expand capabilities and improve measurement reliability in these environments.

In this work, high-speed imaging of spectrally selective emission was performed in the freestream of NASA Langley’s Hypersonic Materials Environmental Test System (HyMETS). This study qualitatively examines the spatial and temporal variability of excited-state atomic oxygen emission at 777 nm using a bandpass filter coupled with a high-speed camera. Multiple flow conditions were tested to assess the effect of arc-current on emission characteristics in both the undisturbed freestream and the shock layer of an end-on, flat-faced cylinder. Radial and axial freestream emission profiles were extracted from the image sequences to evaluate the spatial distributions of the excited-state oxygen population. In addition, line-tracking analysis was applied to identify the locations of shock-layer features, including the shock-front and the region of maximum brightness. These chemiluminescence measurements were conducted simultaneously with a TDLAS experiment, reported by Schwartz et al. in Ref. [15], probing the same 777 nm transition in the freestream, providing quantitative information on the excited-state oxygen population. Compared to the work in Ref. [15], the present study focuses solely on the high-speed imaging results, which are analyzed to extract spatial and temporal variability in the freestream and shock-layer at various arc-current conditions.

Section II describes the HyMETS facility, flow conditions, experimental setup, and spatial calibration procedure. Section III presents the high-speed imaging results, including emission profiles and shock-layer feature tracking. Finally, Sec. IV summarizes the key findings of this study.

II. Experimental Methods

A. HyMETS Arcjet Facility

The NASA Langley HyMETS arcjet facility (Fig. 1) is configured with a segmented arc-heater powered by a 400 kW DC power supply to generate continuous Mach 5 high-enthalpy flow [16]. The facility accommodates discrete gas mixtures composed of nitrogen (N_2), oxygen (O_2), argon (Ar), and, in some applications, carbon dioxide (CO_2). These gases are injected tangentially to the flow to induce vortex motion, promoting spin-stabilization of the electric arc. In addition, N_2 and Ar are injected near the cathode and anode at adjustable ratios to mitigate electrode oxidation and improve arc attachment. The resulting plasma, formed by the electrical discharge, is accelerated through a water-cooled conical nozzle (2.5-inch exit diameter) to nominal Mach 5 conditions—considering that the working gas composition is predominantly air. Downstream, the flow enters a 2×3 ft test-section containing four pneumatically actuated, computer-controlled stings. These stings can be instrumented with a pitot probe for post-normal shock stagnation pressure measurements, two end-on flat-faced cylinder (FFC) heat flux probes (a Gardon gauge and copper slug calorimeter), and either a cylindrical Silicon-Carbide (SiC) sample or an alternate test specimen. The flow is then exhausted through an 8-inch collector into a 6-inch constant-diameter diffuser, where a coiled copper tube heat exchanger decelerates and cools the gas. Finally, a two-stage vacuum system evacuates the flow from the facility.

HyMETS is equipped with viewing ports on the test-section door that provide line-of-sight access to the leading edge or surface of a test article for monitoring with a pyrometer and a facility-operated video camera. Additional ports oriented perpendicular to the flow direction are available for optical diagnostics, such as the measurement system employed for this test and described herein.

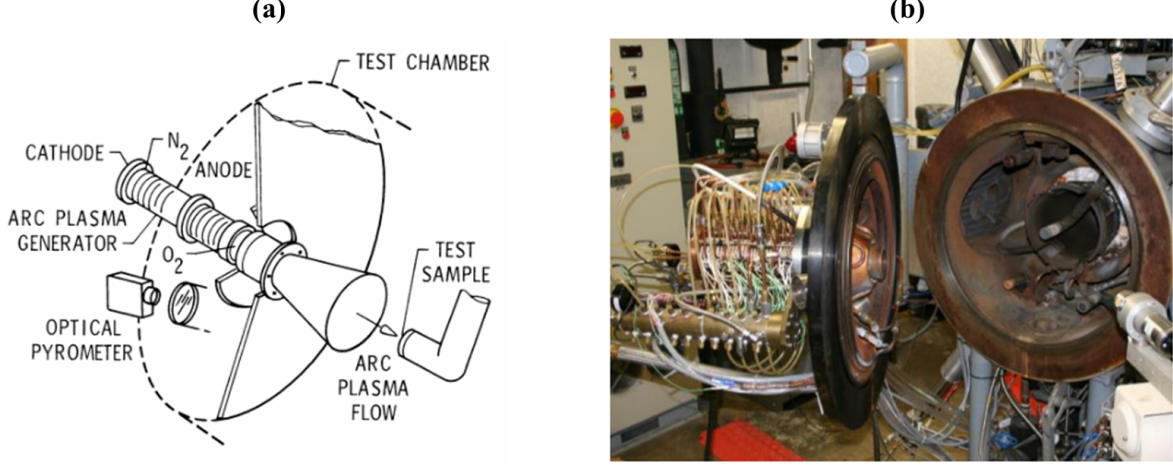


Fig. 1 The HyMETS facility (a) schematic and (b) test setup, reproduced from Ref. [16].

