Temperature and pressure profiles of an ablation-controlled arc plasma in air

Marley Becerra$^{1,2,4}$, Jonas Pettersson$^{1}$, Steffen Franke$^{3}$ and Sergey Gortschakow$^{1}$

1 KTH Royal Institute of Technology, School of Electrical Engineering and Computer Science, 100 44, Stockholm, Sweden
2 ABB Corporate Research, 722 26, Västerås, Sweden
3 INP Leibniz Institute for Plasma Science and Technology, 174 89, Greifswald, Germany

E-mail: marley@kth.se

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Abstract
Experimental measurements of the spatial distribution of temperature and composition of ablation-controlled arc plasmas are a key to validate the predictions of metal evaporation and polymer ablation models. Thus, high-speed photography and space-resolved spectroscopic measurements have been performed to characterize a stable air arc plasma jet controlled by ablation of a polymer nozzle made of Polyoxymethylene copolymer (POM-C) or polyamide (PA6). The spectroscopic analysis is performed along a plane perpendicular to the arc jet axis for a current of 1.8 kA, corresponding to an estimated current density of ~65 A mm$^{-2}$. Temperature and partial pressure profiles of the plasma for copper, hydrogen and carbon in the gas mixture are estimated as an inverse optimization problem by using measured side-on radiance spectra and radiative transfer spectral simulations. It is shown that the generated ablation-controlled arc has a complicated, non-uniform gas composition. Thus, the generated arc jet has a thin metallic core with a lower almost constant hydrogen pressure, surrounded by a thicker hydrogen and carbon mantle at partial pressures slightly lower than atmospheric pressure. The separation of hydrogen and carbon in the core is a consequence of demixing of the polymer vapor in the plasma. It is found that the overall shape of the temperature and pressure profiles obtained for the arc plasmas with the POM-C and PA6 nozzles are similar although differ in peak values and width.

Keywords: thermal plasmas, polymer ablation, plasma diagnostics

(Some figures may appear in colour only in the online journal)
demixing [7]. This process causes that the relative concentrations of the different gases in multi-component plasmas are neither uniform in space nor remain constant in time [8]. This fact has motivated significant progress in the plasma modelling of simple gas mixtures applied to welding arcs, torches and simple waste destruction processes [7, 8]. Recently, air arc plasmas with vaporized metal have also been modelled considering an air-copper gas mixture [10]. Unfortunately, the numerical simulation of ablation-controlled arc plasmas in the gas mixture of air with vapours of metal and polymer is still challenging. This is because models to quantify the injection of polymer vapour, critical for calculating the plasma composition, are rather crude [11]. Similarly, the existing models to quantify the amount of metal vapour injected by evaporation are still based on several simplifying approximations [12]. As a result, the simulation predictions of the arc voltage across air plasmas stabilized by polymer ablation are unsurprisingly in quantitative disagreement with experiments (e.g. in [3]).

One critical aspect hindering the further development of the models of ablation of both polymers and metals in air arcs is the lack of experimental data necessary to validate simulation predictions. Particularly, experimental estimates of the spatial and temporal variations of temperature and partial pressure of different species in air plasmas are still missing. Optical emission spectroscopy, laser scattering or other diagnostic methods have been used in the literature for such estimates in simple gas mixtures [7]. However, standard diagnostic techniques proved to be intractably difficult when applied to ablation-controlled arcs in air [4]. Since such plasmas are generally optically thick at high currents [1, 13], and the partial pressures of the multiple chemical elements in the gas is far from uniform (as will later shown in section 4.2), standard spectroscopic methods fail. For the same reason, alternative diagnostic methods proposed to estimate the temperature of multi-element gases (e.g. [9, 14]) which neglect the reabsorption of the plasma cannot be applied either.

Spectral simulations by radiative transfer calculations assuming local thermodynamic equilibrium (LTE) have been successfully applied to estimate temperature profiles in optically thick plasmas (e.g. [1, 13, 15, 16]). Such estimates are based on the comparison of side-on radiance measurements with simulated line spectra. Recently, estimates of the temperature variation in an ablation-controlled air arc plasma using spectral simulation has been reported [16]. Unfortunately, a uniform, single-component plasma composition was assumed.

