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# TEMPERATURE AND PRESSURE PROFILES OF A PULSED ARC STRIKING AN ALUMINIUM PANEL

F. PAILLOUS<sup>1</sup>, C. ZAEFFEL<sup>1\*</sup>, R. SOUSA MARTINS<sup>1</sup> AND A. SOUFIANI<sup>2</sup>

<sup>1</sup> DPHY, ONERA, Université Paris Saclay, F-91123 Palaiseau, France

<sup>2</sup> EM2C, CNRS UPR288, Université Paris Saclay, CentraleSupélec, 91190 Gif-sur-Yvette, France

\*email of corresponding author: clement.zaepffel@onera.fr

## ABSTRACT

The damage of aircraft outer skin by lightning strike is a complex multi-physics problem and a severe issue in aeronautics. The plasma interacting with the aircraft is a non-stationary and non-optically thin electric arc. Under a 100 kA lightning strike, temperature and pressure up to 40 kK and 20 bars, respectively, are observed in the arc column [1]. Measuring temperature and pressure profile of the arc root is needed to validate numerical simulation of the phenomenon and existing experimental data are seldom in the literature. We propose such measurements in the present study using optical emission spectroscopy and propose a reconstruction method solving the radiation transfer equation to obtain spatial temperature and pressure profiles at different arc lifetimes. We study this interaction on aeronautic aluminium samples 2 mm thick. A 10 cm long pulsed electric arc is generated above the sample. To study the arc root, high speed imaging and optical emission spectroscopy were performed. High speed imaging provides morphology of the arc root and a constriction in the vicinity of the sample is observed. A direct optical setup is developed to obtain emission spectroscopy spectra with an improved spatial resolution compared to previous work. Measurements of temperature and pressure profiles are obtained close to the sample by numerical reconstruction. The reconstruction method based on Spline candidate functions is presented.

## 1. INTRODUCTION

The evaluation of lightning thermo-mechanical constraints for engineering purposes requires an understanding of the macroscopic quantities of the lightning arc, such as the evolution over time of its characteristic dimension and properties.

Among the different diagnostics used to study electrical arc and lightning in particular, optical emission spectroscopy (OES) allows the measurement of electronic temperature and density. Several authors have used Boltzmann plot method or Stark broadening in previous studies [1-3]. However, all these methods require an optically thin plasma hypothesis and, for reliable results, well-isolated and resolved lines, which is a difficult task when working in high current arcs in air. Moreover, in the case of a not reproducible arc as observed during lightning, data need to be determined from a single shot. In a previous study [1], we used a modified Abel inversion method to obtain temperature and pressure profiles of a 100 kA pulsed arc column. In order to measure thermodynamic characteristics of an arc interacting with an aluminium panel, we designed an optical setup to collect directly the light emitted by the plasma along a few centimetres line height with a better spatial resolution compared to our previous work. First, we performed simple observation of the arc interacting with the aluminium panel using a high speed camera and second we used the optical setup to record spectroscopic data. Finally, these data were used to reconstruct temperature and pressure profiles close to the sample as well as mass fraction of aluminium issued from this same sample.

## 2. EXPERIMENTAL SETUP

A lightning current generator from ONERA is used to produce the three current waveforms of the pulsed arcs studied in this work. Figure 1 presents an average of the current measurement and the standard deviation for each maximum level of current. Maximum currents of 100 kA, 50 kA and 25 kA are used.

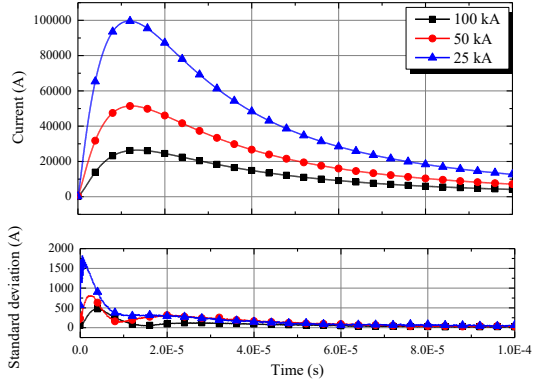


Fig. 1: Average current waveforms and their respective standard deviation for each maximum current used in this study.

