ON THE OPTICAL RADIATION OF ABLATION DOMINATED ARCS IN AIR

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Abstract: The optical emission of high current electric arcs confined between polymeric (PA6 – C6H11ON–and PMMA –C5H8O2–) and ceramic (Al2O3) walls has been investigated experimentally in air. Arcs standing between copper electrodes with a separation of 8 mm under AC currents with peak values of 2 kA are studied here. The arc optical emission in the range between 250 and 700 nm is measured with a fast spectrometer at the mid-section of the arc column, while the spatial variations of the radiation is recorded with high speed photography. It is found that the ablation of the polymeric walls strongly reduce the intensity of emitted copper peaks as well as the arc column radius. Furthermore, a strong hydrogen Balmer-alpha peak is detected, which indicates the strong injection of hydrogen in the arc atmosphere by the ablation of the polymeric walls.

Keywords: Electric arcs, polymer ablation, radiation

Introduction

Ablation-dominated arcs are a special type of arcs cooled convectively by the flow of vapour produced by ablation (vaporization) of a polymer [1]. Such an ablation process is currently used to cool down and extinguish efficiently air plasma arcs during interruption of electrical currents by power switching devices. Since most of the energy used for polymer ablation comes from the arc radiation [2], it is important to characterize the amount of energy and spectral distribution of the emitted radiation. Even though several experimental studies in the literature have reported measurements of the optical emission of free-burning arcs [e.g. 3], only few have investigated the radiation of ablation-controlled arcs in air.

This paper introduces our first experimental results towards the characterization of ablation-dominated, stationary arcs in air. Optical emission spectroscopy is used to measure the amount of radiation emitted in different wavelength bands and to perform rough estimates of temperature and electron density. In addition, high speed photography is used to record the gross spatial behaviour of the arc radiation during the current flow.

2. Experimental system

2.1. Generalities

The arc is ignited in an 8 mm long air gap between two hemispherically capped copper electrodes mounted vertically in a coaxial cage (Figure 1). Parallel plate walls (4 mm thick) are symmetrically placed into the chamber such that the arc is constricted between them. In this paper, walls made of polyamide PA6 and poly(methylmethacrylate) PMMA are tested to evaluate the effect of ablation on the arc radiation. In addition, alumina Al2O3 ceramic walls are used as a reference of a constricted arc with no ablation.

In the experiment, the ignition of the arc is performed by an external impulse source that generates voltages larger than 30 kV. Once the air gap is bridged by a spark, the bulk current through the arc is supplied by the discharge of a charged capacitor (30 mF) connected in parallel with the electrodes. An inductance is connected in series to the circuit to supply a damped sinusoidal current at a frequency of 50 Hz. The experimental results presented in this paper correspond to a prospective peak current of 2.5 kA and a voltage of 300 V.

2.2. Optical emission spectroscopy

A charged-coupled device (CCD) fast optical spectrometer (AVASPEC-1650F-USB2) is used to detect the optical signature of the arc between 250 and 700 nm. The recorded spectra correspond to the radiation at the mid-section of the arc column along the view slice fixed by a horizontal 50 µm (variable) slit (Figure 1.a). The arc radiation is further attenuated with a neutral density filter (10% transmission) and collimated with a fused silica lens with adjustable focus (Figure 1.c). The spectrometer is triggered by the oscilloscope and the spectra is recorded every millisecond. The raw data (counts) are processed by considering the calibration of the spectral response of the spectrometer, the optical fiber and the collimating lens.
2.3. High speed photography
High resolution pictures of the arc are recorded with a high speed camera FASTCAM A3, with 6000 fps and a resolution of 512x512 pixels. A bandpass filter CWL 510 nm together with a neutral density filter ND8 is used to avoid saturation of the camera. In this way, it is possible to grossly estimate the spatial behaviour of the copper radiation during the current flow.

3. Results
3.1. Electrical signals
Figure 2 shows the comparison between the electrical signals (current and voltage) and the computed injected power for the three cases considered. Observe that there is just a minor reduction of the arc voltage and the total injected power when the ablating polymers are used in the configuration. However, the reignition after the first zero-crossing observed in the case of alumina walls is completely eliminated with the PA6 and PMMA walls.

3.2. Emission spectra
The spectrum of the constricted arc in the configuration for all cases is clearly dominated by copper emission. Figure 3 shows an example of the spectra for the considered cases at a time instant (t=2 ms). Characteristic Cu I peaks are clearly identified from the spectra, namely 324.7, 327.4, 465.1, 529.2, 578.2 nm, with the most intense lines 510.5, 515, 521.8 nm. In addition, Cu II peaks (e.g. 250.5, 254.4, 271.3 and 427.3 nm) can also be identified. Nevertheless, the intensity of copper emission is strongly reduced when the PA6 and PMMA walls are used. On the other hand, the spectra did not show measurable lines characteristic for air arcs (e.g. N I 444.7, 463.0 nm) reported in the literature [3]. Interestingly, a well-defined, intense peak for the hydrogen Balmer-alpha line Hα at 656.3 nm is observed when the ablating walls are used (peak 23 in Figure 3). This peak is present in the case of the arc between Al2O3, although with a significantly lower intensity. Furthermore, notice that there is a distinct, wide peak at 485.3 nm (peak 24) which is only present when PA6 or PMMA walls are used. This peak corresponds to the hydrogen Balmer-beta line Hβ shifted as in [5]. Another interesting feature of the ablated-dominated arcs is the emission of CN violet (B'\Sigma→X'\Sigma) transition only during the first two milliseconds (peak 12 in Figure 3.a). This emission line is probably caused by the creation of this
species by reactions of the ablation products and the surrounding warm air during the early stages of ablation of the wall. Notice that such kind of emission has also been measured for laser ablation of PMMA [4].