In order to estimate temperature and composition of an ablation-controlled air arc plasma, spectral simulation is here extended to consider a non-uniform, multi-component plasma composition. Thus, space-resolved temperature and partial pressure profiles of the plasma are calculated as an inverse optimization problem using measured and simulated side-on radiance. The paper is organized as follows. The experimental setup is introduced in section 2, while the spectral simulation is described in section 3. In section 4, the results of the measurements and the simulations are presented and discussed.

2. Experimental method

2.1. The studied ablation-controlled arc plasma

The optical emission spectroscopy measurements are performed for an air arc plasma ignited in a 24 mm air gap in a rod-to-rod configuration. The top electrode is made of copper, with a 5 mm radius hemispheric cap. The bottom electrode is made with a flat, cylindrical, 4 mm radius, tungsten insert mounted on a 5 mm radius copper rod. A polymeric nozzle fitted onto the top electrode is used to control the plasma, generating a reproducible and stable anode-dominated arc plasma jet [11]. The nozzle has an inner radius of 4.5 mm extending 9 mm into the air gap. Nozzles made of standard commercial grade, colourless Polyoxymethylene copolymer POM-C (−CH2O−) and polyamide PA6 (−C6H11NO−) are here reported.

The ablation-controlled arc is ignited by generating a spark between the electrodes. A voltage spike larger than 30 kV generated by an external source is used to ignite the gap. Then, the discharge is fed by a damped, sinusoidal 50 Hz current half-wave. This current is generated by a synthetic circuit with a 2.62 mF capacitor charged at 2.8 kV.

The used spectroscopic setup is shown in figure 1. It consists of an intensified optical spectrograph, a Roper Action SP-2500i and an intensified CCD camera (PI-MAX4). The spectrograph is focused to image a horizontal section of the arc located 5 mm below the nozzle bottom edge. The recorded 2D images contain spectral, side-on information of

![Figure 1. Schematic top-view image of the experimental setup including instrumentation (not at scale).](image-url)
the plasma. The arc emission is reflected by a pivotable plane mirror and passes a high-pass filter (with cut-off at 430 nm) before a focusing mirror projects the arc image on the 40 μm entrance slit of the spectrograph. In total, the spectrograph has a focal length of 500 mm. Absolute calibration of side-on radiation spectra is performed by imaging a tungsten strip lamp (OSRAM Wi 17/G) at the same distance to the plane mirror as the arc axis. Only one image per current pulse at a given delay is acquired with the spectroscopic setup, using an exposure time of 200 μs. The investigated spectral region is set in the visible range between 430 and 670 nm. The spectral resolution of the system is 0.23 nm.

A monochrome Photon FASTCAM camera is also used to record high-speed images of the arc from the opposite side of the spectrograph. A system of two beam-splitters is used to obtain a dual image of the air gap. One image is filtered with a bandpass (BP) filter with central wavelength (CWL) of 510 nm to detect radiation from copper lines. A bandpass filter with CWL of 650 nm is used to detect radiation from the hydrogen-alpha Balmer (Hα) line [11] in the second image. Both bandpass filters have a full-width at half-maximum (FWHM) of 10 nm. A suitable camera lens aperture and neutral density filters have been selected to avoid image saturation. The images are recorded with a rate of 7500 fps and an exposure time of 2 μs.

3. Estimating temperature and partial pressures in a multi-component, non-uniform plasma

3.1. Radiative transfer

The simplest general form of the radiative transfer equation for a plasma at a temperature T and pressure p is given as [17]:

\[ \mathbf{\hat{s}} \cdot \nabla I_\lambda(q, \mathbf{\hat{s}}, \lambda) = \kappa(p, T, \lambda) \cdot (B_\lambda(T, \lambda) - I_\lambda) \]  

(1)

where \( I_\lambda \) is the spectral radiance per unit wavelength λ in W/m² nm sr at a point \( q \) along any direction \( \mathbf{\hat{s}} \). \( B_\lambda \) is the Planck intensity per unit wavelength and \( \kappa \) is the effective absorption coefficient. Under the assumption of LTE, \( \kappa \) is given according to Kirchhoff’s law by:

\[ \kappa(p, T, \lambda) = \varepsilon_\lambda(p, T, \lambda) / B_\lambda(T, \lambda) \]  

(2)

where \( \varepsilon_\lambda \) is the emission coefficient, which includes the effect from all the possible transitions (bound–bound, bound–free and free–free) and induced emission.

