

SPECTROSCOPIC STUDY AND HIGH SPEED IMAGING OF A TRANSIENT ARC

P. L. RATOVOSON, F. VALENSI, M. RAZAFINIMANANA

Université de Toulouse; LAPLACE (Laboratoire Plasma et Conversion d'Énergie); 118 route de Narbonne, F-31062 Toulouse Cedex 9, France
ratovoson@laplace.univ-tlse.fr

ABSTRACT

In this work, we report an experimental investigation of a transient arc discharge. Characterisation of the plasma properties by the mean of optical emission spectroscopy is conducted. Results are correlated with electrode erosion and show the influence of the resulting metal vapour on the plasma. Their repartition is also evaluated qualitatively by high speed imaging using interferential filters.

1. INTRODUCTION

Transient arcs correspond to high current (several hundred or thousand amperes) and short duration (a few milliseconds to a few hundred milliseconds) arcs. They can occur in many fields when an electric circuit is opened, for instance in the case of losing contact between pantograph and catenary in railway electric traction system [1] or with breaking arcs in circuit breakers [2]. Lightning impacts on structures, such as aircrafts, also fall in this category [3]. These arcs are undesired but unavoidable; they can cause damages due to the high energy released to the surrounding. Since energy from the arc leads to electrodes heating, melting and vaporization, the evaporated material will contaminate the plasma. Better understanding of these phenomena is a key issue to improve the systems performances. In literatures, many works deal with the impact of metal vapor on the arc characteristic [5], [6]. In the case of pantograph arcing, it has been reported that the arc lifetime can vary in a wide range [4]. In order to study the influence of arc duration on erosion and the plasma properties, a power supply with adjustable current and time constant has been developed. The arc established between a graphite cathode and graphite or

copper anodes was characterized by mean of optical emission spectroscopy. Repartition of metal vapor generated by electrode erosion is evaluated qualitatively by high speed imaging.

2. EXPERIMENTAL SETUP

Power supply

The power supply consists in a capacitor bank with capacity up to 144 mF (12mF to 144mF by steps of 12mF). Arc initiation is performed using a high voltage source (HV) connected in parallel to the capacitor bank. The discharge circuit is composed of a ballast resistor and the two electrodes arc setup (figure 1). The maximal current is set by choosing the load voltage (up to 430 V) and the ballast resistor (down to 0.04 Ω), leading to a maximal current of about 10 kA. The time constant can be modified independently (from 1 to several hundred milliseconds) by adjusting the number of connected capacitors. Experiments were conducted with load voltage of 300 V, peak current of 500 or 1000 A and time constant of 24 or 43 ms. Cathode is made of a 6 mm in diameter graphite rod (ensuring limited erosion) with tapered end and anode consists in 6 mm diameter sample with flat surface made of graphite or copper. Arc voltage and current was measured respectively by voltage and current probe (figure 1).

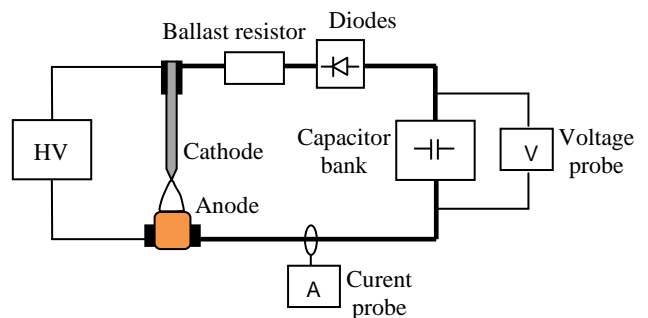


Figure 1: Schematic of the experimental setup

High speed imaging and spectroscopic diagnostic setup

Figure 2 shows a schematic of optical setup for high speed imaging and spectroscopic acquisition. The high speed camera can be adapted on the exit slot of the monochromator for spectra acquisition or placed to view directly the arc for arc geometric configuration observation. In this case the camera gives images of the plasma with high temporal and spatial resolution, allowing study of arc motion and electrode erosion over time. When connected to the monochromator a horizontal plasma slice is observed at a chosen position above the anode, using a dove prism and a two lenses setup with a magnification of 1.

