

Emission Spectroscopy Characterization of Electrodes Species in the Freestream Flow at the NASA Ames Miniature Arc Jet II Facility

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Abstract

The second generation miniature Arc Jet (mARC II) is a subscale arc jet at NASA Ames Research Center that is undergoing initial characterization. During its operation, the electrodes used to produce continuous plasma flows deteriorate and the flow purity decreases. The present work reports the use of optical emission spectroscopy as a characterization tool for impurities in the plasma flow. The discussion is focused on the interpretation of spectroscopic measurements and their evolution under different testing conditions. Special emphasis is given to copper and silver, the main atomic elements of the electrodes. The highest rate of anode deterioration is found to occur during the arc jet ignition, while cathode deterioration is constant throughout the entire run. Based on the experimental spectra, a preliminary numerical characterization of the plasma temperature, enthalpy and number density is conducted.

Keywords: Arc jet, emission spectroscopy, electrodes deterioration, numerical temperature

1. Introduction

The atmospheric entry of a spacecraft is a challenging engineering endeavor. One crucial aspect is the design and implementation of the thermal protection system that protects the spacecraft and its payload from the severe thermal and mechanical loads encountered during planetary entry. Due to the large cost of missions and the difficulty of performing accurate measurements in flight, ground testing facilities have been developed to study different aspects of atmospheric entry flows.

The Ames Arc Jet Complex at NASA Ames Research Center operates four different high-power arc plasma facilities¹ and is currently undergoing integrated systems testing for the second generation miniature Arc Jet (mARC II).² In these types of

facilities, gases are heated to very high temperatures by a continuous electrical arc between two sets of electrodes and then expanded through a nozzle, producing continuous flows of high speed plasma for testing and certification of high temperature materials. However, during operation, the electrodes deteriorate and therefore the flow purity decreases. Even though it is not expected that over a few tests in a row the degradation to be particularly significant, in a long period of test time this deterioration will eventually cause failure of the electrodes. Thereafter this phenomena must be assessed to avoid malfunction of the facility. Additionally, as the elements of the electrodes are already in the flow, they can be used as tracer elements to determine plasma properties without disturbing the flow.

Electrode erosion and degradation has been previously studied. In 1985, a 573 hour long-duration JPL test failed prematurely due to an electrical short between the cathode and the anode, uncovering numerous problems related to arc jet electrodes erosion, cathode filament growth, and arc jet ignition reliability.³ This prompted a more detailed series of mea-

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measurements by Deininger and Pivrotto⁴ and later by Harris⁵ measuring electrode erosion rates, by weighing them after each test, for a number of different cathode geometries and under several testing conditions. To investigate arc-cathode interaction, Zhou and Heberlein⁶ carried out a combination of diagnostic techniques using cathodes of various shapes and sizes. A telemicroscope/high-speed vision system was used to observe the cathode behavior, and an optical multichannel analyzer-spectrometer system was set up to quantitatively measure the radiation from the cathode, distribution of the cathode temperature, electron temperature distributions in the plasma in front of the cathode and electron number densities. Emission spectroscopy was performed in the cathode region to understand the cathode erosion mechanism.

Flow freestream characterization using optical emission spectroscopy has also been carried out before. Winter et al.^{7–10} conducted several works in the plenum and in the free jet of the 60 MW Interaction Heating Facility (IHF) at NASA Ames Research Center to infer flow properties at different heater conditions, to assess the thermodynamic state of the flow, to characterize the facility, and to provide validation for CFD simulations. Other examples of emission spectroscopy measurements for assessment of the thermodynamic state of the freestream plasma include work from Cipullo et al.¹¹ that carried out their research at the VKI-Plasmatron, de Filippis et al.¹² at the CIRA plasma wind tunnel, and Fujita et al.¹³ at JAXA 110-kW-class inductively coupled plasma wind tunnel.

However, no work was found about emission spectroscopy on the flow freestream to evaluate erosion of the electrodes. To better understand and predict the degradation of electrodes with time and how they affect the plasma flow, optical emission spectroscopy measurements in the freestream are performed in this study. Time-varying plasma flow emission spectra, measured at the NASA Ames miniature Arc Jet II (mARC II) are presented. The discussion is focused on the interpretation of spectroscopic measurements performed close to the nozzle exit, and their evolution with different testing conditions. Special emphasis is given to the main atomic elements of the electrodes, copper and silver. A preliminary comparison between the measured spectra and results obtained from a computational radiative model provides an estimate of equilibrium temperature and species number densities. Based on the numerical temperatures, flow

enthalpy and efficiency are also estimated.

The specific objectives of the present work are:

1. To obtain calibrated emission spectra of the freestream plasma and characterize its composition;
2. To analyse the appearance of electrode species in the flow and their evolution over time;
3. To evaluate the flow temperature and species number densities using NEQAIR numerical software;
4. To analyse enthalpy and efficiency based on the numerical results.

2. Experimental procedure

2.1. The mARC II facility

The NASA Ames second generation miniature Arc Jet is a subscale arc jet that reproduces the aerodynamic heating experienced during high speed and high altitude flights. This arc jet is intended to serve as a test bed for low cost testing and as a pre-screening tool for innovative arc jet modifications, instrumentation development, verification of numerical models, and for testing of novel thermal protection system materials in advance of testing in the large arc jets at NASA Ames.¹⁴

The mARC II employs a Hypertherm MAX200 plasma cutting system, a 30 kW power supply system which establishes a high current regulated arc.² The DC arc jet consists of a water-cooled hafnium silver cathode (Hypertherm part 220083), a water-cooled copper (oxygen free high conductivity copper ASME SB-187) anode, a constrictor channel, and a converging-diverging nozzle. The arc extends from the cathode tip, through a constricted arc column channel, and attaches to the anode. The resulting constricted arc heats and ionizes the air within the column.¹⁵ After being directed through the arc column, the hot air is then accelerated out through the convergent-divergent nozzle (18.67 mm exit diameter), forming a plasma jet. Each component is insulated from the adjacent component by a boron nitride disk. A schematic of the cross section of the facility is shown in Fig. 1.

The experiments are performed in a nearly 1 m diameter cylindrical vacuum chamber, maintained at low pressure with an Edwards E2M275 rotary vacuum pump,² capable of providing base pressures of 50 Pa. The facility is water cooled by a Goulds Model e-SV pump, capable of flowing water at 7.9 kg/s.¹⁵

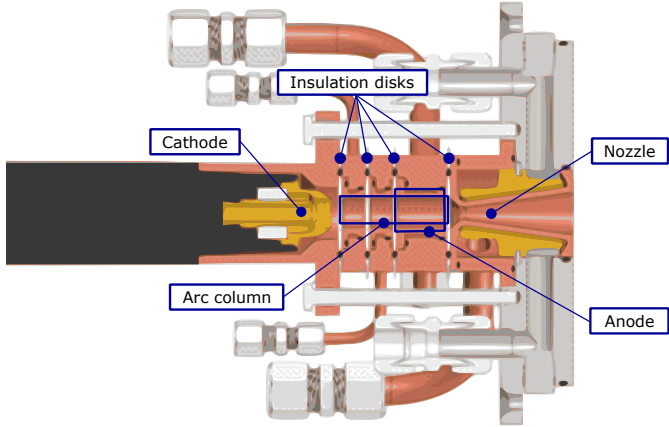


Figure 1: Cross sectional schematic of the mARC II arc heater [Credit: D. Philippidis²]

The mARC II data acquisition system is based on National Instruments CompactDAQ hardware. The gas mass flux is measured by a Sage SIP-030-DC24-AIR, the arc current is measured using a current monitor (Ohio Semitronics CTL-401S/300) paired with a signal conditioner (Ohio Semitronics CTA 201H), the arc voltage is measured by an Ohio Semitronics VT7-007E-11-TP transducer, and the column pressure is measured through a small hole in one of the constricted disks by a Setra Model 730 attached to a pressure tap via a nonconductive nylon tube. The tests are recorded using a GoPro Hero 4 and a Nikon D750 digital camera. More details about the data acquisition system can be found in MacDonald et al.¹⁶

2.2. Optical setup and emission spectroscopy

Radiance measurements of the plasma flow are obtained with the SpectraSuite software through an OceanOptics STS-VIS-L-100-400-1 spectrometer with a wavelength range between 350-800 nm and a 1-second integration time. The optical diagnostic bench (Fig. 2) consists of an OceanOptics ZWF-100406 VIS/NIR fiber optic (100 μm core diameter) and an optical coupler (Thorlabs PAF-SMA-5-B FiberPort) installed on an optical table. The coupler has an effective focal length of 4.6 mm and is used to collect radiation from the plasma jet into the fiber. The optical path is aligned perpendicular to the centerline of the chamber and through the center of the jet, 25 mm from the nozzle exit, with a beam diameter of 15 mm and a focal distance of 365 mm.

Alignment of the collection optics is done with a white light source (Fiber-Lite MH-100 Metal Halide Illuminator) which is reverse fed into the optical system, illuminating the field of view of the spectrometer (Fig. 3).