Considering only the spontaneous emission of a spectral line centred at a wavelength \( \lambda_0 \), the emission coefficient \( \varepsilon_\lambda \) is given by:

\[ \varepsilon_\lambda(p, T, \lambda) = \frac{hc}{4\pi \lambda_0} A_{\text{ad}} n_u(p, T) P_\lambda(p, T, \lambda), \]  

(3)

where \( h \) and \( c \) are the Planck constant and the speed of light in vacuum. \( A_{\text{ad}} \) is the transition probability for spontaneous emission from the upper level \( u \) to the lower level \( l \) and \( P_\lambda \) is the spectral profile of the emitted line. Since all the components in a LTE plasma have the same temperature, the level population density \( n_u \) is Boltzmann distributed according to:

\[ n_u(p, T) = g_u n_e(p, T) e^{-\frac{E_u}{k_B T}} \]  

(4)

with the energy level \( E_u \) and the statistical weight \( g_u \) of the upper level. \( n_e \) is the total density of the emitting atomic or ionic species and \( Z_i \) is its partition function. \( k_B \) is the Boltzmann constant.

3.2. Spectral simulations

Consider the section of an arc in a gas mixture having partial pressure \( p^{(i)} \) for each \( i \)th emitting element. This section is axial-symmetric and centred at the origin of a \( xy \) plane \( (r = \sqrt{x^2 + y^2}) \) as illustrated in figure 2. If the radiation of this plasma is imaged on the slit of a spectrometer placed along the \( y \) direction (at a given distance \( x_0 \) from the axis), a side-on spectral radiance \( L(y, \lambda) \) of the plasma is measured. In this case, \( L(y, \lambda) \) is equivalent to the spectral radiance \( I_\lambda \) calculated at \( (x_0, y) \) for radiation emitted only along the direction of the \( x \) axis.

The simulation of the spectrum emitted by the arc section requires the calculation of \( I_\lambda \) for each wavelength \( \lambda \) within the band detected by the spectrometer. If the partial pressure \( p^{(i)} \) of the emitting species is assumed uniform in space, simpler analytical or integral versions of (1) can be used to calculate \( I_\lambda \). However, the analysis of arcs with non-uniform partial pressures requires the spatial solution of (1) for the entire plasma section.

In order to analyse a non-uniform, multi-component plasma, (1) is here solved in a three dimensional space domain \((x, y, \lambda)\) using a finite element program [18]. Since the theory and available data for continuum radiation has a limited accuracy [15], only line radiation is considered. The effective absorption coefficient \( \kappa \) at each point in the domain is evaluated as the summation of the coefficients \( \varepsilon_{\lambda}^{(l)} \) emitted by each \( l \)th line \((l = 1, 2, \ldots, n_l)\) out of \( n_l \) lines considered from each \( i \)th species \((i = 1, 2, \ldots, m)\):

\[ \kappa(r, \lambda) = \frac{\sum_{i=1}^{m} \sum_{l=1}^{n_l} \varepsilon_{\lambda}^{(l)}\left(p^{(i)}(r), T(r), \lambda\right)}{B_\lambda(T(r), \lambda)}, \]  

(5)

The parameters \( E_u, A_{\text{ad}} \) and \( g_u \) for each considered line are obtained from the NIST atomic spectra database [19]. The
partition function \( Z_n \) for each emitting species is calculated using the Planck–Larkin function [20]. The total density \( n_0 \) for the emitting species is calculated based on the principle of minimization of the Gibbs free energy with the code described in [21]. Since the full width at half maximum (FWHM) of the profile function \( P_\lambda \) depends on temperature and plasma composition, its radial variations should be considered. Due to the uncertainties and limitations of the calculation of broadening defining the width of the line profile [15], the FWHM of each analysed line is experimentally obtained. For this, each considered peak is best-fitted to a Lorentzian profile \( P_\lambda \) at each measured side-on location. As a first approximation, the obtained FWHM values are directly correlated to the line profile as a function of radius. Even though this approximation is not rigorous, it is valid in plasmas with constant or decreasing FWHM with radius. The validity of this approximation is later checked by comparing the simulated FWHM of the considered peaks at different side-on locations (after the procedure described in the next section is executed) with the measurements.