1. Testing Conditions

Three flow conditions were investigated, defined by variations in the arc-current set to 150, 175, and 200 A. For all cases, the working gas composition was fixed at 95% argon and 5% oxygen, which enhances the population of electronically excited atomic oxygen relative to nominal air operation [15]. The three test conditions were executed sequentially within a single facility run, with each condition held constant for approximately 60 s before performing the 30 s transition to the next.

B. Targeted Species Transition

The primary emission targeted in this study was the atomic oxygen triplet near 777 nm, corresponding to the $3s^5S^o \leftrightarrow 3p^5P$ transition. These emission lines originate from a high-lying excited state of atomic oxygen with an energy level of 10.74 eV and are therefore most intense in high-temperature, oxygen-containing plasmas, such as those present in the shock-layer.

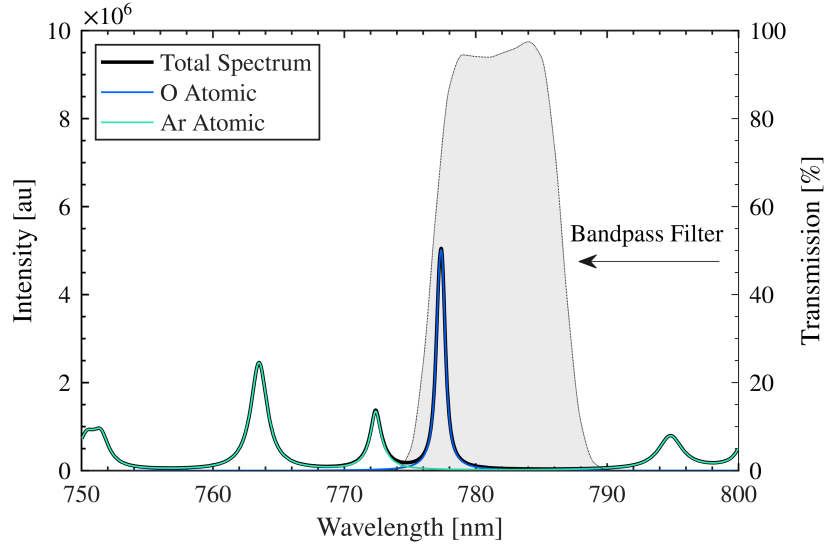


Fig. 2 Simulated emission spectrum of a 95% Ar, 5% O₂ equilibrium plasma at 10,000 K computed using SPARKLbL [17]. The dominant atomic oxygen triplet near 777 nm is indicated, along with the transmission percentage of the bandpass filter used in the experiment (shaded region).

As shown in Fig. 2, the simulated spectrum demonstrates that the 777 nm emission is well isolated within the bandpass filter, which is utilized in the experimental setup described in the following section. This configuration ensures that the measured emission primarily represents excited atomic oxygen, minimizing interference from adjacent lines.

C. High-speed Bandpass-Filtered Imaging

A Photron™ FASTCAM SA-Z high-speed camera was equipped with a 25 mm diameter ThorLabs™ hard-coated bandpass filter (P/N: FBH780-10) mounted between the detector and lens using a lens adapter. The filter has a center wavelength of 780 ± 4 nm and a full-width half-maximum (FWHM) of 10 nm. A Canon™ EF 200 mm f/2L IS USM lens was attached to the opposite end of the adapter and aligned to the test-section side window, as shown in Fig. 3. The camera assembly was mounted on a vertical translation stage to enable precise adjustment in the y -plane and positioned 2.44 m from the test sample centerline in the z -direction. As a result of these measurements being performed in conjunction with a separate TDLAS diagnostic [15], the camera was laterally offset by ~ 0.1 m in the x -direction from the front of the test sample and angled back 2.4° to avoid interference with the laser optics while still maintaining an effective line-of-sight.

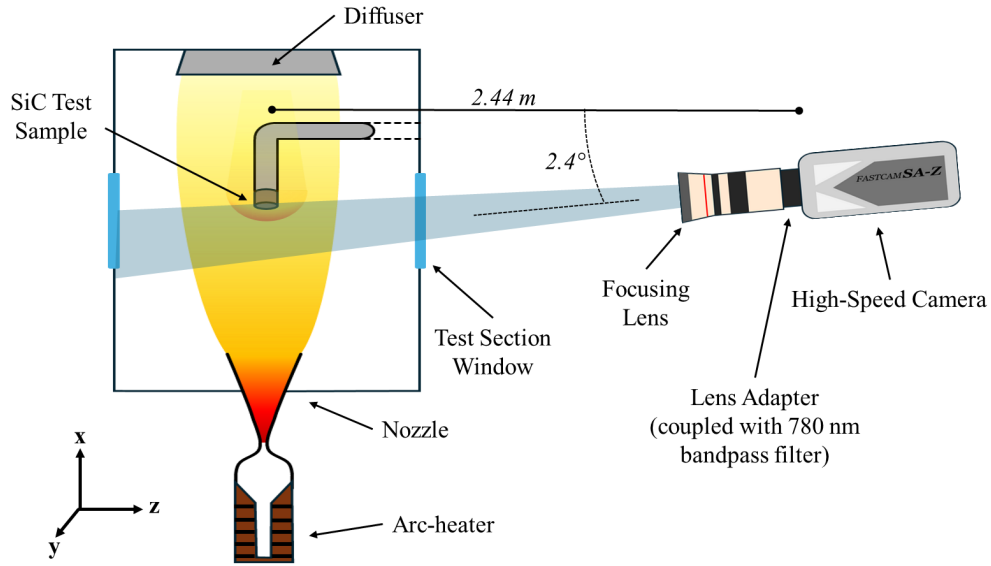


Fig. 3 Schematic of the experimental setup with the test sample inserted into the freestream (not to scale).