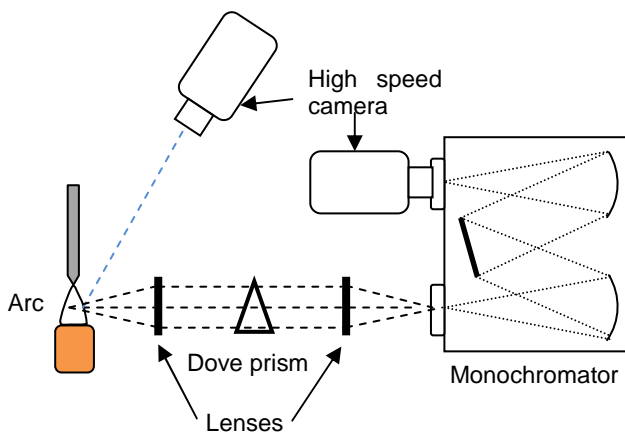


Figure 2: Schematic of high speed imaging and spectroscopic observation system

3. SPECTROSCOPIC DATA PROCESSING

Since the arc is established in atmospheric air, plasma is composed by atom or ion from metal vapour and from air. To determinate the plasma temperature we used the Boltzmann plot method, assuming local thermal equilibrium (LTE), on nine ionized nitrogen lines (N^+) presented in table 1 with their spectroscopic constants. These lines are largely separated in wavelength and cannot be obtained in a single acquisition; absolute intensity was then used after calibration with a tungsten ribbon lamp.

For all spectroscopic results presented on this paper, acquisition was made halfway to a 4 mm electrodes gap (at a position $Z=2$ mm above the anode).

Table 1: List of ionized nitrogen line with their spectroscopic constant

| Species | λ (nm) | E (eV) | A_{jk} | g_j |
|---------|----------------|--------------------|--------------------|-------|
| N II | 444,7 | 23,19 | $1,12 \times 10^8$ | 5 |
| | 460,1 | 21,15 | $2,22 \times 10^7$ | 5 |
| | 463,05 | 21,15 | $7,48 \times 10^7$ | 5 |
| | 566,6 | 20,65 | $3,45 \times 10^7$ | 5 |
| | 567,9 | 20,66 | $4,96 \times 10^7$ | 7 |
| | 571,07 | 20,65 | $1,17 \times 10^7$ | 5 |
| | 592,7 | 23,23 | $3,19 \times 10^7$ | 3 |
| | 595,2 | 23,24 | $1,24 \times 10^7$ | 5 |
| 661,05 | 23,47 | $6,01 \times 10^7$ | 7 | |

4. RESULTS AND DISCUSSIONS

Arc geometric configuration

In the case of copper anode, images in figure 3 show the temporal evolution anode erosion and metal vapour distribution in plasma under the following condition: maximal current peak at 500A and electrode gap of 2mm. Interferential filter centered on strong copper lines ($\lambda=515$ nm, fwhm of 10 nm) is used for the acquisition: the brighter zones will then correspond to high copper vapour concentration. The first image shows the position of electrodes. We observe that anode erosion doesn't occurs instantly when the arc ignites ($t=0$) but after 3 ms of arcing. It increases up to $t=10$ ms then decrease gradually until the arc extinction. The presence of a brighter part, close to the anode, follows the anode erosion: it is stronger between $t=3$ ms and $t=10$ ms and decreases towards arc extinction. It is then expected that the properties of the plasma are significantly modified by strong metal vapor presence. We also observe droplets of copper forming on the anode during the high erosion step (figure 3). After each experiment one can observe a hole formed on the anode surface with droplets randomly disposed on the fringe of it.