3.3. Inverse optimization

The spectral simulation described above requires as input the temperature and the multi-component partial pressure profiles, which are unknown for the generated arc plasma. For this reason, the analysis of the spectroscopic measurements using spectral simulation can be treated as an inverse problem. Its solution can be stated as the search of suitable profiles \( T(r) \) and \( p_j(r) \) that produce a simulated spectrum similar to that measured within a given wavelength band. In such a case, no Abel inversion of the measured side-on radiances is required and optically thick plasmas can also be readily treated. This problem is here solved by inverse optimization with the Nelder–Mead algorithm [18].

The formulation of the problem first requires the definition of the optimization parameters. However, it is difficult to define the profiles of temperature and pressure by an analytical function with few parameters since they can have any arbitrary shape. Thus, the optimization parameters are here defined instead by a set of finite data points for temperature \( \{T_j\} \) and partial pressures \( \{p_j(r)\} \) at \( q \) discrete radial locations \( \{r_j\} \) (where \( j = 1, 2, \ldots, q \)), within a spatial interval \([0, r_q]\). The temperature profile \( T(r) \) is then defined by interpolation of the corresponding data points by using the piecewise function:

\[
T(r) = \begin{cases} 
C_1(r), & r_1 < r < r_2 \\
C_j(r), & r_j < r < r_{j+1} \\
C_{q-1}(r), & r_{q-1} < r < r_q 
\end{cases}
\]

given by a set of cubic Hermite polynomial functions \( C_j \) with continuous first derivatives. Similar piecewise function interpolation is used for the partial pressure profiles \( p_j(r) \).

Given that the spectral simulation does not include continuum radiation, its contribution on the measured side-on radiation needs to be estimated. For this, the vertical offset of Lorentzian profiles \( P_\lambda \) best-fitted to the side-on radiance measured at each side-on location was used to define the level of the continuum of radiation. For spectral bands with overlapping lines, the continuum was obtained instead through peak-deconvolution of two or three different Lorentzian profiles centered at dominant peaks. The obtained continuum background map was then subtracted from the spectral measurements to estimate the measured side-on line radiance.

Since the solution of (1) within an optimization loop is computationally demanding and time consuming, the inverse problem is implemented in sequential steps as follows:

1. The datasets of temperature \( \{T_j\} \) and the partial pressure of the primary element \( \{p_j^{(1)}\} \) are estimated. The chosen primary element should emit at least two well-defined lines (centred at \( \lambda^{(0)} \) and \( \lambda^{(1)} \)). These lines should be measured with a high signal to noise ratio. They can be emitted by the same species (although with a significant difference in upper energy levels) or radiated by two different species (e.g. one atomic and one ionic). Furthermore, they should not overlap with lines from other elements. Then, the squared residual function between the measured side-on line radiance and the simulated spectral radiance is calculated within a suitable wavelength band (containing \( \lambda^{(0)} \) and \( \lambda^{(1)} \)) as:

\[
\varepsilon^{(1)} = \sum_{j=0}^{l} \left( \int_0^r \left( L(y, \lambda^{(h)}) - I_\lambda(x_p, y, \lambda^{(h)}) \right)^2 \, dy \right) \quad (7)
\]

and used to minimize the optimization function given by:

\[
\min_{\{T_j\}, \{p_j^{(1)}\}} \varepsilon^{(1)}. \quad (8)
\]