To balance high temporal resolution with sufficient image resolution, the camera was operated at a frame rate of 300 kHz with a pixel resolution of 256×128 pixels. A total of 10,000 consecutive frames were acquired and analyzed for each test condition, resulting in acquisition times of 33 ms. Exposure times were adjusted between freestream and shock-layer acquisitions to avoid saturation caused by higher flow-density emission in the shock region. All freestream images (with the sample retracted) were acquired with an exposure time of $1.37 \mu\text{s}$, while shock-layer imaging (sample inserted) used a reduced exposure time of $0.35 \mu\text{s}$ for all listed arc-current settings. For each exposure time, background images with the plasma off were also acquired and subtracted from the corresponding dataset to remove non-plasma contributions. Finally, the background-subtracted images were corrected by dividing each dataset by its respective exposure time.

An alignment grid consisting of 1 mm diameter holes with 2 mm spacing was placed along the center axis of the test sample to establish the pixel-to-length scale and local coordinate system. The distance between hole centers was measured to determine linear scaling factors across both the x and y directions. The variation among these factors was less than 5%, allowing the determination of a uniform calibration of 0.172 mm per pixel. Therefore, the calibrated field of view (FOV) for the 256×128 pixel images was approximately 44×22 mm.

To predict the spatial blurring of the acquired images, estimations of the freestream and post-shock flow velocities were multiplied by the corresponding exposure times for each condition. Considering that the working gas was composed primarily of argon, estimations of the Mach number were made using the isentropic flow and normal shock relations for a perfect gas with inputs of the known nozzle geometry and a specific heat ratio of 1.67. The Mach number was

assumed to be 7.12 in the freestream and 0.46 post-normal shock. Utilizing results from the atomic oxygen TDLAS diagnostic acquired in conjunction with this experiment [15], the freestream temperature was estimated to be between 450–1200 K across the selected arc-current conditions. From these values, the freestream velocity was approximated at 3700 ± 900 m/s, while the post-shock velocity was estimated at 1000 ± 200 m/s, where increases in arc-current correspond to higher velocities. These estimations lead to an approximate spatial blurring of 3.9–6.3 mm for the freestream images and 0.26–0.43 mm beyond the shock-front.

III. Results and Discussion

A qualitative intensity analysis and a quantitative frequency analysis of the 777 nm excited-state atomic oxygen emission were performed using 10,000 consecutive frames divided into six test cases. As mentioned in the previous section, these correspond to arc-current settings of 150, 175, and 200 A under freestream (sample retracted) and shock-layer (sample injected) conditions. A sample of the instantaneous freestream emission images is shown in Fig. 4. Each row of this figure corresponds to a different arc-current condition, with the first row representing 150 A, the second row 175 A, and the third row 200 A. For this short duration, each condition displays an apparent level of temporal variability in the freestream emission intensity, with large-scale flow structures that clearly suggest unsteady flow behavior. To evaluate the implications of this variability, spatial and temporal analyses were performed in both the freestream and shock-layer regions, as described in the following sections.