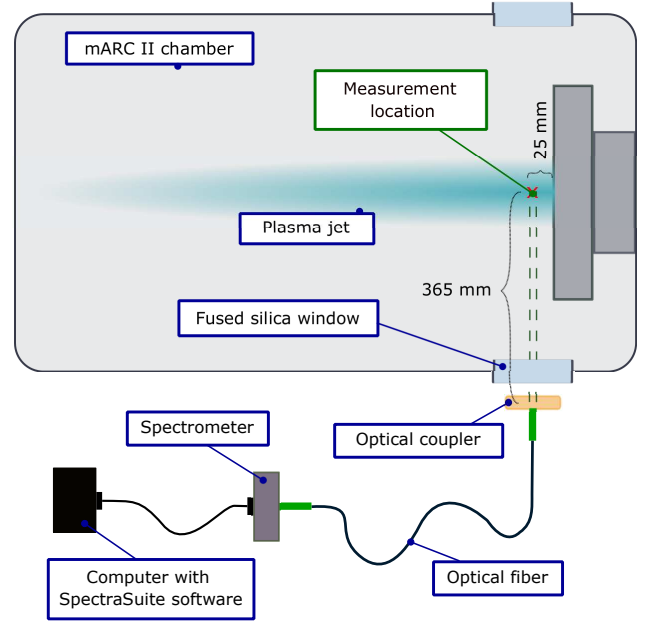


Figure 2: Experimental setup with measurement location (top view)

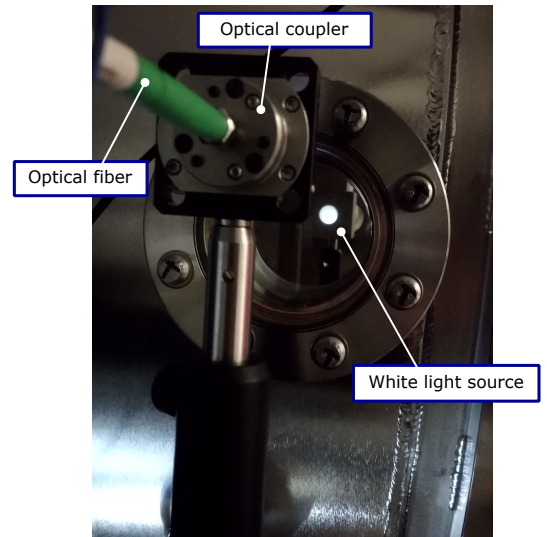


Figure 3: Alignment of the collection optics

2.3. Spectrometer calibration

Calibration of the spectral irradiance is done after each test using a Gigahertz-Optik DN-0102-2 integrating sphere, with a wavelength range between 300 and 1675 nm, placed in the mARC vacuum chamber at the same location where measurements are taken during a run. This procedure replicates the actual distance between the coupler and the center of the flow, the window interference, and similar lighting conditions.

For the arc jet measurements, the detector integration time is set sufficiently high (1 s) to acquire

enough light to keep the signal to noise ratio reasonable. However, the output intensity of the calibration source is higher than the measured arc jet intensities. To avoid detector saturation, the integration times for the calibration measurements are lower. As these integration times differ, the detector linearity is assessed as a function of integration time. By measuring the detector response to the calibration source at 20 unsaturated integration times, it is determined that the detector response is nonlinear. Thus, this is taken into account when extrapolating the curve for 1 s (Fig. 4), which is used posteriorly to calibrate the arc jet measurements. As seen in Fig. 4, the lowest wavelength region is not well extrapolated. However, the measured transmission below 490 nm is quite low due to the characteristics of the optical fiber used in these experiments. Therefore, only spectral measurements above that wavelength are considered.

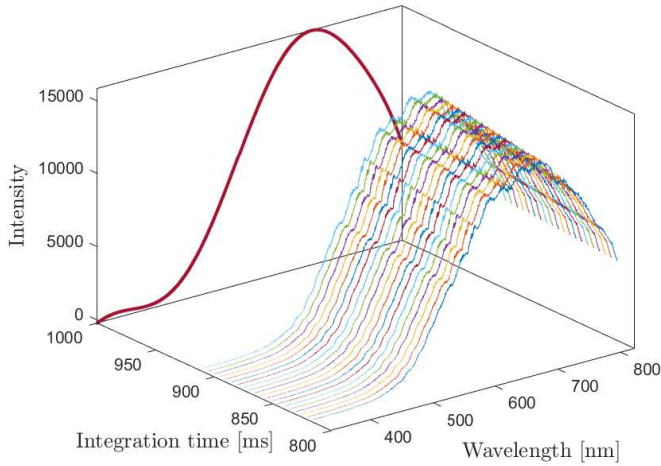
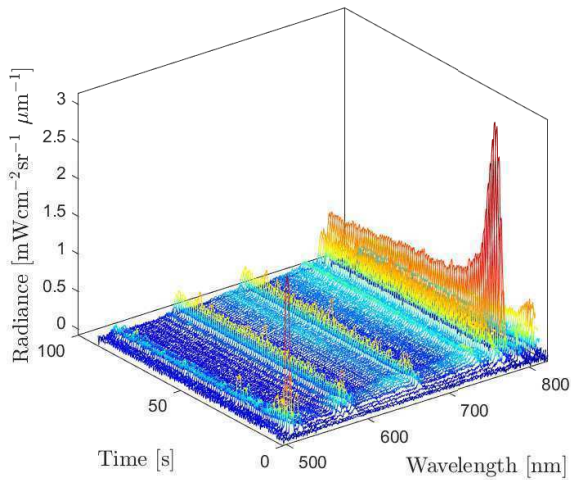
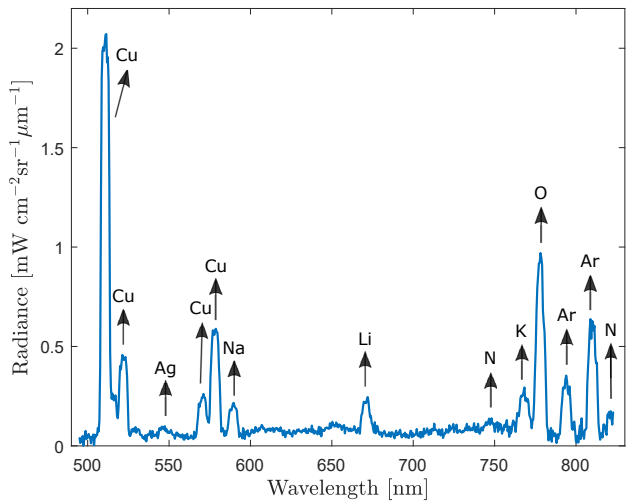


Figure 4: Extrapolated calibration curve



(a) Entire test time



(b) Time instant $t = 4.1$ s

Figure 5: Calibrated emission spectra (100 A, 0.5 g/s air)

3. Results

Testing conditions for the mARC II are set by the desired arc current and gas mass flux. To explore the changes on the atomic composition of the plasma, initial testing is carried out over a range of arc currents (40, 100, 160 and 200 A) and gas mass flows (0.25, 0.5 and 0.8 g/s). These arc currents cover the entire facility range; while the mass fluxes are fairly centered within the interval of values that allow maintaining an arc at all of the current conditions. Only at the minimum current and highest mass flux (40 A, 0.8 g/s), the facility is not able to maintain the arc. The test gas for all of these experimental conditions is bottle air (N_2 and O_2 mixture¹⁷). Each run is set to a duration of 60 seconds, which begins once steady state conditions are reached after the startup process.

During the entire experimental run, absolute magnitudes of intensity are measured as function of the wavelength. Simultaneously, the data acquisition system is collecting arc current, arc voltage, gas mass flux, column pressure and chamber pressure, and temperatures of the chamber and vacuum pump. Subsequent to the run, the measured intensity is converted to spectral radiance using the calibration from the integrating sphere.

Figures 5a and 5b present, respectively, the typical calibrated emission spectra acquired during the entire test time and a single time instant of that test. The respective atomic elements are identified over the corresponding spectral line (Fig. 5b), in the visible wavelength region between 490 and 830 nm. Prominent emission lines are identified using the NIST Atomic Spectra Database.¹⁸ For all the runs, there is

a constant presence of impurities such as copper and silver (main elements of the electrodes), sodium, lithium and potassium. Argon is also present in the flow and, under certain conditions, atomic oxygen and atomic nitrogen become prominent. In fact, the most prominent peak in Fig. 5a at 777 nm corresponds to atomic oxygen.

The sodium emission line at 589 nm is attributed to the Krytox grease,¹⁹ which has a sodium nitrite anticorrosion additive that is used to lubricate the o-rings in the arc column. Lithium (670 nm) and potassium (769 nm) origins are unknown. However, these elements, as well as sodium, were previously identified during a past experimental campaign at the first generation miniature arc jet.¹⁵ In that paper, the high levels of potassium emission were attributed to a paint used in the samples, which contained potassium silicate, but also considered inherently present in the sample materials. The sodium and lithium emission lines were also attributed to impurities within the sample material. As no sample materials have been tested in the mARC II to date, the impurities are inherent to the facility or the flow itself. Spectra obtained at the NASA Ames EAST shock tube have also shown contamination of sodium.^{20,21} Its presence was associated with the natural sodium chloride in the atmosphere, which was adsorbed on the wall of the driven tube and dissociated to sodium atoms when the tube was heated.

3.1. Copper and silver irradiance

The presence of copper and silver in the flow represents degradation of, respectively, the anode and the cathode. The presence of copper in the flow is in fact visible during the test, as the flow presents an intense green color (Fig. 6), a characteristic color of copper.

