Spectroscopic study and high speed imaging of a transient arc

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Abstract. An experimental investigation of a transient arc discharge is reported in this work. The following parameters affecting the discharge properties and electrode erosion were investigated: current, time constant, electrode types. Plasma temperature and electron density were characterized by spatial and time resolved emission spectroscopy. Results are correlated to electrode erosion and show the influence of the resulting metal vapours on the plasma characteristics. Their repartitions were also visualised by high speed imaging using interference filters.

1. Introduction

Transient arcs conform to high current (several hundred or thousand amps) and short duration (a few milliseconds to a few hundred milliseconds). They occur during the separation of two electric contacts 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 and modify its characteristics [4], [5]. Better understanding of transient arc and its interaction with electrode is the key issue to improve systems performances. In order to reproduce and to study this kind of discharge a specific experimental device was conceived. It is composed of a power supply with adjustable current and time constant. The arc established between a graphite cathode (which vaporization can be neglected) and graphite or copper anode was characterized by mean of optical emission spectroscopy. The distribution in the plasma of vapor resulting from anode erosion was analyzed qualitatively by high speed imaging using appropriate interference filter.

2. Experimental setup

2.1. The power supply and electrode configuration

The power supply consists of a capacitor bank with capacity up to 144 mF (12mF to 144mF by steps of 12mF). Arc ignition 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. Electrodes are placed vertically with a gap of 4 mm. The cathode in the upper position is constituted by a 6mm in diameter graphite rod with sharp end. Anode in lower position consists of 6mm diameter
with flat surface made of graphite or copper. All experiments are carried out at atmospheric pressure in air.

Figure 1. Power supply and spectroscopic acquisition system

Arc voltage and current were measured respectively with voltage and current probes. In figure 2, we present the temporal variation of the current for \( I_{\text{max}} = 500 \text{A} \) for three different time constants \( \tau = 24 \text{ms}, 41 \text{ms}, 91 \text{ms} \) and for \( I_{\text{max}} = 1 \text{kA} \) for two different time constants \( \tau = 24 \text{ms}, 41 \text{ms} \). For both studied cases, maximum of current value is reached after 0.1ms as shown in figure 2.

Figure 2. Time variation of the arc current

2.2. Spectroscopic and high speed imaging observation system

Phantom V9.1 high speed camera is used for spectra acquisition and was adapted on the exit slit of the monochromator type Jobin Yvon with 1m of focal distance and a 1200 grooves/mm grating or placed to view directly the arc. In this case the camera gives images of the plasma with high temporal and spatial resolution allowing study of arc displacement and electrode erosion during the discharge extinction. When connected to the monochromator an 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 1). For spectra acquisition, frame rate was 1000 fps and resolution was 800 x 800 pixels and for images of plasma, frame rate was 4000fps and resolution was 480 x 400 pixels.

3. Spectroscopic data processing

3.1. Temperature determination

Plasma is composed by atom and ion from metallic vapours from anode erosion and air. Plasma temperature was deduced from the Boltzmann plot method. Due to the strong presence of copper vapours in the plasma when using copper anodes, copper lines are self-absorbed and cannot be used.
Beside, the observed neutral nitrogen and oxygen lines do not present significant gap between the upper energy transition levels. Thus, we used ionized nitrogen lines (NII) ($\lambda$ = 444.7, 460.1, 463.05, 566.6, 567.9, 571.07, 592.7 and 661.05 nm). They are largely separated in wavelength but unfortunately cannot be obtained in a single acquisition which requires calibration of these lines by the use of tungsten ribbon lamp. For all spectroscopic results presented in this paper, acquisition was made at an intermediary vertical position z = 2 mm above the anode.

3.2. \textit{Electron density}

Electron density was determined by using two different methods:

- Saha’s law applied to N I neutral nitrogen line at $\lambda = 744.2$ nm and N II ionized nitrogen lines at $\lambda = 661.05$ nm
- Stark broadening of H$\alpha$ hydrogen line at $\lambda = 656.2$ nm and of N I neutral nitrogen line at $\lambda = 744.2$ nm

3.3. \textit{Reproducibility}

It is important to verify the reproducibility of the lines used because they can’t be obtained in a single acquisition. We have done several acquisitions for each line in order to have a mean value. Figure 3 shows four measurements of relative intensity of an N II ionized nitrogen line situated at $\lambda = 661.05$ nm at 4 ms and for $I_{\text{max}} = 1$ kA and $\tau = 24$ ms as a function of radial distance x. Maximal deviation from the average value is estimated at 8%.