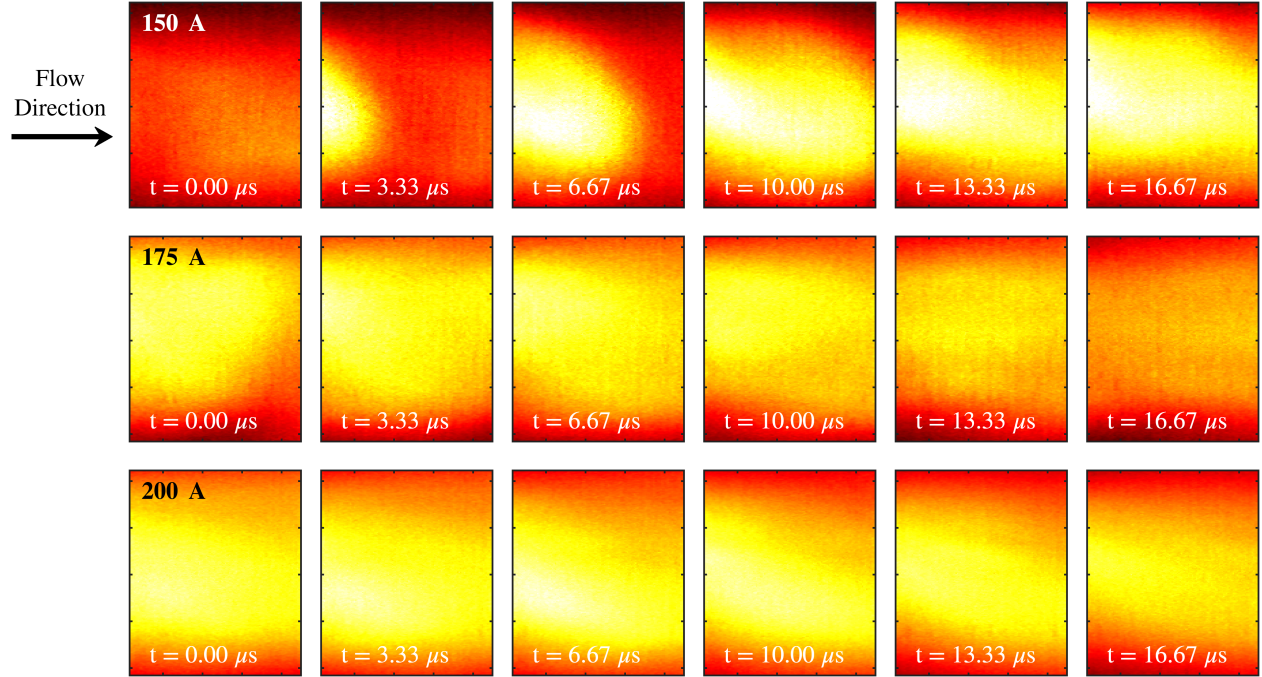


Fig. 4 Sequential freestream emission images at arc-currents of 150 (first row), 175 (second row), and 200 A (third row).

A. Freestream Measurements

Initial examination of the freestream emission is performed using the images shown in Fig. 5. In this figure, each image presents the time-averaged emission for each arc-current setting, with an illustration indicating that the flow direction moves from left to right (negative x direction). Additionally, the x and y coordinates, presented in millimeters, are referenced from the front edge and centerline of the test sample. As such, $x = 50.8$ mm (outside FOV) corresponds to the nozzle exit, and $y = 0$ mm corresponds to the nominal centerline of the nozzle.

In the freestream, changes in emission intensity are notably affected by moderate deviations in arc-current, indicating a clear correlation between the population of excited-state atomic oxygen and the selected arc-current. Across all current settings, the strongest emission occurs near the nozzle exit and close to the centerline. To characterize spatial variations,

one-dimensional profiles were extracted from the freestream images (Fig. 5) along the radial and axial directions. These profiles are shown in Figs. 6a and b, respectively, with shaded regions indicating 1- σ variability.

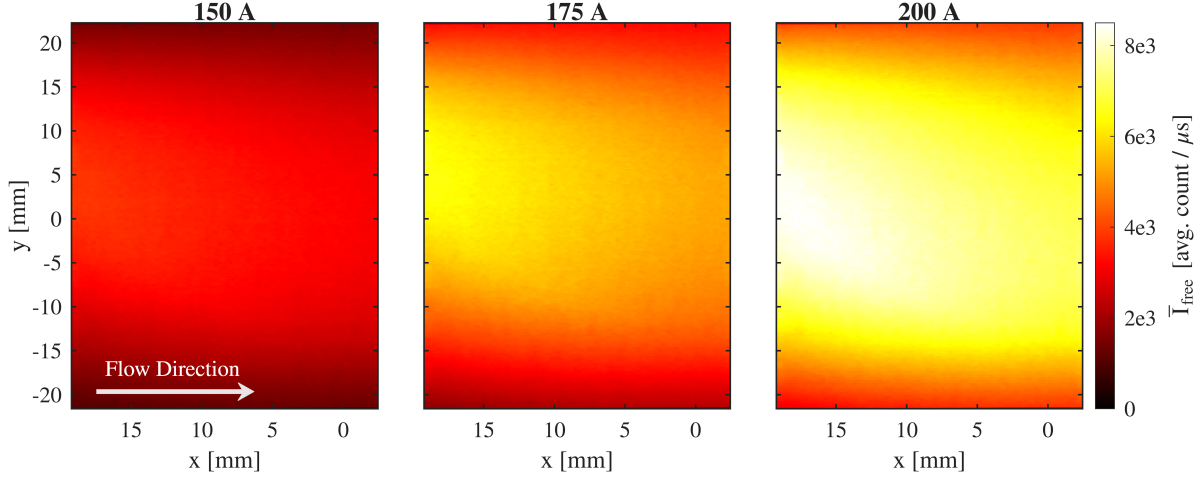


Fig. 5 Time-averaged emission images for freestream and shock-layer measurements at arc-currents of 150, 175, and 200 A.