2. A similar optimization procedure is performed to find the partial pressure dataset \( \{p_j^{(2)}\} \) of the second gas element. For this, the radiative transfer is solved using the profile \( T(r) \) obtained from the temperature data points obtained in the first step. The analysis is performed for a single wavelength \( \lambda^{(2)} \) emitted by the second element from either an atomic or an ionic species. This line should also have a strong signal, dominating over a narrow wavelength band around it. Overlap with lines from any other element significantly contributing to the radiance at \( \lambda^{(2)} \) should be avoided. The minimization is then performed for the second element \( (i = 2) \) with the optimization function defined as:

\[
\min_{\{p_j^{(2)}\}} \int_0^r \left( L(y, \lambda^{(i)}) - I_\lambda(x_p, y, \lambda^{(i)}) \right)^2 \, dy. \quad (9)
\]

3. The partial pressure dataset \( \{p_j^{(i)}\} \) of each remaining gas element \( (i = 3, \ldots, m) \) is performed for a single wavelength \( \lambda^{(i)} \) at a time, in a similar manner as in the previous step.
4. Results

4.1. Electrical measurements and high speed photographs

Figure 3 shows typical electrical measurements recorded in the experiment. As can be seen, a 50 Hz sinusoidal current half-wave of about 1.85 kA peak is applied. Following the fast fluctuations occurring due to the gap ignition, the arc voltage ranged between 35 to 210 V for the POM nozzle and between 50 to 180 V for the PA6 nozzle. Notice that the arc voltage with the POM nozzle is about 27 V larger than for the PA6 nozzle when the spectrometer is triggered at 4 ms.

High-speed images of the arc plasma for the two nozzles at the moment when the spectrometer is triggered are shown in figure 4. Observe that a symmetric, anode arc plasma jet emerging from the copper top electrode bridges the entire gap in the experiment. Interestingly, the images also show a different structure of the arc jet when observed considering the emission of copper or hydrogen. Thus, a thinner copper core is surrounded by a thicker, hydrogen mantle. Detailed description of that structure will be later discussed based on the spectroscopic data in section 4.2. The current density at the plane of observation of the spectrometer at 4 ms can be estimated roughly as 65 A mm$^{-2}$ for both polymer nozzles.

As can be seen, the arc jet produced with the PA6 nozzle has a rather homogeneous emission along the axis, while the plasma emission generated with the POM nozzle is more structured and characterized by the formation of a Mach disk [21]. This brighter area located about 10 mm below the nozzle edge is similar to those formed by standing wave patterns in supersonic exhaust plumes of jet engines or other aerospace propulsion systems [23]. A Mach disk is formed when a gas jet at high pressure is released from an axisymmetric nozzle to a lower pressure surrounding [22]. Thus, the presence of a Mach disk in the experiment shows a significantly higher ablation rate of POM (compared with PA6), such that an underexpanded supersonic flow is produced.

4.2. Side-on spectra

A typical space-resolved spectral image of the absolute side-on radiance measured along the plane of observation (i.e. the red dashed line in figure 4) for the PA6 and POM nozzles are shown in figure 5. This image is composed by the results of two different tests recorded with a spectral window between 420 to 580 nm and 500 to 660 nm. Unsurprisingly, nearly the same emission lines populate the spectra from both nozzles, although each is characterized with a different intensity and spatial width. Due to the large number of detected lines, the analysis is here limited to three narrow bands 420–435 nm, 505–525 nm and 650–665 nm. These bands contain emission lines with the minimum overlapping possible and measured with a sufficient signal to noise ratio.

Figure 6 shows a detailed view on the spectral lines within the considered bands along the axis of symmetry ($y = 0$). Overall, ionic copper Cu II radiation dominates the entire spectrum in a similar way as in [1]. Some few distinct atomic copper Cu I lines can be seen at 427.5, 458.7, 515.3 and 521.82 nm. The metal vapour released by evaporation of the anode causes all these copper lines. No emission from the tungsten cathode electrode is detected. Furthermore, there is a strong emission of the hydrogen alpha Balmer peak H$_\alpha$ at...
axis (y position. absolute radiance of the arc as a function of wavelength and side-on POM (right) nozzles taken at 4 ms. The colour map represents the optimization lines for Cu I, Cu II, H I and C II. The accuracy for and carbon as secondary elements. Table 1 shows the chosen gas element for the optimization calculation, with hydrogen Since copper emission dominates, it is chosen as the primary can be evaluated with the procedure described in section 3.3. too weak to be observed.