As this study is related to lightning in aeronautics, we used standard procedures from this area of expertise to perform each test. We used a diverter electrode (a dielectric ball at the tip of a tungsten electrode) for the anode, and an aluminium T3-2024 sample, 2 mm thick, 400x400 mm, for the cathode. To initiate an arc normal to the sample, a wire composed of less than ten carbon fibres was used. Each carbon fibre has a diameter of  $7 \mu\text{m}$ . This small amount of carbon decreases the contamination of the plasma compared to a metallic wire and still allows a precise positioning on the sample. Figure 2 presents a schematic of the experimental setup. A vision research high speed camera V711 at 370 kfps is used to characterize the arc root. A 512x512 pixels Pi-max2 camera coupled to a SP2750 spectrometer is used to record spectroscopic data. Previously, a 16-fibers bundle was used coupled to the spectrometer mainly to avoid EMC issue on the camera. We designed a direct optical setup consisting in 3 mirrors and 4 lenses, positioned 1 meter from the test area allowing the use of more than 200 lines on our ICCD camera with an optimum light collection. A grating of 300 gr/mm and an entrance slit of  $20 \mu\text{m}$  were used. The camera is triggered and synchronised with the pulsed arc using a high-speed photodiode collecting light emission from the arc.

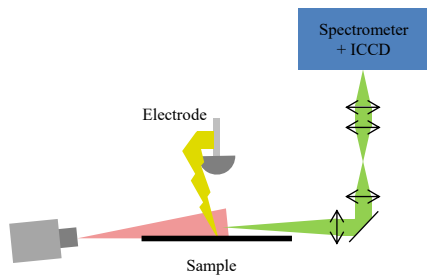


Fig. 2: schematic of the experimental setup.

### 3. RESULTS

In figure 3, three images at different times show the shape of the pulsed arc during the main part of the current waveform, the maximum current being at  $12 \mu\text{s}$ . At 2 cm from the sample, we observed a cylindrical shape similar to the free arc column observed in our previous study [1]. A slight constriction is observed near the sample. Figure 4 is a comparison of the arc radius versus time at 0.2 mm and 20 mm from the sample. A difference between 10 and 17% is observed for the three current waveforms. As each sample was cleaned before the shot, an explanation to this phenomenon is the presence of Laplace forces near the sample constricting the plasma. Those forces are due to the current streamlines in the arc interacting with the magnetic field produced by the current in the sample. The maximum radius is almost doubled between the 25 and 100 kA current waveforms. These values are useful to define a current injection area for numerical simulation of similar sample subjected to lightning.

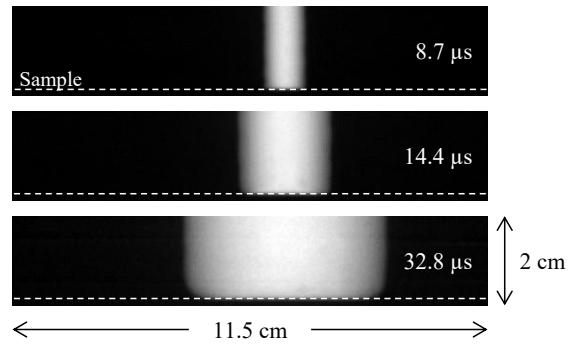


Fig. 3: High-speed camera images of the electric arc above the sample in the case of a 100 kA current waveform at three different times. Exposure time is 300 ns.

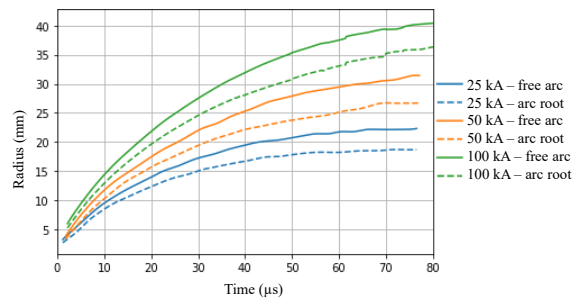


Fig. 4: Comparison of the free arc and arc root radius versus time for three current waveforms.