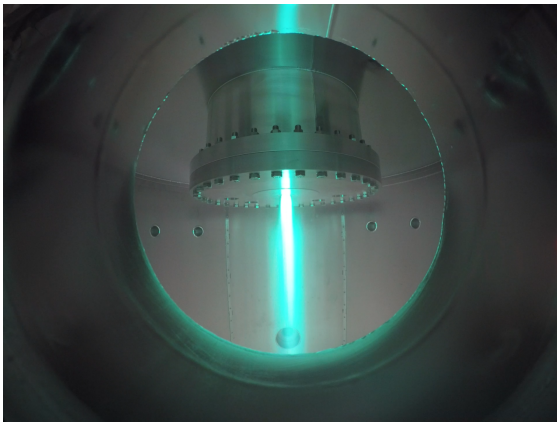


Figure 6: Copper peak at $t = 3.1$ s (100 A, 0.5 g/s air)

Copper emission lines are isolated and well defined at wavelengths of 510, 521, 570 and 578 nm. Figure 7 presents the irradiance of these four copper lines present in the wavelength region measured and their evolution over time. The irradiance of a spectral line is computed by integrating the respective line over the wavelength, for each of the time frames recorded. This wavelength region is chosen by analyzing the minimum and maximum wavelengths in which the spectral radiance is substantially different than its neighbor point (where the integration would be approximately zero). As the four spectral lines always present a similar behavior over time, only the line with highest intensity (maximum intensity at a wavelength of 510 nm) will be shown hereafter.

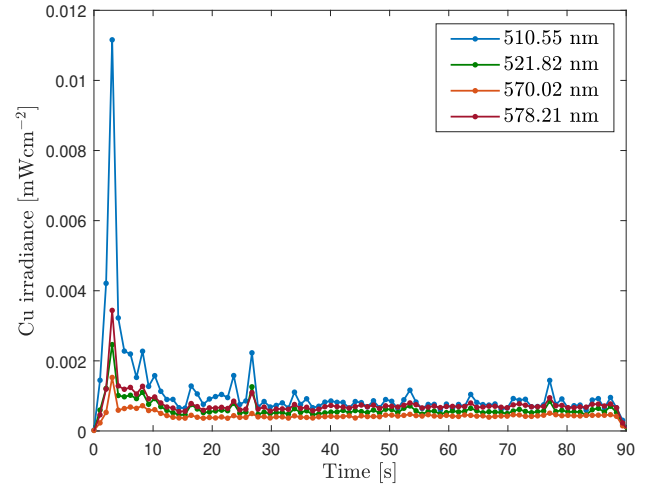


Figure 7: Copper spectral lines (100 A, 0.5 g/s air)

The plots in Fig. 8 show the irradiance of copper overlapped with the arc current measured over time for each set arc current. Only the initial 35 s are shown as this period contains the initial start up and the beginning of steady state. Some points are removed from this figure, as they are affected by a phenomenon that is not related to copper emission. These points correspond to the instant when a flash occurs (the appearance of flashes is discussed in detail in Section 3.3) and a continuum spectrum appears in addition to the atomic spectra normally observed, increasing the irradiance at the wavelengths where copper emission is being measured at that instant.

Although the measured current for the 40 A cases matches the set point, the measured current at high powers falls below the set point. According to MacDonald et al.¹⁶ and Haw,²² this deviation could be due to an inherent characteristic of the power supply, non-linear response of the current monitor, or a

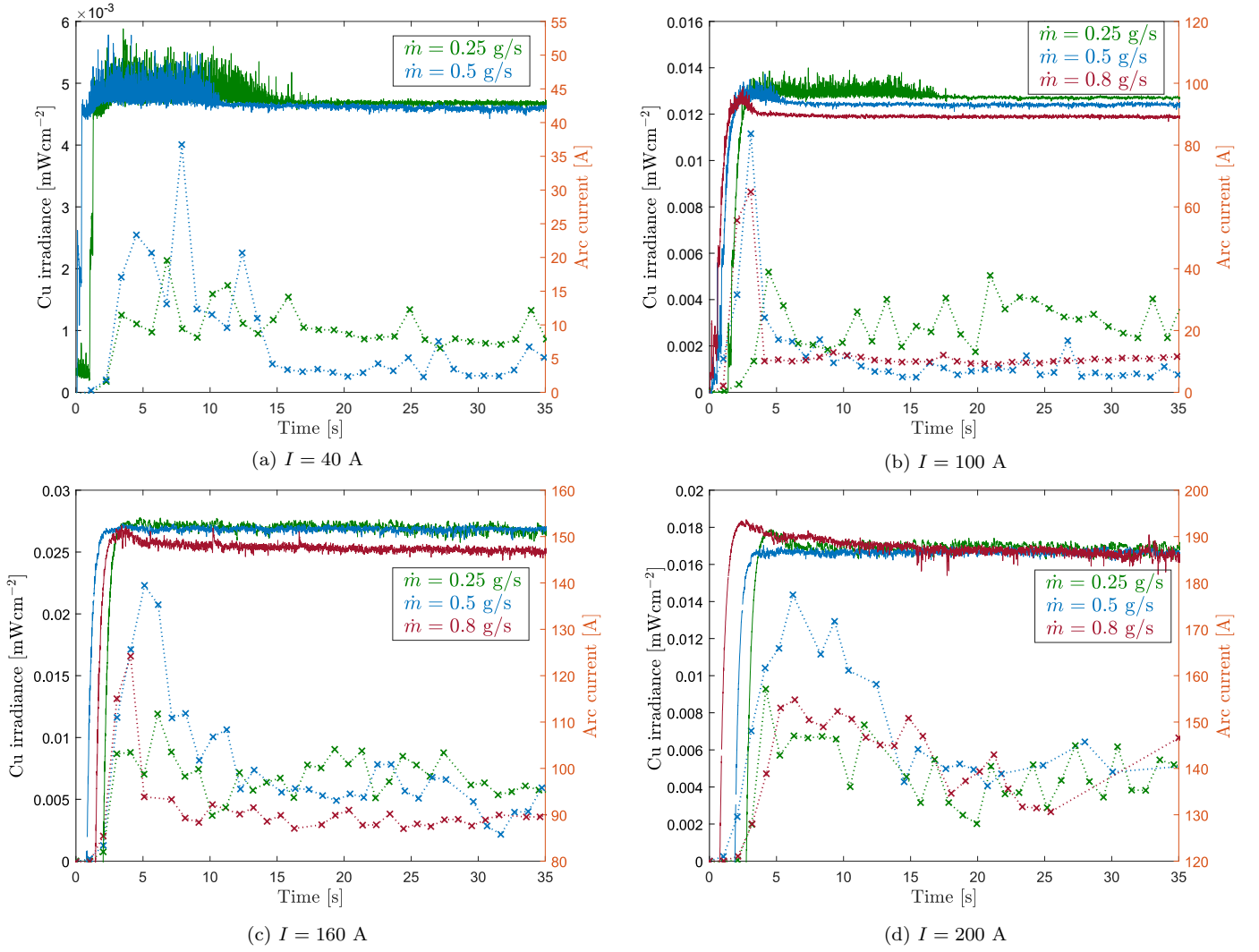


Figure 8: Copper irradiance and temporal evolution of the arc current for each run - dotted lines: copper irradiance (left axis); solid lines: measured arc current (right axis); green, blue and red lines: 0.25 g/s, 0.5 g/s and 0.8 g/s, respectively

resistive path to ground which does not pass through the current monitor.

The highest rate of anode deterioration typically occurs during the arc jet startup. This high degree of deterioration is caused by the highly unstable arc current during this phase. During this state for a certain mass flux, when increasing the arc current the irradiance of copper typically increases. An exception occurs for 200 A and 0.8 g/s, as the mass flux startup process was different for that particular run. The temporal evolution of the measured mass flux for a set condition of 0.8 g/s for each of the arc currents is represented in solid lines in Fig. 9. While in the other tests the set mass flux was programmed before the test and then the valve opened all at once letting the system reach the set value (which causes the initial mass flux overshoot), in this case the mass flux was set for a smaller value and then slowly increased

after the beginning of the test until reaching the desired value (eliminating the initial mass flux overshoot). Comparing the dashed lines in Fig. 9 during startup copper irradiance for 200 A is smaller than for 160 A, yielding a smaller deterioration of copper with this method. For future runs, the authors recommend starting the arc at low mass flux and gradually increasing to the desired set point, as this has the potential to extend the anode lifetime. A study of anode mass loss during startup is, additionally, recommended to quantitatively determine the influence of startup procedure on anode health and performance.

Once the current stabilizes, the copper deterioration tends to stabilize too. During steady state, for a constant arc current, the irradiance of copper decreases with the increase of the mass flux; and when increasing the arc current, for a constant mass flux, this deterioration increases too.