[24]. Even though both polymers release significant amounts polymeric vapours released by ablation of the nozzle surface emission from hydrogen and carbon are mainly caused by the at the right flank of the Hα peak (at 657.8 and 658.3 nm). The emission from hydrogen and carbon are mainly caused by the polymeric vapours released by ablation of the nozzle surface [24]. Even though both polymers release significant amounts of oxygen and PA6 also releases nitrogen [25], including their natural presence in air, emission lines from these elements are too weak to be observed.

From the analysis above, only copper, hydrogen and carbon can be evaluated with the procedure described in section 3.3. Since copper emission dominates, it is chosen as the primary gas element for the optimization calculation, with hydrogen and carbon as secondary elements. Table 1 shows the chosen optimization lines for Cu I, Cu II, H I and C II. The accuracy for the transition probabilities for these lines is better than 18%.

Figure 5. Measured side-on spectral image for the PA6 (left) and POM (right) nozzles taken at 4 ms. The colour map represents the absolute radiance of the arc as a function of wavelength and side-on position.

Figure 6. Measured line spectra along the chord through the arc axis (y = 0) for the PA6 (dashed line) and POM (solid line) nozzles.

656.28 nm. However, the hydrogen beta Balmer line Hβ at 486.1 nm could not be clearly identified due to severe overlapping with Cu II lines. Emission from ionic carbon lines can also be measured for the C II triplet at 426 nm and the doublet at the right flank of the Hα peak (at 657.8 and 658.3 nm). The emission from hydrogen and carbon are mainly caused by the polymeric vapours released by ablation of the nozzle surface [24]. Even though both polymers release significant amounts of oxygen and PA6 also releases nitrogen [25], including their natural presence in air, emission lines from these elements are too weak to be observed.

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Figure 7 shows the side-on radiance measured at the CWL for these lines (and extracted from the spectral image in figure 5). Notice that the shape, maximum and width of the radiation profile for each species is different. The side-on radiance of both copper species is narrow and bell-shaped, with maximum intensity around the axis of symmetry. The radiance profile for hydrogen is wider, with a roughly flat plateau around the axis while that of carbon has also a wide profile although with a well-defined off-axis maximum. Unsurprisingly, the shape of the radiation profiles for Cu II and H I are consistent with the brightness profiles obtained from the high speed images (figure 4) when filtered around these lines.

Using the measured side-on radiance profiles shown in figure 7, the optimization parameter sets \{T_j\}, \{P_j^{(1)}\}, \{P_j^{(2)}\}, \{P_j^{(3)}\} are searched. Each set is defined by q = 9 radial distances \{r_j\} (with j = 1,...,q) located within the spatial interval [0, r_q = 0.035 m]. The temperature T(r) and the partial pressure profiles \( p_j^{(1)} \)(r), \( p_j^{(2)} \)(r), \( p_j^{(3)} \)(r) for copper, hydrogen and carbon obtained from the optimized datasets are shown in figure 8.

The calculated temperature profile at the observation plane is relatively flat, with an average of about 20000 K regardless of the nozzle material. Observe that this high plasma temperature is required to reach radiation levels of copper and carbon as high as those measured (above \( 3 \cdot 10^4 \) W m\(^{-2}\) nm sr for the selected lines). Small variations of ±1000 K around the average are also estimated. Interestingly, a central minimum in the arc temperature is found. Such a local reduction in the central temperature can be attributed to the strong axial copper radiation as in the case of gas-metal welding arcs [26]. The edge of the high temperature plateau for the plasma with the PA6 nozzle is located at about 3 mm from the axis, which is slightly wider compared to the arc with the POM nozzle (at 2.5 mm). The transition zone from the hot plateau to temperatures lower than about 6000 K is less than 5 mm in width for both cases.