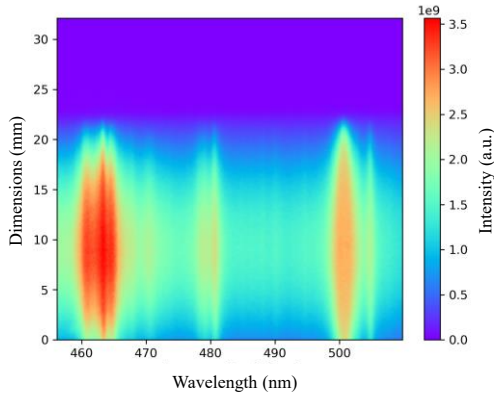


Fig. 5: ICCD camera typical spectroscopic image for a 100 kA current waveform.

Figure 6 is a calibrated image from the ICCD camera. The image of the optical setup is a segment parallel to the sample with adjustable height function of its magnification. The width of this segment is around 500  $\mu\text{m}$  depending also on the magnification. Each line of the camera is a spectrum, several  $\text{N}^+$  multiplets are visible. The aim of the reconstruction methods presented in the next section is to deduced temperature profile from those spectra.

#### 4. TEMPERATURE AND PRESSURE PROFILES

Our previous approach to reconstruct temperature and pressure profiles presented in [1] solved the radiation transfer equation using a modified Abel inversion method. Figure 5 is a schematic of the principles of this method. We consider a cylindrical axisymmetric arc at local thermodynamic equilibrium and the optical setup collect a number of chord crossing this arc. Each chord is a spectrum. A fit of those spectra is possible using radiation model of atomic and ionic lines ( $\text{Ar}^+$ ,  $\text{N}$ ,  $\text{N}^+$ ,  $\text{O}$ ,  $\text{O}^+$ ,  $\text{Al}^{++}$ ,  $\text{Al}^{+++}$ ) as well as continuum emission. In pulsed arc, the stark effect is the main broadening mechanism imposing a Lorentzian spectral line shape. By fitting first the outer chord, we can deduced the temperature and pressure of this annular area. By repeating this method along each chord up to the centre, we can deduce complete temperature and pressure radial profiles. As mentioned, the details of the method are presented in [1] and [5].

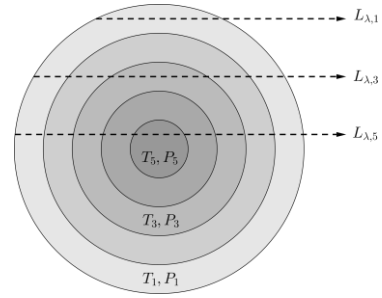


Fig. 6: previous modified Abel reconstruction method [1].

Unfortunately, since an error cumulates at each new chord, this method is not suitable for a direct measurement with 200 spectra. For this reason, we developed a global reconstruction method with the algorithm presented in figure 7. Here we define a candidate function for the profile of temperature  $T$ , pressure  $P$  and aluminium mass fraction  $w_{\text{Al}}$ . As before, the continuum emission is taken into account with a linear polynomial. To avoid imposing a predefined profile, we use Spline function as proposed by Wang [6]. Each Spline function is defined with only a spatial discretization. The advantage of this method is that it solves the whole image and uses the information of all the chords and not just the chord already passed as in the modified Abel method previously employed.