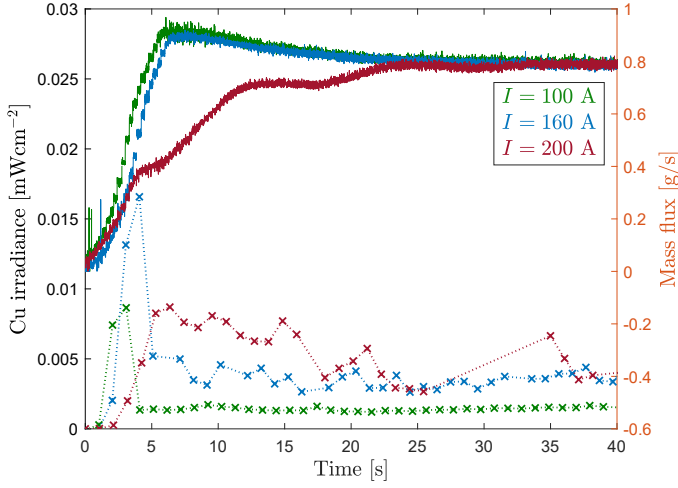
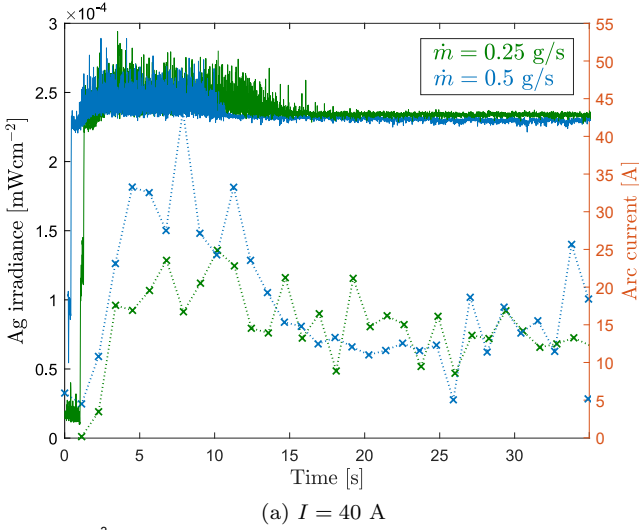
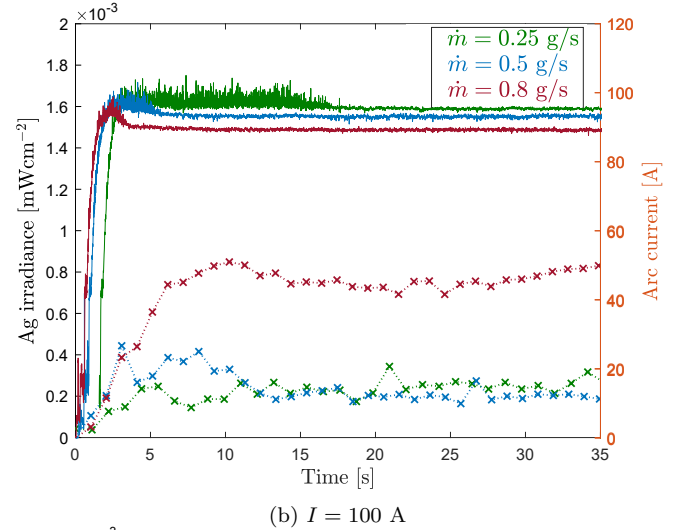


Figure 9: Copper irradiance and temporal evolution of the mass flux for set $\dot{m} = 0.8$ g/s - dotted lines: copper irradiance (left axis); solid lines: measured mass flux (right axis); green, blue and red lines: 100 A, 160 A and 200 A, respectively

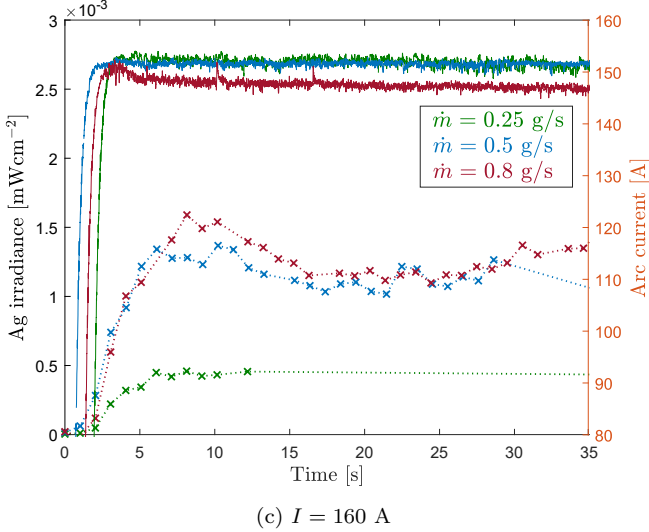
The silver emission line (546 nm) is always very faint and relatively constant throughout any given run (Figs. 10). For higher arc currents, its average deterioration is higher. Regardless of the smaller silver irradiance when compared with copper (which may be associated with the line strength of each atom), the anode is the one designed for extended use.¹⁶ The cathode is a consumable part of the Hypertherm system that is designed to be replaced relatively frequently.¹⁶ According to Nawaz et al.,¹⁴ the cathode should be replaced after approximately 90 minutes of accumulated run time. MacDonald et al.¹⁶ presented a relation between the measured current and the accumulated run time on cathode for the initial runs on the mARC II facility that yield some apparent trends. For the 40 A, 100 A and 160 A settings a slight decrease in measured current is observed as accumulated cathode time increases; while for the 200 A settings, the measured current remains



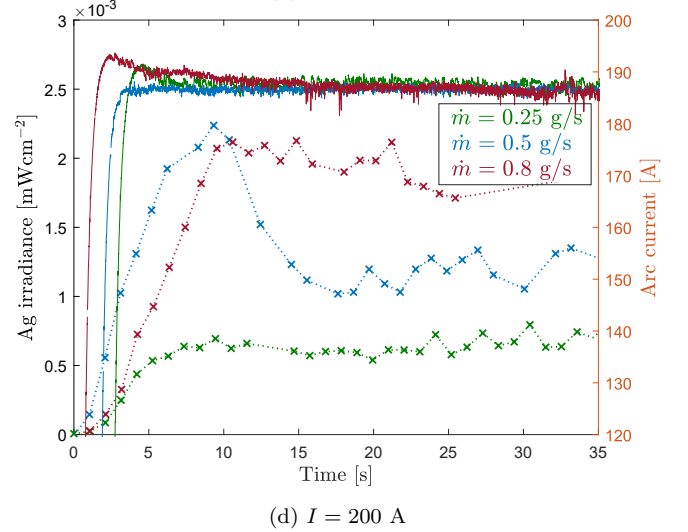
(a) $I = 40$ A



(b) $I = 100$ A



(c) $I = 160$ A



(d) $I = 200$ A

Figure 10: Silver irradiance and temporal evolution of the arc current for each run - dotted lines: silver irradiance (left axis); solid lines: measured arc current (right axis); green, blue and red lines: 0.25 g/s, 0.5 g/s and 0.8 g/s respectively

relatively constant. However, the data presented by MacDonald et al. and in this work are initial results, and additional data is necessary to come to a definite conclusion about the deterioration of the electrodes and an eventual relation with the arc current.

3.2. Oxygen and nitrogen dissociation

Another phenomenon verified in the spectral measurements is the appearance of atomic oxygen, caused by dissociation of the diatomic oxygen present in the test gas. The oxygen feature is isolated and the intensity of the unresolved triplet at 777 nm is by far the highest in the spectrum.

The plots in Fig. 11 show the atomic oxygen irradiance and the corresponding mass flux acquired during the test. Under certain testing conditions (40 A, all mass fluxes; 100 A, 0.25 g/s; and 160 A, 0.25 g/s), the presence of measurable atomic oxygen is almost

nonexistent. For the other conditions, the greatest amount of atomic oxygen occurs during the initial overshoot, before the mass flux has settled to the set value. Then, typically, the atomic oxygen irradiance stabilizes with the stabilization of the mass flux. As the set mass flux and arc current increases, the maximum irradiance of atomic oxygen also increases. The only exception occurs for 200 A and 0.8 g/s air due to the different mass flux startup process used for that particular run, as previously explained. Also for this case, the atomic oxygen overshoot is smaller than for 160 A, 0.8 g/s (differing from the trend).

Figures 12 show that atomic nitrogen becomes prominent for 0.5 g/s and 0.8 g/s and arc currents equal to or greater than 100 A, indicating measurable dissociation of diatomic nitrogen. The atomic nitrogen unresolved doublet at 821 nm is also very distinct, and its highest irradiance also occurs during the mass