The estimated partial pressure profiles shown in figure 8(b) demonstrate that the spatial composition of the plasma is not uniform, showing large and complicated changes with radius. The copper profiles are bell-shaped, further diffusing into a low-pressure skirt as the radius increases. Interestingly, hydrogen and carbon have completely different profiles compared with that of copper, having a local radial minimum at the axis. Hydrogen has a rather constant partial pressure around the axis, suddenly increasing to its maximum value as the copper decreases into its low-pressure skirt. Then the hydrogen pressure decreases with radius as the temperature rapidly decreases below the hot plateau. A similar profile is estimated for carbon, although the partial pressure of carbon around the axis is zero. Thus, the arc jets in the experiment have a metallic arc core with lower constant pressure of hydrogen, surrounded by a wider hydrogen and carbon mantle. Observe that the presence of hydrogen in the core cannot be attributed to ambient humidity since the estimated partial pressure is much larger than that present in saturated air. Interestingly, carbon does not diffuse into the central metallic core, in contrast to hydrogen. This separation of carbon and hydrogen is a
clear consequence of demixing of the polymer vapour mixture [6]. Therefore, the ratio of the partial pressures of H and C vary with radius and cannot be defined by the stoichiometric composition of the polymers.

The predicted partial pressures of Cu, H and C for the arc jets produced with the POM and PA6 nozzles mainly differ in the maximum values and width of the different profiles. In the PA6 nozzle, the maximum copper pressure is larger and narrower compared with that estimated with the POM nozzle. The peak pressures for the POM and PA6 nozzles are 70 and 100 kPa, respectively. The hydrogen mantle around the copper core with POM is wider and has a slightly lower maximum than that for the PA6 nozzle (with a peak at 80 kPa). The carbon mantle has also a higher peak (at 55 kPa) with the PA6 nozzle, although it is narrower than for the POM nozzle. Unfortunately the total pressure of the plasma cannot be obtained since the contribution of oxygen and nitrogen could not be calculated from the measured spectra.

Table 1. Characteristics of the chosen lines for analysis.

| Chosen lines | Specie   | Wavelength (nm) | \( A \) (10^6 s\(^{-1} \)) | Accuracy on \( A \) (%) | \( g \) | \( E_l \) (eV) | \( E_u \) (eV) |
|--------------|----------|-----------------|-------------------|------------------------|-----|------------|------------|
| \( \lambda^{(0)} \) | Cu I     | 521.8202        | 75                | \( \leq 18 \)           | 6   | 3.8166     | 6.19202    |
| \( \lambda^{(1)} \) | Cu II    | 505.1792        | 155               | \( \leq 18 \)           | 11  | 14.4281    | 16.8817    |
| \( \lambda^{(2)} \) | HI       | 656.2819        | 44.101            | \( \leq 0.3 \)          | 18  | 10.1988    | 12.0875    |
| \( \lambda^{(2)} \) | C II triplet | 426.7          | 223               | \( \leq 18 \)           | 6   | 18.0458    | 20.9506    |

Table 1. Characteristics of the chosen lines for analysis.

Figure 7. Side-on radiance (shown with + marks) measured for the arc plasma for the PA6 (left) and POM (right) nozzles at the CWL for the chosen lines of (a) Cu I, (b) Cu II, (c) H I and (d) C II in table 1. The side-on radiance simulated from the optimized solution for temperature and partial pressures is also shown with solid lines.

Figure 8. Estimated (a) temperature profile and (b) partial pressure profiles of copper, hydrogen and carbon for the arc for the PA6 (left) and POM (right) nozzles at \( x = 0 \).
differences between the simulated and measured radiances are found at low levels. These differences can be caused by misestimation of the contribution of the continuum radiation from the measured data or by not including the line emission from W, O or N in the simulation. They could have also been caused by uncertainties in the input data for some lines, by measurement noise or by local lack of axial symmetry in the emission.

5. Discussion

The used inverse optimization methodology is here proposed as a flexible alternative to analyse radiance-calibrated measurements of multi-component, heterogeneous plasmas, regardless of their optical thickness. On one hand, the method provides reliable estimations without the need of arbitrary assumptions about the actual spatial variation of temperature and partial pressures in the plasma. On the other hand, no assumption about the optical thickness of the plasma needs to be considered since no Abel inversion is used.