\textbf{Figure 3.} Measured relative intensity of ionized nitrogen line ($\lambda = 461$ nm) along radial distance x

4. \textit{Results and discussion}

4.1. \textit{Imaging}

In the case of copper anode, we compared images obtained using two different interference filters, one centered on Cu I copper lines ($\lambda = 515$ nm, FWHM of 10 nm) (figure 4) and the second one centered on N I nitrogen lines ($\lambda = 750$ nm, FWHM of 10 nm) (figure 5). The aim is to evaluate qualitatively the temporal evolution of anode erosion, copper vapours and nitrogen distribution in the plasma. These acquisitions were made with a maximal current of 1 kA.
In figure 4, the brighter zones correspond to high copper vapours concentration. One can notice that erosion is very weak and no anode deformation is observable until 3 ms. Then erosion increases as a function of time. It reaches a maximum between 8ms and 10ms and then decreases gradually until the arc extinction. Copper vapours distribution are not uniform in the plasma. On the other hand, the repartition of brighter zones corresponding to high emission of nitrogen lines in figure 5 indicates that nitrogen is distributed uniformly in the plasma. Indeed the lines emission changes seems mostly due to neutral nitrogen concentration; conclusions regarding power density cannot be drawn yet just on the basis of these pictures.

We also see the cathode which radiate like a blackbody, especially within the range of transmitted wavelength by the filter. The arc presents as a bell-shape that shrinks gradually until the arc extinction.

4.2. Influence of Metal vapour on plasma properties

Ablated masses for the two different maximal currents, three different time constants and two different anode materials are presented in table 1. These are average values obtained by weighting the anode before and after the arc for several experiments. According to the ablated mass difference, we suppose that plasma obtained with graphite anode can be considered as pure air plasma for $I_{\text{max}}=500\text{A}$. Thus, comparison between graphite and copper anodes reports the influence of metallic vapours on the plasma characteristics. It is important to mention that for the case of $I_{\text{max}}=1\text{kA}$, droplets of copper forming on the anode and ejected outside were observed during the arc discharge (figure 4). They were taken into account in the ablated mass values presented in table 1 but do not contribute to plasma contamination.
Table 1. Ablated mass for copper and graphite anode

| Maximal current $I_{\text{max}}$ (A) | Time constant $\tau$ (ms) | Mass loss $m$ (mg) |
|------------------------------------|--------------------------|-------------------|
| 500                                | 24                       | 1.35              |
|                                    | 41                       | 1.92              |
|                                    | 91                       | 2.78              |
| 1000                               | 24                       | 14.81             |
|                                    | 41                       | 53.03             |

4.2.1. Influence of time constant on plasma temperature

a) **Case of $I_{\text{max}} = 500A$**

We have reported in figure 6 a) and figure 6 b) the temporal variation of plasma temperature on the axis ($x=0$) at $z=2$mm respectively for the case of graphite anode and cooper anode and for three different time constants ($\tau = 24$ms, 41ms, 91ms). One can note that temperature decreases for the two different anodes from a maximal temperature around 14kK. In the case of graphite anode and considering that erosion is negligible, temporal evolution of the temperature depends only on the variation of current. In the case of cooper anode, the temperatures drop more rapidly than with graphite. We have reported in table 2 cooper anode erosion and the time during which the temperature is above 10kK for the two anode materials and the three time constants.

![Figure 6](image)

**Figure 6.** Temporal variation of temperature for $I_{\text{max}}=500$A and for different time constant: a) graphite anode b) copper anode

Table 2. Comparison of time during which temperature is above 10kK

| Time constant (ms) | Time for $T>10kK$ | Copper anode erosion (mg) |
|-------------------|-------------------|---------------------------|
|                   | graphite anode (ms) | cooper anode (ms) | |
| 24                | 7                 | 6                         | 1.35 |
| 41                | 12                | 10                        | 1.92 |
| 91                | 18                | 15                        | 2.78 |

In both cases, temperatures above 10kK are observed for a longer time as time constant. For the cooper anode, we noticed that erosion increases the same way as the time during which $T>10kK$. This is consistent to the stronger temperature decrease with cooper anode.
To highlight these observations, we reported in figure 7 the difference of the temperature between graphite and copper anodes for the three time constants.