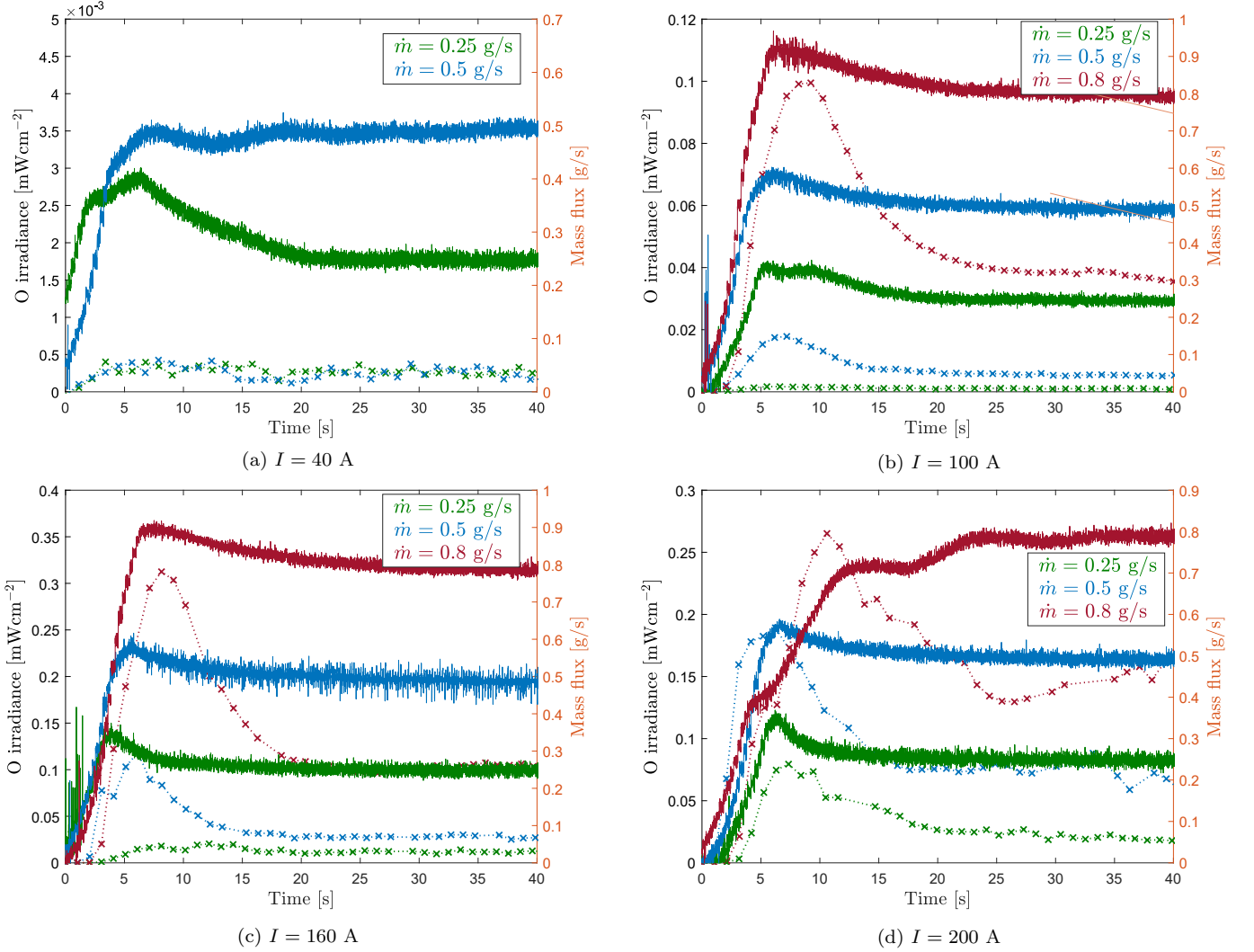
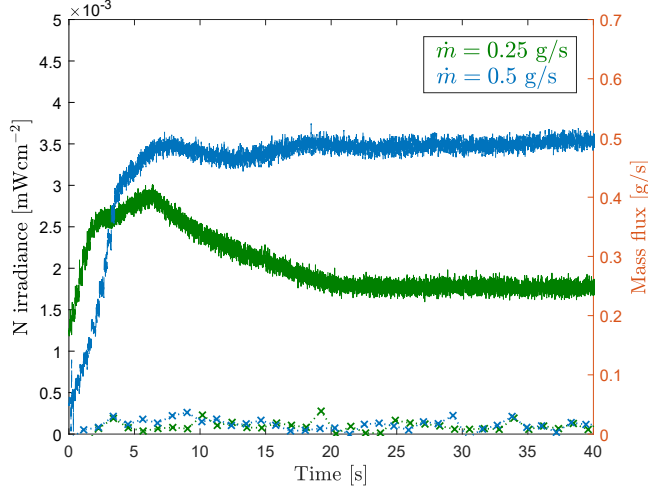
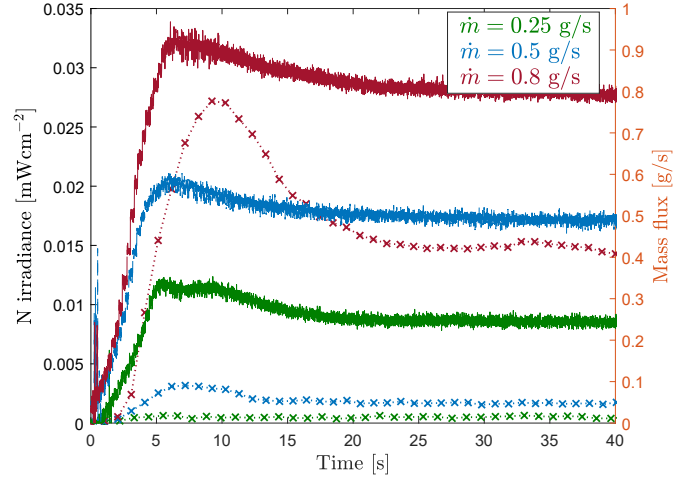


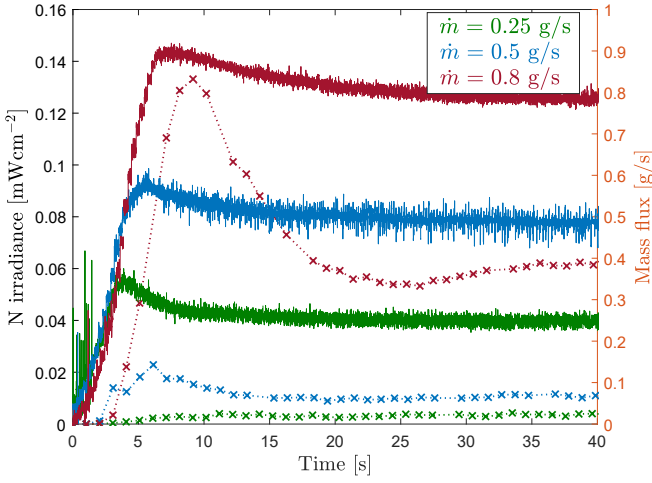
Figure 11: Atomic oxygen irradiance and temporal evolution of the mass flux for each run - dotted lines: atomic oxygen irradiance (left axis); solid lines: measured mass flux (right axis); green, blue and red lines: 0.25 g/s, 0.5 g/s and 0.8 g/s respectively



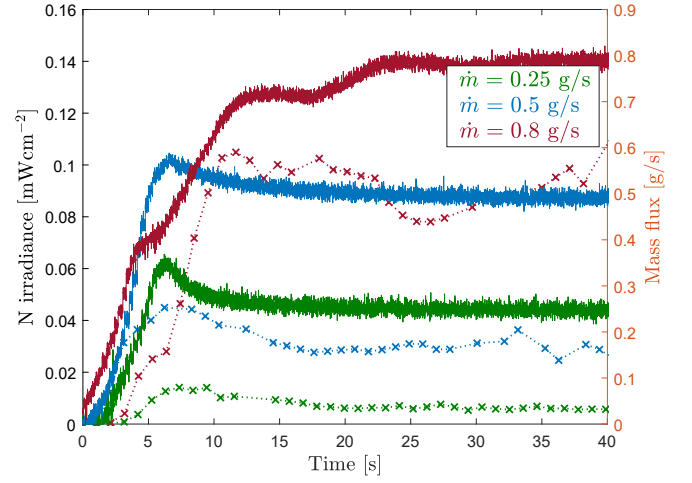
(a) $I = 40$ A



(b) $I = 100$ A



(c) $I = 160$ A



(d) $I = 200$ A

Figure 12: Atomic nitrogen irradiance and temporal evolution of the mass flux for each run - dotted lines: atomic nitrogen irradiance (left axis); solid lines: measured mass flux (right axis); green, blue and red lines: 0.25 g/s, 0.5 g/s and 0.8 g/s respectively

flux overshoot after which it tends to stabilize. Similarly to copper and atomic oxygen, for 200 A and 0.8 g/s air, the initial pattern for the irradiance is different. In this case, there is no initial irradiance overshoot. Instead, the presence of atomic nitrogen remains relatively constant throughout the entire run.

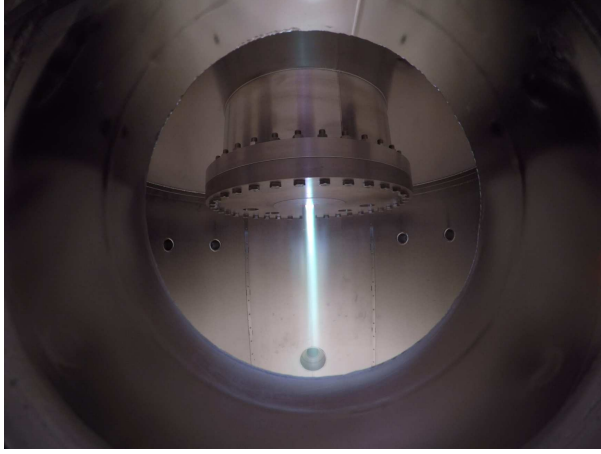
3.3. Bright flashes

For the two higher arc current conditions (160 A and 200 A), regardless of the mass flux, occasional bright flashes are visible in the plasma flow. Figures 13a and 13b show two consecutive instants when the flow has, respectively, a common appearance and a bright flash. These flashes appear throughout the tests and as the mass flux increases, their intensity and frequency also increase. No changes are observed in the arc current nor in the injected mass flux

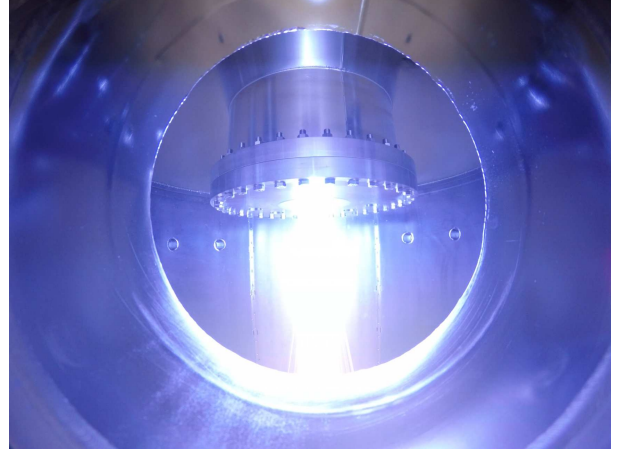
measurements during the flashes.