It is however important to keep in mind that any analysis of spatially-resolved spectroscopic measurements is a challenging task since it is inherently an inverse problem. Solutions to such problems are strongly sensitive to small measurement perturbations (noise) and therefore are generally not unique [28]. Despite of this fact, the proposed method shows a positive convergence until the error in the evaluation of the optimization function falls towards zero. Since the proposed method is based on the minimization of the mean-square error between the simulated and measured side-on radiances, the calculations are also stable and reproducible. Thus, the here obtained estimates should be considered as a good approximate solution to the exact solution.

The estimation of the temperature and partial pressure profiles allows the evaluation of the absorption coefficients in the plasma. For the considered lines in Table 1, the absorption coefficient in the high-temperature region of the generated arc jet are below 50 m$^{-1}$ as shown in figure 10. The absorption coefficient for Cu I lines however has a sudden peak of up to 100 m$^{-1}$ at the arc skirt as the gas temperature drops below 8000 K. The optical thickness calculated from the calculated absorption coefficients ranges between 0.01 and 0.1 m for the considered lines. These values indicate that the generated arc jets emit radiation in the transitional regime between optically thin and thick plasmas [17]. This also can be crosschecked by the fact that radiance levels measured in the arc core (shown in figure 5) are larger than the upper limit at which optically thin plasmas are expected to emit (at about 10$^5$ W m$^2$ nm$^{-1}$ sr$^{-1}$) [1].

The complicated Cu, C and H distributions here reported mean that the actual local thermodynamic, transport and radiative properties of such ablation-controlled arcs are different to those calculated assuming a simplified, uniform gas composition. In order to illustrate this, the electrical conductivity $\sigma$ and the specific heat at constant pressure $c_p$ calculated using [21] are shown in figure 11 for the arc plasma generated with the POM nozzle. These properties are calculated assuming a uniform, single-gas approximation for a purely copper or POM vapour composition, as generally assumed in the literature (e.g. [3, 5, 6]). Furthermore, they are also calculated using the actual partial pressure distribution for copper, hydrogen and carbon as reported in figure 8. In all cases, the total
plasma pressure is assumed equal to 140 kPa (based on rough estimates of the electromagnetic and gas flow axial pressures [29]). As can be seen, significant errors can be produced when the properties of an ablation-controlled arc are calculated using a single-composition, uniform plasma approximation. For properties with a weak dependence on composition at high temperatures (such as \( \sigma \), the thermal conductivity or the viscosity), these errors can be lower than 20\%–40\%. However, errors larger than 100\% can be reached for other plasma properties (such as \( c_p \), or the absorption coefficients) strongly affected by the actual composition of the plasma.

Since accurate input thermodynamic, transport and radiative properties are a key for successful plasma simulations, future studies of ablation-controlled arcs should address in more detail the actual composition of the plasma. This requires proper modelling of the injection of both metallic and polymeric vapours as well as the simulation of different demixing effects in the plasma. Such simulations could be validated using the results presented here by replicating the conditions during the experiment.

6. Conclusions

The temperature and partial pressure profiles of an ablation-controlled arc plasma jet in air under high currents are determined from spectroscopic measurements using inverse optimization. This methodology does not require Abel inversion of spectroscopic results and can be applied to heterogeneous plasmas in gas mixtures regardless of their optical thickness. It is performed by minimizing the square residual function between measured side-on radiances and spatially resolved spectral simulation.

The analysis here is performed for an arc plasma jet controlled by ablation of a polymeric nozzle made of Polyoxymethylene copolymer POM-C or polyamide PA6 from a copper electrode. It is found that the temperature is relatively constant across the plasma section, with a slight central minimum. Furthermore, it is shown that demixing takes place in the generated ablation-induced arc, causing separation of the different elements in the plasma. Therefore, complicated partial-pressure profiles are found, defining a thin copper core with low hydrogen pressure surrounded by a high-pressure hydrogen and carbon mantle. These results indicate that the actual thermodynamic and transport properties of the plasma cannot be obtained by assuming simplified, uniform composition of the gas.

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ORCID iDs

Marley Becerra  
https://orcid.org/0000-0002-6375-6142

Jonas Pettersson  
https://orcid.org/0000-0002-5304-191X

Steffen Franke  
https://orcid.org/0000-0002-2806-5055

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