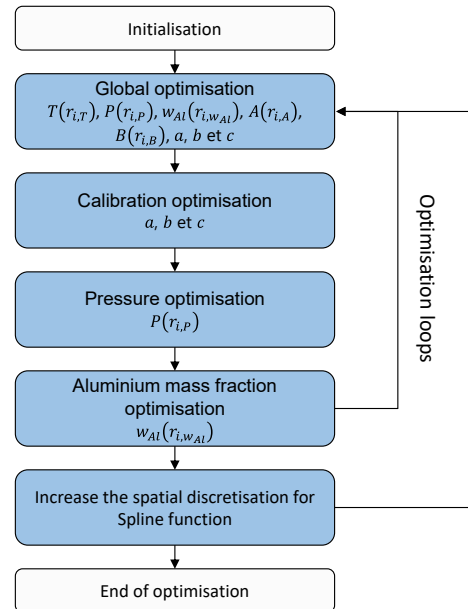


Fig. 7: Algorithm for the reconstruction of the temperature and pressure profile.  $A$  and  $B$ , coefficients for the continuum emission (linear) and  $a$ ,  $b$  and  $c$  coefficients for the wavelength calibration (quadratic).

This method was used to obtain the profiles presented in figure 8. We observe temperature and pressure values in the same range as the free arc

column measurements from [1]. Since we solved the mass fraction of aluminium, we observed the presence of aluminium close to the sample during the first times of the lightning test. This aluminium vapour is then rapidly ejected away from the sample. Unfortunately, this method may be unstable during the minimization process, especially in the pressure optimisation loop. This limits the spatial discretisation of pressure (4-6 points) even if the number of points for the temperature is higher and reaches a converged profile. We still need to asses if pressure profiles, especially at the outskirts of the arc where signal to noise ratio is lower, is physical or a result from the Spline profile determination.

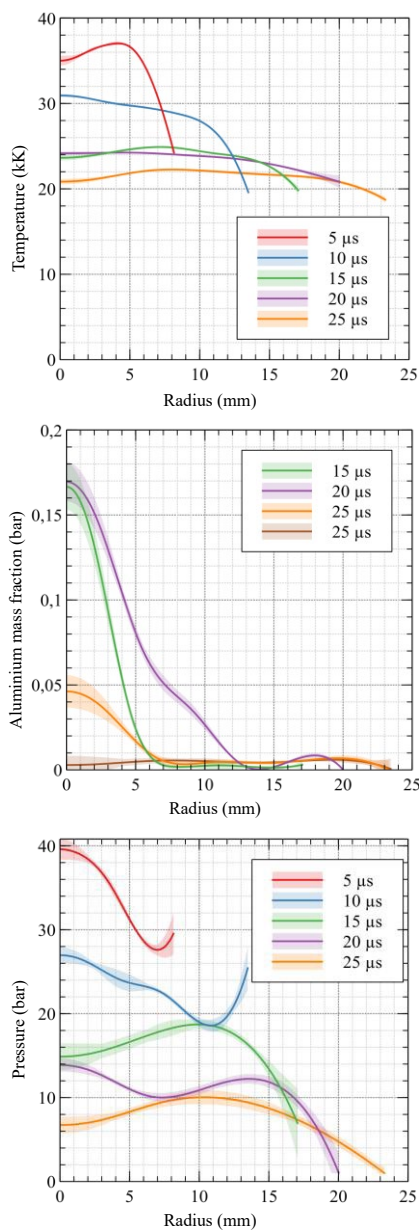


Fig. 8: temperature, aluminium mass fraction and pressure profiles 5 mm above the aluminium sample for different times.

## 5. CONCLUSION

We measured the luminous shape and the emitted spectra of a pulsed electric arc simulating lightning with an aluminium panel. An arc with a cylindrical shape is observed normal to the panel for each current waveform tested. Close to the sample under test, a constriction decreasing the radius by 10-17% appears in each case.

To determine quantitative data to be compared with numerical simulation, a new optical emission spectroscopy setup was designed and tested. This setup allows a better spatial discretisation of the measured plasma cylindrical section. To process the resulting image consisting of an increased amount of spectra, a new method is presented fitting the full image with Spline candidate profile functions. First profiles were obtained and are similar to previous measurements. Despite those results, the developed model is not necessarily stable and improvements are needed to tackle this issue. Especially a physical model for the continuum emission would help stabilize the algorithm in future works.

## ACKNOWLEDGMENTS

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