Figures 14a and 14b present, respectively, the calibrated emission spectra acquired during the stable state of the test (initial 20 s of overshoot removed) and for the two consecutive instants shown in Fig. 13. As expected, the appearance of the flashes is clearly observable in the spectra acquired. There are five spectral lines that appear together, as well as a broad continuum, for all the instants in which a flash occurs, as seen in Fig. 14a. Some of these spectral lines have been identified relying on Pearse and Gaydon²³ work.

The first feature is associated with boron monoxide (BO) at 555 nm, a reaction of detached boron from the insulation disks and the atomic oxygen in the chamber. The second feature is associated with copper monoxide (CuO) at 606 nm, a reaction between the copper released from the anode and the

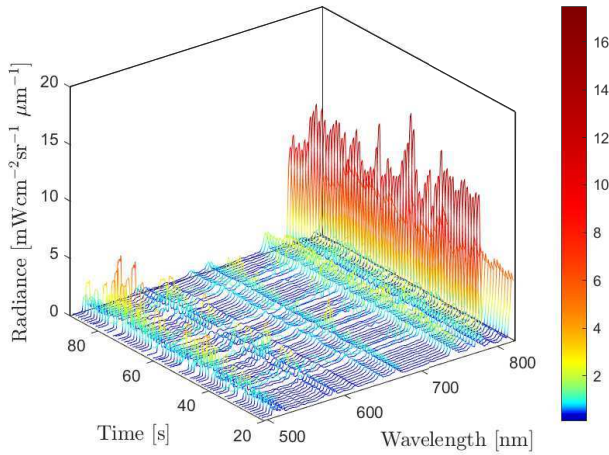


(a) Normal operation at $t = 31.1$ s

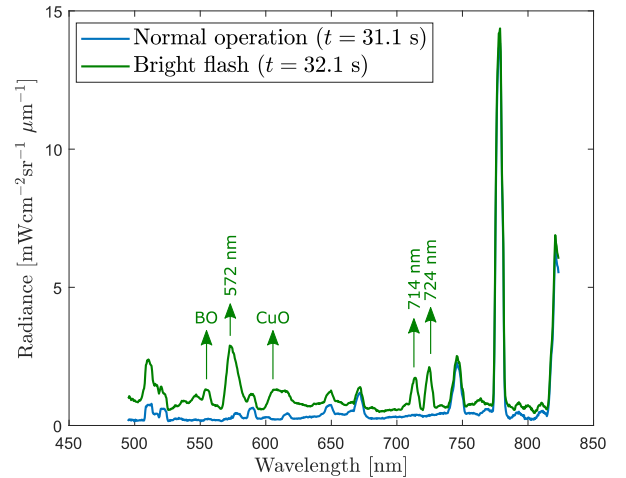


(b) Bright flash at $t = 32.1$ s

Figure 13: Plasma at consecutive instants (200 A, 0.5 g/s air)



(a) Spectra during steady state



(b) Two consecutive instants at $t = 31.1$ s and $t = 32.1$ s

Figure 14: Calibrated emission spectra (200 A, 0.5 g/s air)

atomic oxygen in the chamber. The other spectral lines are measured at 572 nm, 714 nm and 724 nm, as shown in Fig. 14b. Even though these lines remain unidentified, all of the features appearing due to the bright flashes are likely to be fragments of either the electrodes, the insulation disks, or species produced from reactions between these components and the atomic elements present in the chamber during the test. As the data gathered so far corresponds only to a first step in characterizing the facility, further tests are needed to discover the exact causes of these flashes and how to reduce their occurrence as much as possible.

4. Numerical simulations

NEQAIR (Nonequilibrium Air Radiation) is a line-by-line radiation code that computes spontaneous emission and absorption from transitions between various energy states of chemical species along a line-of-sight.²⁴ The simulations for modeling the radiation measured at the mARC facility are an idealized approximation of the actual flow phenomena. The NEQAIR simulations in this work are based on an assumption that the flow is in equilibrium, with the conditions calculated by CEA (Chemical Equilibrium with Applications).²⁵ NEQAIR is used to create synthetic spectra for interpretation of the spectroscopy measurements taken at the mARC II facility. The characteristics of the plasma are estimated by fitting the experimental calibrated spectrum with a numerically calculated synthetic spectrum (Fig. 15 and later Fig. 22). As each fitting of the spectrum is well matched with the NEQAIR prediction assuming thermochemical equilibrium, the plasma can be considered to be in equilibrium.

The radiation spectrum from the arc jet is measured using a line-of-sight that runs perpendicular to the chamber axis (see Fig. 2). The simulated spectrum considers a constant property gas, uses a constant slab with a width set to the diameter of the exit of the nozzle, and assumes a Voigt line shape. To simulate the spectra of the impurities present on the flow, the NEQAIR database has been updated to include lithium, sodium and silver atomic spectral lines and levels based on the NIST Database.¹⁸

The following analysis is conducted using an average of all of the spectra measured once steady state is reached, approximately 60 s total, hence

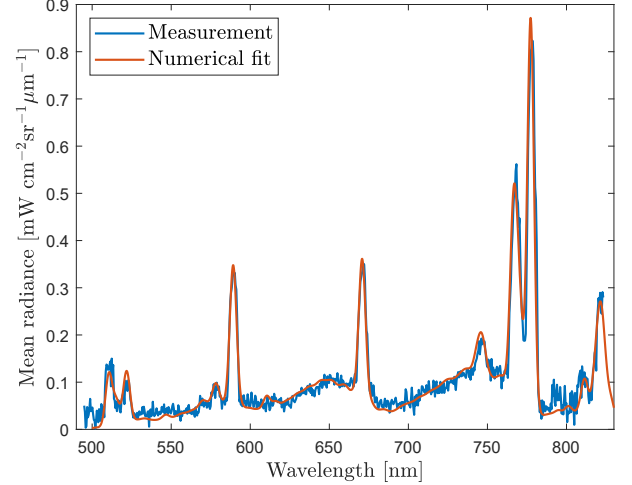


Figure 15: Experimental and numerical spectra (100A, 0.5 g/s air)

discarding the period when the initial overshoots occur. As the spectra are line of sight averaged, the estimate of the temperatures are also an average across a range of temperatures.

4.1. Equilibrium temperature

Fitting the experimental spectrum allows an estimate of the equilibrium temperature of the plasma flow. Figure 16 presents the numerical freestream flow temperature as a function of the arc power. The error bars shown are due to the uncertainty in fitting a synthetic spectrum to the measured spectrum and are a standard output of NEQAIR. The power is computed multiplying the average arc current by the average arc voltage. Arc current and arc voltage are measured in real-time by the data acquisition system and averaged throughout the steady state period.

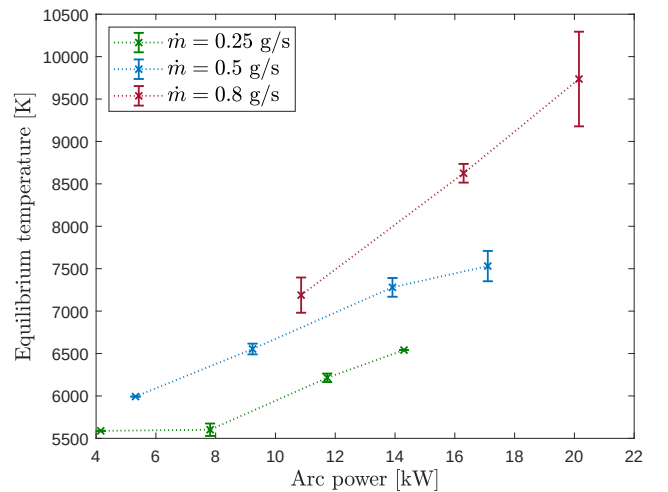


Figure 16: Numerical freestream flow temperature

These numerical results also allow an estimate of enthalpy if assuming isentropic flow of a thermally perfect gas. The total specific enthalpy of a thermally perfect gas is the sum of static specific enthalpy and the flow kinetic enthalpy given as

$$h_t(T) = h_{static} + h_{kinetic} = \int c_p(T) dT + \frac{1}{2} v^2 \quad (1)$$

where c_p [$\text{J kg}^{-1} \text{K}^{-1}$] is the specific heat capacity at constant pressure, T [K] the numerical equilibrium temperature, and v [m s^{-1}] the exit velocity. The static specific enthalpy is computed using NASA CEA^{25,26} code for each of the numerical temperatures presented in Fig. 16 and average steady chamber pressure, recorded by the data acquisition system. These CEA simulations also yield the heat capacity ratio γ , and the speed of sound [m s^{-1}]. The exit velocity for the kinetic part of the enthalpy is estimated recurring to the well-known isentropic nozzle flow equations²⁷ relating conditions between two locations. The exit Mach number can be inferred by solving the equation

$$\frac{A}{A^*} = \left(\frac{\gamma + 1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1 + \frac{\gamma-1}{2} M^2 \right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M} \quad (2)$$

where $A/A^* = 11.28$ is the known areas ratio between the throat and the exit, and γ is the heat capacity ratio computed by CEA code. The determination of the exit Mach number together with the speed of sound from CEA provides the exit velocity. The total enthalpy results are shown in Fig. 17. The minimum and maximum standard deviations for the static enthalpy are computed by running CEA code for, respectively, the minimum and maximum numerical temperatures and the maximum and minimum chamber pressure based on the experimental uncertainty for each point. The standard deviations for the kinetic enthalpy are computed from the limit values obtained by the CEA computations. The sum of the both standard deviations allows to estimate the error bars for the total enthalpy.