![Figure 7](image)

**Figure 7.** Temporal variation of temperature differential for three time constants

During the first 3 ms after arc ignition, the temperature differences are weak for the three considered time constants. Significant difference is observed from 4 ms and the larger the time constant, the higher the temperature difference.

b) **Case of** $I_{\text{max}} = 1000$A

Results presented in this paragraph concern the case of maximal current fixed at 1kA. Two different time constants were considered ($\tau = 24$ms and 41ms). In figures 8 a) and b), we reported temporal variation of temperature on the discharge axis ($x=0$) at $z=2$mm for the two different time constants and for cooper and graphite anodes.

![Figure 8](image)

**Figure 8.** Temporal variation of temperature for different anode materials: a) $\tau = 24$ms b) $\tau = 41$ms

For the first 3ms the two curves overlap. This corresponds to the delayed erosion noticed by high-speed imaging (figure 4). Difference occurs from 4 ms when erosion begins to appear for the copper anode, with temperature significantly lower in this case. This difference is about 900K at 4 ms and increases up to 1600K at 8ms for the two time constants ($\tau = 24$ms and $\tau=41$ms). Considering the ablated mass in both cases (table1) and with the hypothesis that in the case of copper only half of it was distributed into the plasma, copper vapour rate is five times higher than that of graphite for $\tau = 24$ms and about ten times higher for $\tau = 41$ms. This explains the fact that temperature is lower in
the case of copper. Moreover, graphite anode erosion is not negligible, so plasma formed is composed by air and carbon vapours mixtures. Thus, even with lower erosion, plasma in this case undergoes to a cooling effect since carbon like copper is highly emissive. These results can be explained by the following reasons [6]:

- the presence of metallic vapours leads to an increase of the plasma electrical conductivity. The resulting widening of the conduction area causes plasma cooling.
- the metallic vapours increase the energy loss by radiation leading also to the plasma cooling.

4.3. Electron density number $n_e$

For the electron density number, we consider the case of the maximal current $I_{\text{max}} = 1\text{kA}$ and the time constant $\tau = 24\text{ms}$. Figure 10 shows the temporal variation of electron density on the axis ($x=0$) at $z=2\text{mm}$ for the two different anode materials (copper and graphite).

![Figure 10](image)

Figure 10. Comparison of the temporal variation of electron density for different copper and graphite anode for $I_{\text{max}}=1000\text{A}$ and $\tau = 24\text{ms}$.

One can see that electron density presents a plateau during the first 4 ms for the graphite and the first 2 ms for the copper. These instants correspond to temperature higher than 15kK (figure8). Let us note that at atmospheric pressure, electron density maximal value is about $2 \times 10^{23} \text{m}^{-3}$ corresponding to a temperature value of about 15kK. At 4 ms electron density presents a difference with lower value in the case of copper anode. This difference increases until 8ms. This observation can be explained by the fact that the electron density in the plasma results mainly from ionization of the air (nitrogen and oxygen) beyond temperatures of 10kK [7]. We presented in figure 11, the theoretical value of electron density calculated from the equilibrium composition assuming LTE at atmospheric pressure, in function of mole fraction of copper and for different temperatures. At high temperature ($T>10\text{kK}$) electron density does not vary much whatever the proportion of copper vapour in the plasma between 0.1 %mol and 10%mol.
Figure 11. Theoretical values of electron density depending on copper proportion

The variation of electron density in function of the position deduced from the two different methods are presented in figure 12 under the following conditions: \( I_{\text{max}} = 1 \text{kA} \), \( \tau = 24 \text{ms} \) and copper anode.

- Electron density deduced from Stark broadening of H\( \alpha \) and N I are in good agreement along the profile on a distance of about 2.5mm from the discharge axis.

- Good agreement is observed between electron number densities deduced from Stark broadening measurements and from Saha’s law which assume LTE on a distance from the discharge axis. This distance in which LTE assumption is valid decreases with the time: \( x = 2 \text{mm} \) at \( t = 2 \text{ms} \), \( x = 1.5 \text{mm} \) at \( t = 4 \text{ms} \) and \( x = 1 \text{mm} \) at \( t = 6 \text{ms} \). Deviation from LTE is observed at the edge of the plasma.

5. Conclusion

In this paper, experimental setup simulating transient arc was described. A qualitative analysis of anode erosion, metal vapour and nitrogen atom distributions in the plasma was made by the mean of high speed imaging. A delay of about 3ms is observed for the anode erosion. Results allow expecting modification of plasma characteristics. Plasma temperature and electron density obtained by spectroscopic study are presented for various value of current, time constant and for different anode materials. Results show that presence of copper vapours tends to cool down the plasma. Comparison
between electron densities obtained using Saha’s law and Stark broadening measurement allows us to confirm that LTE is valid within a distance from the discharge axis which decreases with the time.

6. References

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