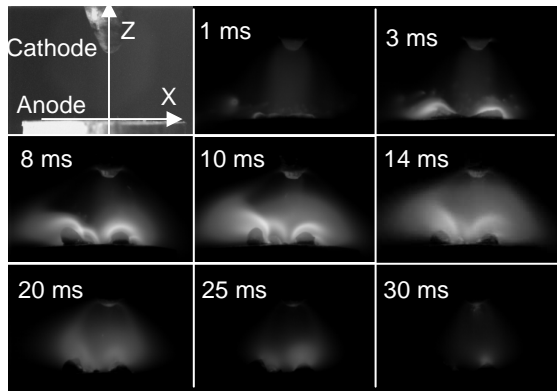


Figure 3: Images of the evolution of copper vapour using copper line filter ($\lambda=515\text{nm}$)

Influence of time constant on plasma temperature

Results presented in this paragraph concern the case of graphite anode. The maximal current was fixed at 1000A. Figure 4 shows the temporal evolution of plasma temperatures on the axis ($X=0$) and at the plane $Z=2\text{mm}$ for two different time constant ($\tau=24\text{ms}$ and 43ms), electrode gap is 4 mm. Temporal variation of currents are also presented in the same figure.

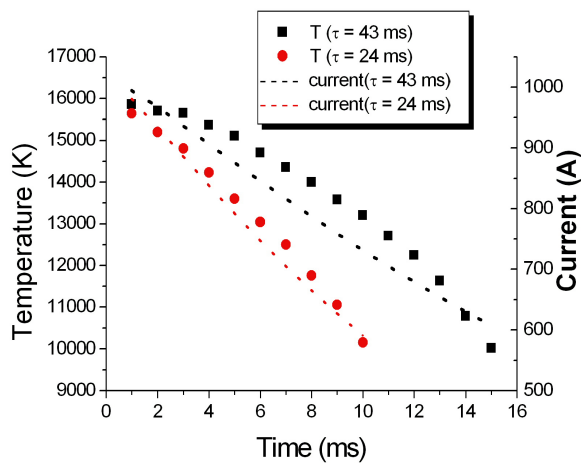


Figure 4: Temporal variation of Temperature at $X=0\text{mm}$, $Z=2\text{mm}$ and current waveform for different time constant

One can see in Figure 4 that variation of temperature is in accordance with the variation of current for the lower time constant ($\tau=24\text{ms}$). With about twice that value ($\tau=43\text{ms}$), temperature and current variation is in accordance for the arc firsts milliseconds then temperature deviates before the two curves intersect again at $t=14\text{ms}$. We have reported on figure 5 the difference between the two experimental conditions for temperature and current as a function of time.

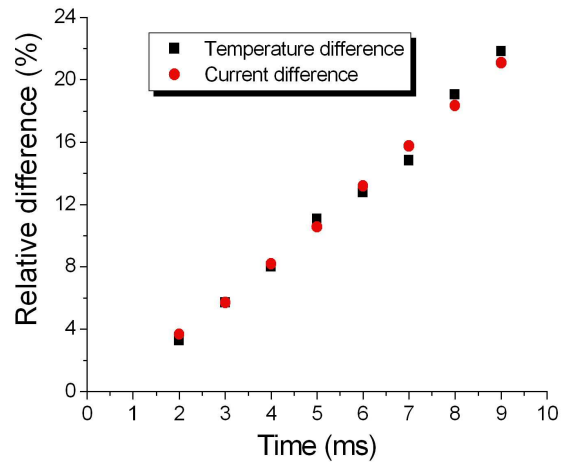


Figure 5: Evolution of temperature and current difference when doubling the time constant.

One can see that the temperature increase when doubling the time constant grows linearly with time and the behaviour is similar for temperature. This confirms the dependence of temperature to arc current. In particular, one can consider that the temperature decrease over time directly corresponds to the current decrease.

Influence of metal vapour on the plasma temperature

To study the influence of metal vapour on the plasma properties, we need to compare plasma contaminated by metal vapour with pure gas plasma. Our system doesn't allow us to have pure air plasma, so we compare plasma using graphite anode with copper anode, considering that erosion in the case of graphite is much lower in comparison with copper or iron, as confirmed by ablated mass measurements. The ablated masses presented in table 2 are average values obtained by weighting anode before and after the arc for several experiments. We have noticed that in the case of copper anode with higher maximal current ($I_{\text{max}} > 1000\text{A}$), droplet of copper (as seen in figure 3) can be ejected from the electrode. Then we chose to consider first the case for maximal current at 500A. Electrode gap is 4mm.