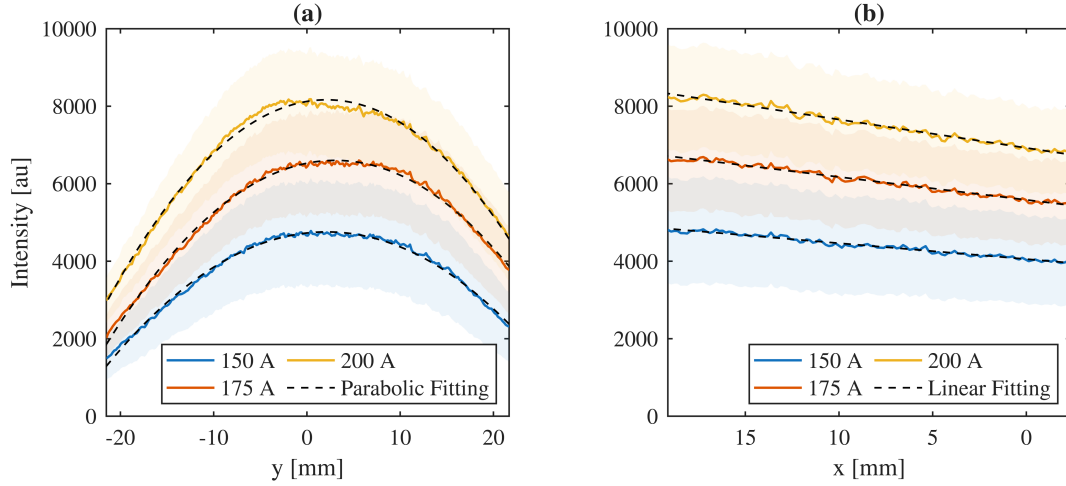


Fig. 6 Time-averaged freestream intensity distributions: (a) radial profiles at $x = 15$ mm, and (b) axial profiles along the centerline. Shaded regions denote 1- σ variability.

The time-averaged radial profiles of the oxygen emission at $x = 15$ mm are shown in Fig. 6a. These profiles are accurately modeled using parabolic fittings, each exhibiting a minor shift from the nominal centerline. The complete widths of these parabolic emission profiles measure between 55 and 60 mm, which is slightly less than the nozzle exit diameter of 63.5 mm. This profile likely reflects the hot core region exiting the nozzle, where both the temperature and enthalpy are highest, and the populations of excited-state atomic oxygen are at their maximum. Considering that this second-order polynomial distribution continues downstream, estimates for the core flow diameter and center position are presented in Fig. 7.

Figure 7a shows a gradual core diameter expansion with downstream distance, increasing by approximately 5–7 mm over a 21.5 mm axial span. This trend is consistent with a slightly underexpanded jet at the nozzle exit, in agreement with prior investigations [10, 18]. In this consideration, the gas would reduce in pressure and temperature as it expands radially, leading to a decrease in the excited-state atomic oxygen population and corresponding emission intensity. This occurs through a reduction in the total number density of the gas, as well as possible electronic relaxations and recombination of atomic oxygen atoms. This phenomenon would explain the observed linear decrease in the centerline

intensity with axial distance, as shown in Fig. 6b, where the decrease in intensity occurs at nearly the same rate for all arc-current settings.

For all conditions, the center position of the core flow (Fig. 7b) also varies with axial location, beginning near $y = 3\text{--}4\text{ mm}$ upstream and gradually approaching the nominal centerline downstream. This slight offset could be an artifact of the camera alignment or a small asymmetry between the nozzle exit and the test sample. Further investigation is required for a definite conclusion.

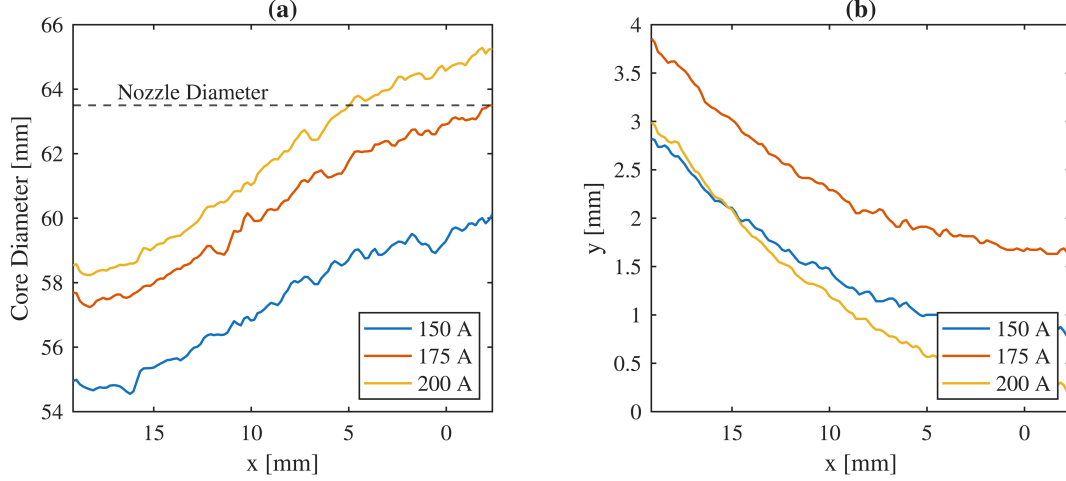


Fig. 7 Freestream flow parameters derived from parabolic fits: (a) core flow diameter versus axial location and (b) distribution center position versus axial location for each arc-current condition.