Even though the emission intensity being measured is dominated by the hottest part of the flow, the center of the jet, these enthalpy results consider the emission from the entire path, which includes the edges of the flow as well. Consequently, these are considered path-integrated enthalpies and they are not really comparable to the bulk values presented by MacDonald et al.¹⁶ Those values are around 8 times lower than the enthalpy values reported in Fig.

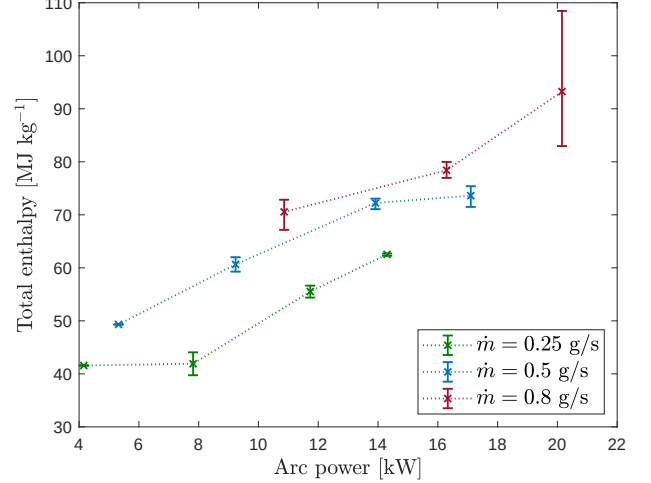


Figure 17: Total enthalpy computed based on the numerical temperatures

17. One explanation is that the enthalpy values here, while not exactly centerline enthalpies, are strongly influenced by the emission in the hottest part of the jet (centerline). Another explanation could rely on the fact that the measurements in this work are conducted 25 mm downstream of the nozzle exit. Although this location is probably not exactly on a shock/shock interaction, Fig. 18 shows that position can be close. That would lead to higher-than-average measured temperatures at this measurement location and consequently higher enthalpies. This hypothesis leads to the recommendation of carrying out these measurements at multiple axial locations.

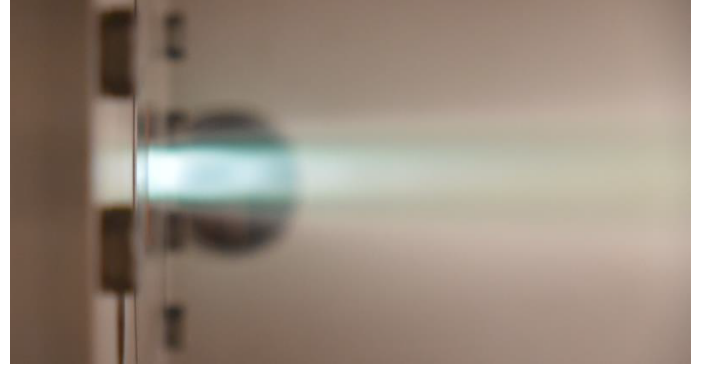


Figure 18: Photo of the jet (40A, 0.25 g/s air; 1/60 sec, f/2.8, 35 mm, ISO 1600, with UV filter)

Additionally, an estimate of the effective efficiency η can be provided based on the enthalpy²² as

$$\eta = \frac{\dot{m} \cdot h}{I \cdot V} \quad (3)$$

where $\dot{m}$ [kg s^{-1}] is the mass flux, h [J kg^{-1}] the specific enthalpy of the flow, and $I \cdot V$ [J s^{-1}] the arc

power given by the multiplication of the arc current and arc voltage, respectively. However, as the enthalpies are not bulk values, these values should not be interpreted as traditional arc jet efficiencies. For this reason the vertical scale on Fig. 19 is left entirely relative. Nevertheless, these efficiencies yield tendencies that are considered worth discussing. At higher arc powers, the efficiency drops indicating that more energy is removed from the flow by the

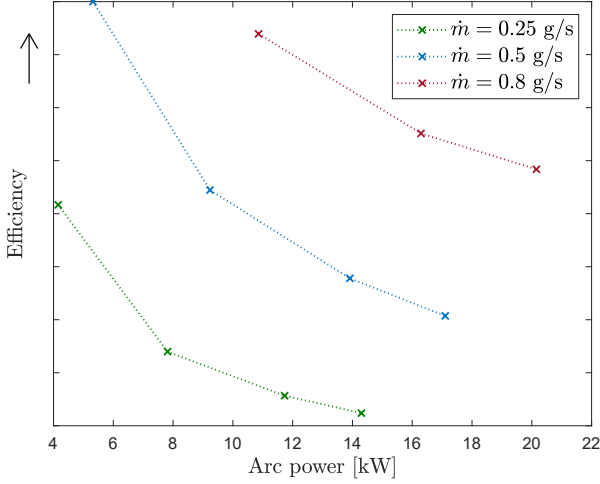


Figure 19: Efficiency

water-cooled column wall; and at higher mass fluxes, the efficiency rises indicating that more of the power remains in the flow and less heat is lost to the walls.

These conclusions are corroborated by the analysis of the flow profiles shown in Fig. 20. The top half of this figure presents the gradient magnitude for an instant during steady state flow, for all conditions recorded by video (100 A, 160 A and 200 A; all mass fluxes); while the bottom half presents the distribution of the flow intensity along the line of sight at around 25 mm downstream of the nozzle exit (coloured lines), for each of the conditions. Figure 21 presents the distance between the peaks for each line of sight marked in Fig. 20. The vertical scale is again left relative, as only the trend is worth discussing. For a given current as the mass flux is increased, the profile narrows due to an increase of the chamber pressure and, consequently, an overexpansion of the jet, implying less wall losses. Inversely, as the arc power is increased for a given mass flow rate, the gas inside the column is heated more, increasing the column pressure and leading to a less overexpanded flow and a larger jet diameter. This typical enlargement of the radiation profile indicates

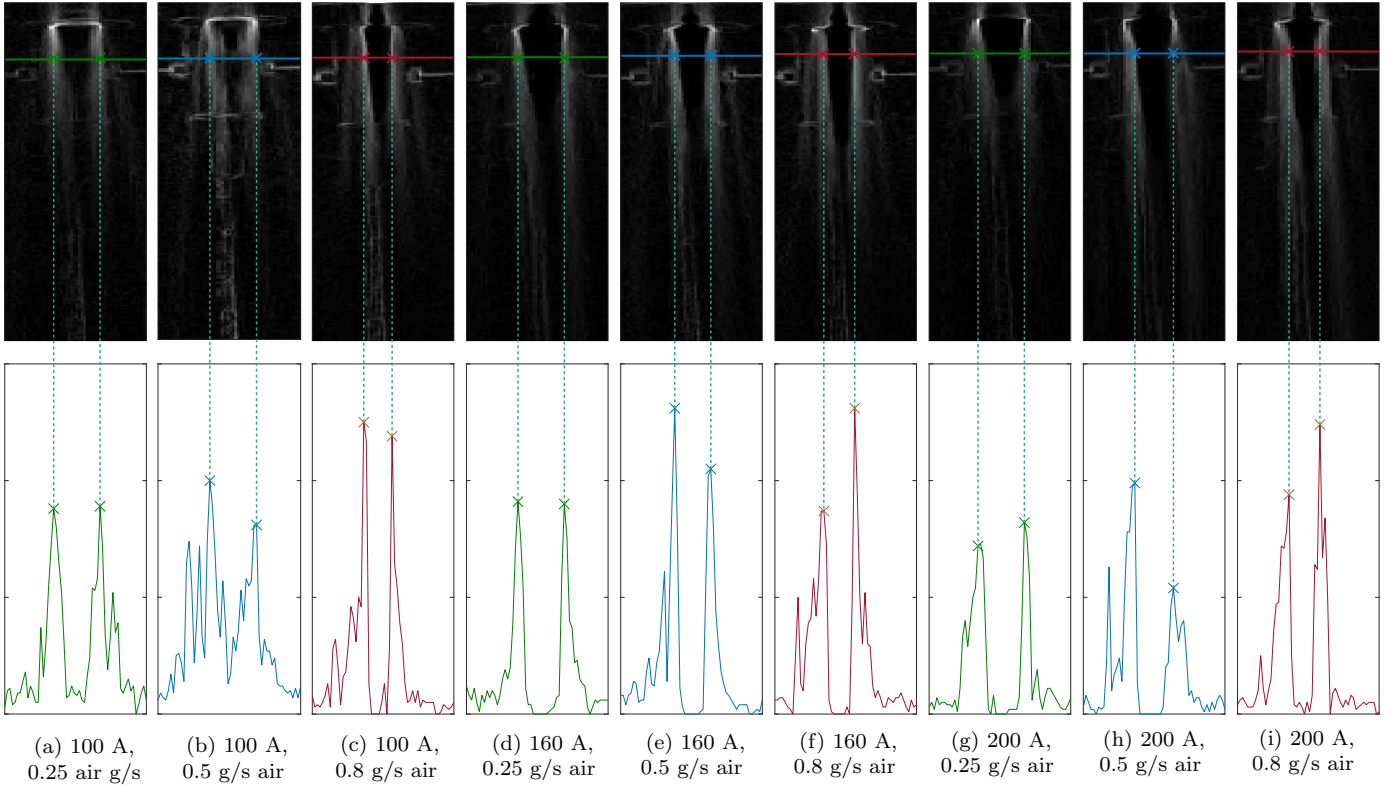


Figure 20: Flow profiles for an instant during steady state flow for different testing conditions - top: capture of the flow profile with line of sights represented by a solid line; bottom: distribution of the flow intensity at the marked position.

more losses at the wall. An exception is visible for the lowest mass flux. It can be that the 0.25 g/s jet diameter is insensitive to power because as the lowest mass flow rate, the vacuum system can actually keep the chamber pressure low enough that the flow is nearly perfectly expanded.