Table 2: ablated mass for copper and graphite anode

| Anode material | Ablated mass (mg) |
|----------------|-------------------|
| Copper | 2,63 |
| Graphite | 0.45 |

Figure 6 shows temporal evolution of the plasma temperature on arc axis ($X = 0\text{mm}$) and at the plane $Z = 2\text{mm}$ under these conditions. Curve of current waveform is presented in the same figure.

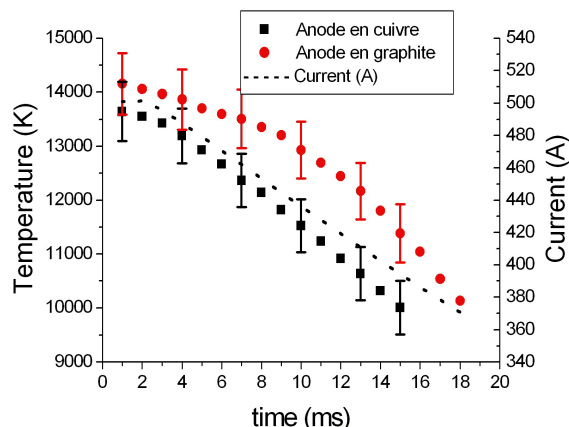


Figure 6: Temporal evolution of temperature with copper and graphite anode

Considering the errors bars, temperature, is significantly lower in the case of copper anode, especially 5 ms after arc ignition.

Considering the difference of ablated mass for copper and graphite material presented in table 1 and assuming that the eroded material spreads in the plasma similarly in both cases, one can suppose that the degree of plasma contamination is higher in the case of copper between 3 ms and 10 ms. This is confirmed by high speed imaging, as shown in figure 3. These results can be explained by the following reasons:

- abundance of metal vapor leads to an increase of the electrical conductivity. The resulting widening of the conduction area causes plasma cooling.
- metal vapor increases the energy loss by radiation which leads also to the plasma cooling.

5. CONCLUSION

The experimental investigation of transient arcs with copper and graphite anodes led to two main results:

- the effect of time constant on plasma temperature has been evaluated and shows that temperature evolution is in good agreement with arc current modification.
- temporal plasma temperature profile shows lower values on arc axis and drops more rapidly in the case of copper anode in comparison with

that of graphite anode. This difference becomes significant a few milliseconds after arc ignition. This result is consistent with ablated mass measurement and observation with high speed imaging: graphite anode erosion is very low and strong copper anode erosion is significant in the time interval 3ms to 10 ms after arc ignition. The cooling effect of copper vapours can then be related to the temperature drop.

REFERENCES

- [1] D. Bormann, S. Midya, and R. Thottappillil, «DC components in pantograph arcing: Mechanisms and influence of various parameters» in Proceedings of 18th International Zurich Symposium on Electromagnetic Compatibility, Munich, Germany, Oct. 2007, pp. 369–372.
- [2] J.W.McBride, P.M.Weaver « Review of arcing phenomena in low voltage current limiting circuit breakers » IEEE Proc.-Sci. Meas. Technol., Vol. 148. No. 1, January 2001
- [3] L. Chemartin, P. Lalande, B. Peyrou, A. Chazottes, P.Q. Elias, C. Delalondre, B.G. Cheron, F. Lago «Direct Effects of Lightning on Aircraft Structure: Analysis of the Thermal, Electrical and Mechanical Constraints» Journal Aerospacelab, Issue 5, 2012
- [4] Miche Jutard, Marc Fitaire, Emile Le Duc, « Moyens d'étude des arcs de rupture du contact pantographe-catenaire » Revue générale des chemins de fer, Nov 1989 – 108th year
- [5] MA Qiang, RONG Mingzhe, WU Yi, XU Tiejun, SUN Zhiqiang « Influence of Copper Vapor on Low-Voltage Circuit Breaker Arcs During Stationary and Moving States » Plasma Science and Technology, Vol.10, No.3, Jun. 2008
- [6] Serge Vacquie « Influence of metal vapours on arc properties » Pure &Appl. Chem., Vol. 68, No. 5, pp. 1133-1136, 1996