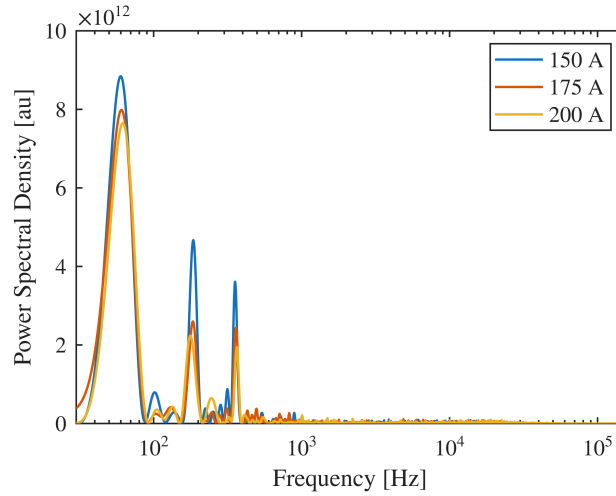


Fig. 8 Frequency spectra of integrated freestream emission intensity.

To assess the temporal stability of the freestream emission and to understand the propagation of fluctuations into the shock-layer, a Fast Fourier Transform (FFT) was implemented on the integrated intensity signal over the entire field of view for each arc-current condition (Fig. 8). This approach captures the overall frequency content of the freestream emission between 30 and 150,000 Hz, with a frequency resolution of 30 Hz. These frequency spectra are dominated by prominent frequencies at 60, 180, and 360 Hz. These frequencies are consistent with the first, third, and sixth harmonics of a fundamental 60 Hz frequency, suggesting their propagation from an upstream occurrence.

Between the three arc-current conditions, the relative amplitudes of these frequencies remain fairly consistent, with only modest variations in the magnitudes of the three notable frequencies at 150 A compared to the higher arc-currents. This suggests that low frequency emission fluctuations in the freestream are largely unaffected by changes in arc-current. These observed freestream fluctuations are in agreement with those presented in the concurrent investigation by Schwartz

et al. [15], which were extracted from a separate tunnel operation with an identical working gas composition and an arc-current of 200 A.

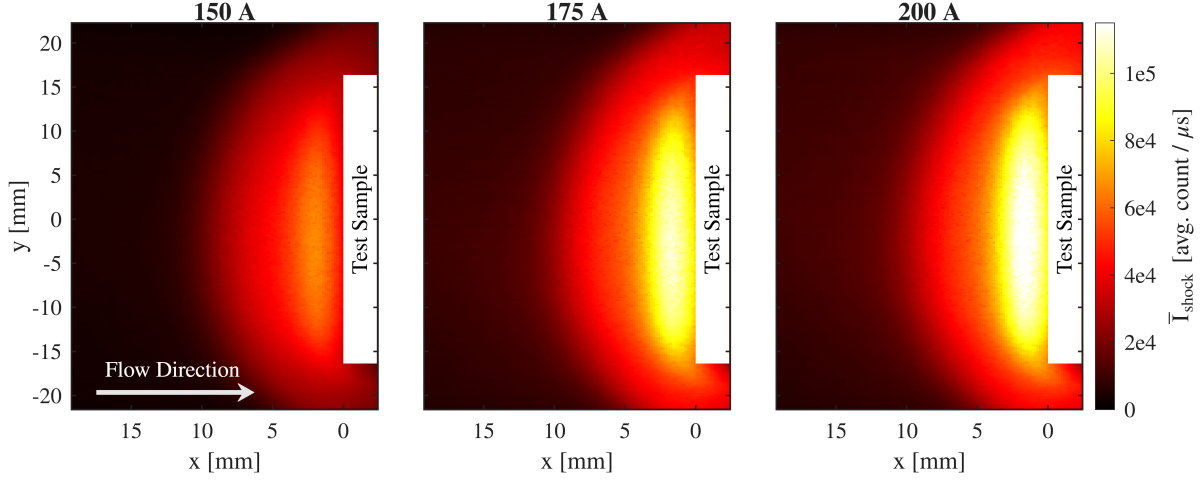


Fig. 9 Time-averaged emission images for shock-layer measurements at arc-currents of 150, 175, and 200 A.

B. Shock-Layer Measurements

Images acquired upon the insertion of the test sample (Fig. 9) show a marked increase in emission intensity immediately downstream of the bow shock, corresponding to the steep rise in pressure and temperature across the shock, which produces an increase in excitation and dissociation. As a result of the reduced exposure time utilized during these acquisitions, all measured emission intensities upstream of the shock are relatively negligible, as their signal intensities are substantially lower than those measured in the shock-layer. To observe the spatial variation in shock-layer emission, Fig. 10 presents the time-averaged intensity along the centerline ($y = 0$ mm) for the three arc-current conditions.

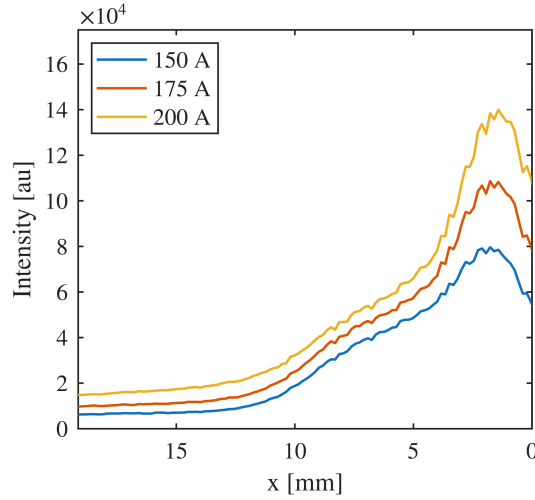


Fig. 10 Time-averaged shock-layer centerline intensity distributions for arc-currents of 150, 175, and 200 A.