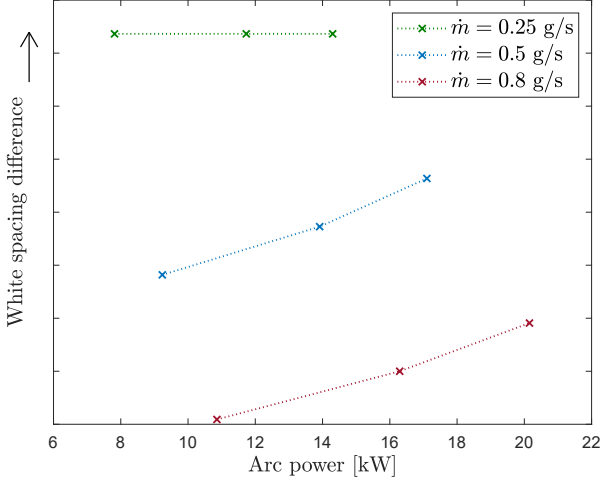


Figure 21: Spacing between the peaks for each flow profile

As the observed radiation is most likely dominated by the core of the flow that only comprises a fraction of the total mass flow, the numerical temperatures and enthalpies are overestimations of their average values. Thereafter these parameters should be considered as upper bounds due to the changing flow profile.

4.2. Number densities

Fitting the experimental spectrum also provides an estimate of the number density of the species present in the flow. Even though all of the atomic species identified in Section 3 are used during the numerical fit, hereafter special emphasis is given to copper and silver number densities as they correspond to the main atomic elements of the electrodes. For the cases with set arc currents of 160 A and 200 A, the spectral features causing the flashes are not fitted, as the identified molecules are not included in NEQAIR database. Nevertheless, as these simulations fit an average of all data taken during steady state, the features due to the flashes are not very significant and the numerical fit is still good (Fig. 22).

Figure 23 presents the average number density of copper. For each mass flux, the order of magnitude of the number density of copper is the same, regardless of the arc power. When increasing the mass flux,

the number density decreases since the volume of gas in the chamber increases significantly for a small increase of the quantity of copper.

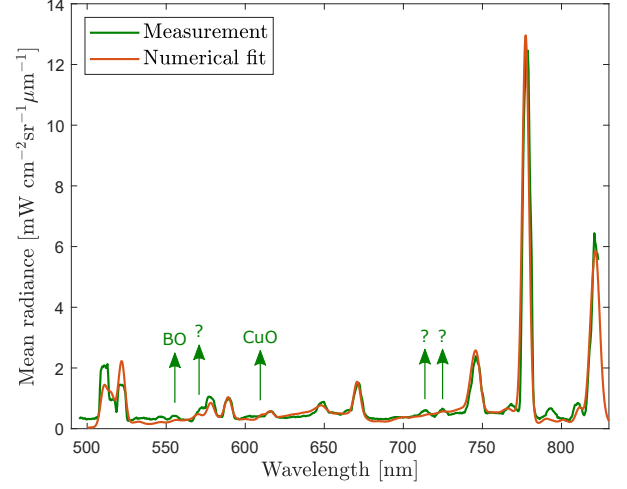


Figure 22: Experimental and numerical spectra (200A, 0.5 g/s air)

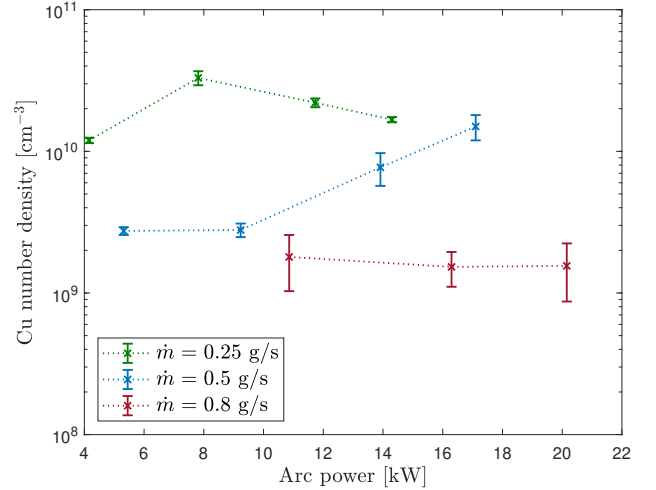


Figure 23: Copper number density

Figure 24 presents the average number density for silver. For small arc powers, the number density of silver is fairly constant regardless of the mass flux, abruptly decreasing for arc currents higher than 100 A. For number densities lower than 10^3 cm^{-3} , the strength of the spectral line is very small and, consequently, the measured spectra cannot be well fit with NEQAIR. Since the shapes of the cathode and anode are different, it is not surprising that the behaviours shown in Figs. 23 and 24 differ. However, the drop off in silver number density at higher powers is somewhat counterintuitive. The particular mechanism causing this is not currently known. It is possible that the arc

attachment to the cathode changes at higher powers such that less cathode material is ejected into the flow. Additional measurements of cathode species in both the arc column and the flow are planned for the future, and it is hoped that these will shed more light on this particular observation.

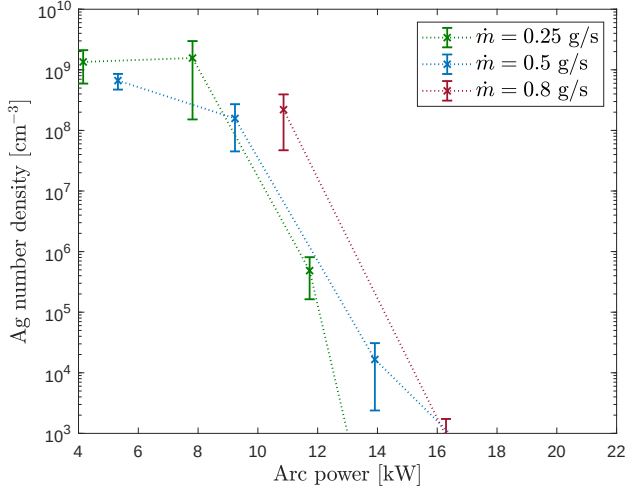


Figure 24: Silver number density

The number densities of impurities such as potassium, sodium and lithium are also estimated from the NEQAIR fit of the measured spectra. For all of these species, the number densities are around 10^7 cm^{-3} regardless of the testing condition. These elements have very high line strength, which produces a high measured intensity, despite their relatively low number densities.

5. Conclusions

The objective of this study was to obtain calibrated time-varying radiance measurements in the visible region for the flow freestream of the mARC II facility. These were then used to analyze the deterioration of the electrodes, and to characterize the plasma flow and its impurities. Measurements employed optical emission spectroscopy. Different testing conditions within the operating envelope of the facility were evaluated to study their influence on the measured radiance, temperature and number density.

The emission spectra showed a constant presence of impurities such as copper, silver, sodium, lithium and potassium. The existence of copper and silver in the flow represents degradation of, respectively, the anode and the cathode. The highest rate of anode deterioration was found to occur typically during the arc jet startup, when the arc current is highly

unstable, while the deterioration of the cathode was found to be relatively constant throughout the entire run. Starting the arc using an alternate startup method resulted in a lower copper irradiance peak than what was expected for the original startup method. This new method thus results in less anode deterioration during the initial arc current overshoot. In this method, the mass flux was gradually increased after the beginning of the test until it reached the set value. For higher arc currents, occasional bright flashes were observed in the flow. These flashes appeared throughout the tests and were most likely caused by released small fragments from the electrodes or the insulation disks.

A preliminary numerical characterization of the plasma flow was also conducted to predict equilibrium temperature and species number densities. From the numerical temperatures, flow enthalpy and efficiency were also analysed. The flow temperature and enthalpy were both found to follow the same trend and increasing with the increase of the mass flux and arc power. Efficiency was found to decrease with the increase of the arc power, and to increase with the increase of the mass flux. The latter conclusions were also corroborated by the analysis of the flow profiles. During steady state, copper number density was found to be fairly constant for the arc power and to decrease with the increase of the mass flux; while for silver the number density was found to be constant for small arc powers and insignificant for higher arc currents.

The characterization of the freestream flow of the mARC II presented in this work was carried out based on the first spectral results obtained at the facility. In the future, more conditions should be tested to corroborate the conclusions stated over a broader range of conditions. Further tests should also be run to confirm if electrode deterioration is indeed less significant with the alternate startup method that was only used one time during these tests. A study of anode mass loss is also recommended to quantitatively determine the influence of start procedure. Moreover, the team should also test anodes with different atomic compositions to try to find an anode that minimizes the quantity of small fragments released to the flow, thus with smaller deterioration. Computational fluid dynamic simulations should also be performed to confirm the flow temperature, enthalpy and efficiency, and the assumption of thermochemical equilibrium.

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