Figure 10 shows that, for the three arc-current conditions, emission intensity rises with a consistent trend along the axial direction. The only major deviations in this trend occur closer to the front face of the cylindrical sample ($x < 4$ mm), where the intensity sharply increases to a peak value before rapidly decreasing near the surface. This peak intensity location—displaced from the front face of the cylinder—is likely associated with the heat transfer between the flow and the SiC surface, which would reduce the flow temperature and, therefore, the emission intensity as it approaches the stagnation region.

1. Standoff Distance Tracking

To evaluate the location of the initial intensity increase near the shock-front and the maximum intensity near the stagnation region, line tracking was applied over the 10,000 consecutive frames for each condition. With the high acquisition rate of 300 kHz, fluctuations in these standoff distances are also effectively measured between 30 and 150,000 Hz. It is considered that these fluctuations are primarily driven by dynamic changes in the flowfield and thermal environment, which would essentially propagate from the upstream flow.

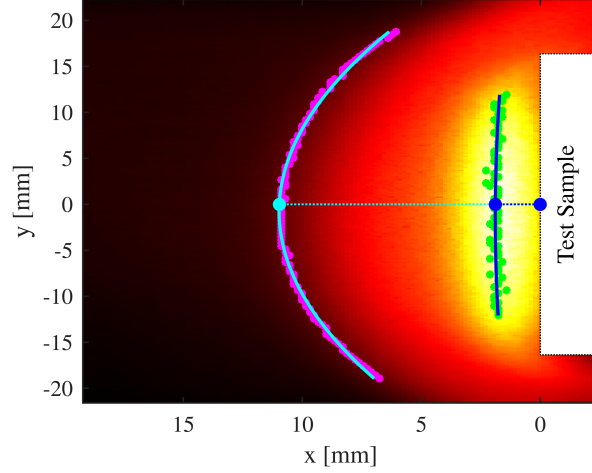


Fig. 11 Example of line tracking used to measure shock-front and peak emission standoff distances.

Figure 11 illustrates the tracking method, where an adaptive parabolic fit is applied to x - y coordinates that meet the prescribed intensity threshold. The shock-front location is defined as the first x position, in the streamwise direction, where the intensity exceeds twice the maximum time-averaged freestream intensity for each arc-current condition. The location of peak emission is defined as the x position of the maximum intensity. The adaptive parabolic fits are used as a criterion to reject outliers and reduce noise in the measurement.

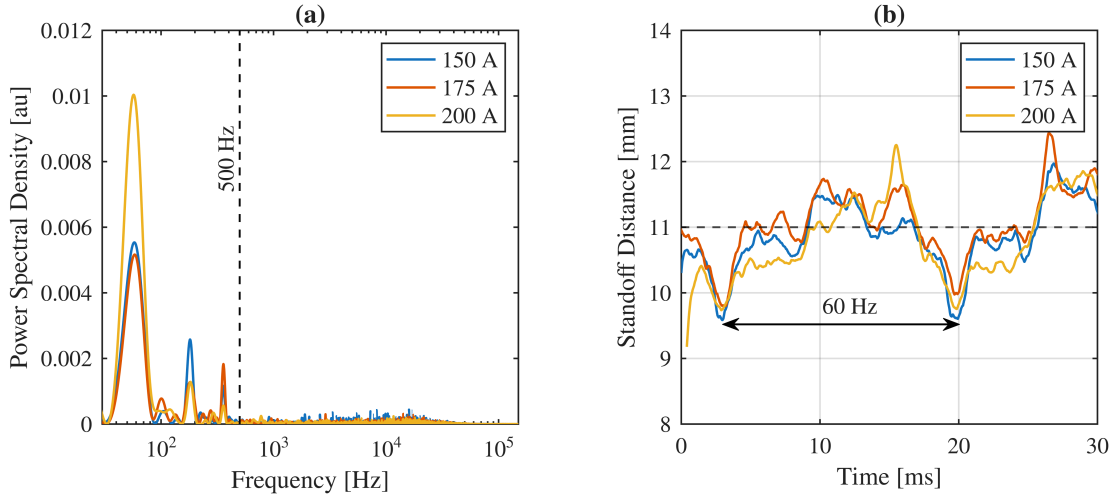


Fig. 12 Shock-front standoff distance: (a) frequency spectrum and (b) filtered time-domain signal.

The results from the shock-front standoff distance analysis are shown in Fig. 12. Fluctuations in this standoff distance were analyzed using a Fast Fourier Transform (FFT) over 30–150,000 Hz (Fig. 12a), revealing the same fundamental frequency of 60 Hz observed in the freestream, as well as its harmonics at 180 and 360 Hz. To assess the impact of these frequencies in the time-domain, zero-phase low-pass filtering was applied at 500 Hz and is displayed in Fig. 12b. After applying a small time offset to align the 60 Hz oscillations, consistent behavior is observed between all three

arc-current conditions. Each of the conditions exhibits an average standoff distance of approximately 11 mm, with notable fluctuations exceeding 1 mm in magnitude.

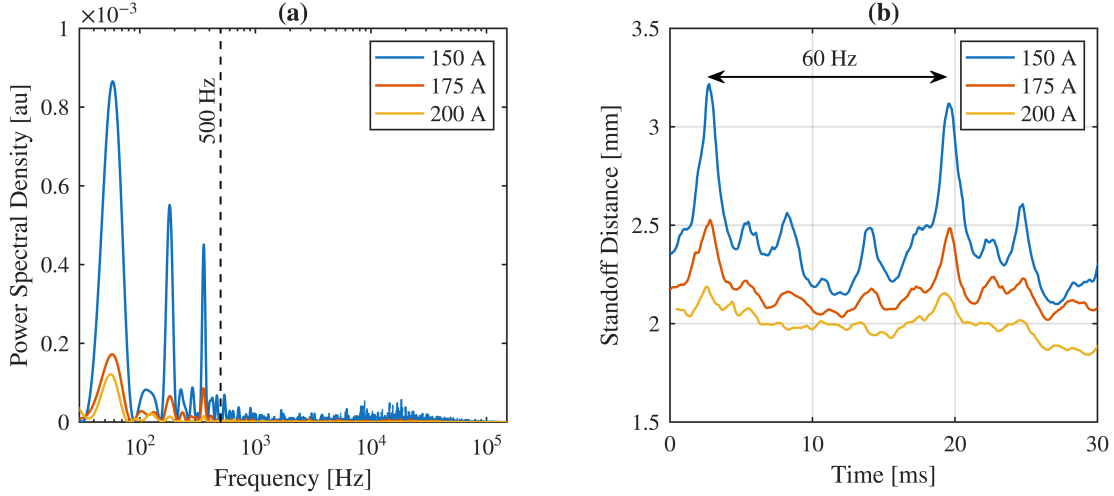


Fig. 13 Standoff distance of the maximum intensity location: (a) frequency spectrum and (b) filtered time-domain signal.

Downstream of the detected shock-front location and close to the surface of the test sample, the standoff distance of the peak emission is monitored and reported in Fig. 13. The FFT results (Fig. 13a) again revealed the dominant frequencies of 60, 180, and 360 Hz; however, their relative magnitudes varied significantly with arc-current, unlike the shock-front results. For the 150 A case, the amplitudes of the three frequencies were nearly an order of magnitude larger than those at the higher arc-currents. This is portrayed by the significant fluctuations in the time domain (Fig. 13b), where fluctuations greater than 1 mm are observed over the 33 ms duration. At higher currents, however, the location of peak emission began to stabilize and approach closer to the front face of the cylinder. This is observed in Fig. 13b, where the mean standoff was approximately 2.4, 2.2, and 2.0 mm at 150, 175, and 200 A, respectively.

IV. Conclusion

Spatially-resolved atomic oxygen emission at 777 nm was successfully captured in the freestream and shock-layer of the Mach 5 HyMETS arcjet tunnel using high-speed imaging at 300 kHz. Evaluating this emission at three different arc-currents (150, 175, and 200 A) revealed a positive correlation between arc-current and emission intensity, consistent with expectations. The freestream emission was observed to have a parabolic radial distribution, with an expanding core diameter that can range from 55 to 65 mm over a 21.5 mm axial distance. This core diameter expansion is consistent with a slightly underexpanded jet at the nozzle exit, in agreement with prior investigations [10, 18]. Additionally, the diameter of the core flow was found to increase with arc-current. Evaluating temporal fluctuations in the freestream emission intensity revealed dominant frequencies at 60, 180, and 360 Hz, which were independent of arc-current. These low-frequency oscillations are likely associated with some upstream facility phenomena, such as fluctuations in the arc attachment or mass flow rate, which subsequently propagate through the freestream.

Following the insertion of a SiC test sample into the flow, a distinct increase in emission intensity was observed at locations just beyond the shock-front, where the population of excited-state atomic oxygen is expected to steeply increase. Downstream of the shock-front, the emission intensity quickly rises to a maximum before decreasing towards the front face of the cylindrical sample.

Using a prescribed intensity threshold, the standoff distance of the shock-front was estimated to be 11 mm for all current conditions, with maximum fluctuations of approximately ± 1 mm at low-frequency (< 500 Hz). Performing a FFT of the fluctuations over the 33 ms acquisition period revealed dominant frequencies of 60, 180, and 360 Hz, consistent with those observed in the freestream emission, suggesting that low-frequency fluctuations in the freestream propagate through the shock-front and into the shock-layer, as previously reported by Schwartz et al. [15].

The location of peak emission was found to be located 2.4 mm, 2.2 mm, and 2.0 mm from the front of the sample for arc-currents of 150, 175, and 200 A, respectively. Fluctuations in the peak emission location were also observed to have

the same dominant frequencies of 60, 180, and 360 Hz. However, in contrast to the shock-front and freestream, these fluctuations were found to be dependent on arc-current, with maximum deviations occurring at 150 A of approximately 1.0 mm, decreasing to 0.1 mm at 200 A.

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