Figure 3. Comparison of the spectra of an arc constrained between Al$_2$O$_3$, PA 6 and PMMA at instant $t=2$ ms. The peaks are labeled with numbers for Cu I (3, 8-10, 15–20,22), Cu II (1, 2, 5,6,13,21), H I (23, 24) and CN transition (12).

Irradiance for different bands: In order to compare the differences in the radiating power from the constricted arc with and without ablation, the irradiance for different bands is shown in Figure 4. It is obtained by integrating the spectral irradiance detected with the spectrometer for the bands 250-300, 300-350, 350-400, 400-550 and 550-700 nm. Observe that the arc constricted between Al$_2$O$_3$ walls strongly emits radiation in the UV region (wavelengths lower than 350 nm) compared to the ablation-dominated arcs (accounting for about 60% of the total power in the spectrometer spectral range). The arc radiation is more evenly distributed between the different bands for the case of the polymeric walls. The UV radiation in such case is lower than 40% of the total power in the considered spectral range.

Temperature estimation: The average temperature across the 50 µm mid-section of the arc column is estimated with the line intensity ratio [5] of two copper lines (465.1 and 510.5 nm). These two lines have a large difference in the upper energy levels (7.74 and 3.81 eV respectively) and have a relatively low self-absorption (with absorption coefficients of about 0.39 and 1.2 m$^{-1}$ for 15 kK and 50% Cu concentration [6]). Figure 4.b shows the estimated average temperature of the arc mid-section for the constricted arc with and without ablation. Due to the saturation of the 510.5 nm line for the Al$_2$O$_3$ walls, the temperature in that case is only reported for the first two milliseconds. For the sake of comparison, the arc temperature simulated for the configuration with ceramic walls with our in-house CFD code is also shown.

As it can be seen, the arc temperature is slightly reduced by the ablation of the polymeric walls (compared with the case between Al$_2$O$_3$ walls). This slight reduction of the arc temperature is consistent with the minimum decrease of the arc voltage shown in Figure 1 for PA6 and PMMA walls. Nevertheless, notice that the estimated reduction of 2 kK in the arc temperature for the case of the polymeric walls is comparable with the typical errors of the two line method.

Electron density estimation: Estimations of the electron density by Stark broadening of the H$_\alpha$ are in the order of $10^{23}$ electrons/m$^3$ for the cases here considered.

Figure 4. Estimated values of a) spectral irradiance integrated for different wavelength bands for the considered conditions at time $t=5$ ms, b) the estimated arc column temperature
3.3. High speed photographs

In general, a well-defined arc column is observed in the high speed photographs. However, clear differences are found in the photographs taken for the cases with and without ablating walls. It is found that the arc constricted by Al$_2$O$_3$ walls slowly expands reaching the walls at about 2 ms, while ablation dominated arcs (with PA6 and PMMA) remain confined within well-defined region away from the walls (Figure 5). Thus, the volume of high temperature plasma is significantly larger with non-ablating walls. This would lead to stronger emission intensity for the Al$_2$O$_3$ walls compared to the case of the polymer walls, as reported in the previous section. This decrease in the arc column volume is also consistent with the reduction of the emission intensity reported in Figures 3 and 4. An interesting feature of the ablation-controlled arcs is that the anode jet appears to dominate over the cathode jet. Different to the case with Al$_2$O$_3$, the anode jet between polymeric walls is roughly cylindrical and long (covering more than two thirds of the air gap distance). For the experimental conditions reported here, the radius of the anode jet after the current peak (and for more than 3 milliseconds) is fairly constant and equal to 1.5 mm.

Moreover, observe that there are three distinct regions delimited by a sudden (discontinuous) variation of the radiated intensity in the case of arcs constricted by the PA6 and PMMA (Figure 5 b, c). These regions correspond to the high-temperature bright arc column, an intermediate warm zone around it and a thin layer of colder gas next to the walls. It is noteworthy that radiating gas in the Al$_2$O$_3$ constricted arc is mostly confined in the air gap (i.e. the electrode body appears dark), while the warm gas in the ablation dominated arc appears to flow in all directions (i.e. illuminating the electrodes).

Figure 5. Photographs of the constricted arc for a) Al$_2$O$_3$, b) PA6 and c) PMMA walls at the time $t = 4.5$ ms.

4. Conclusions

The optical emission of ablation-dominated arcs in air between polymeric walls (PA6 and PMMA) is reported and compared with arcs constricted between Al$_2$O$_3$ walls. It is found that the ablation of polymeric walls produces significant changes in the optical signature of the arc (i.e. the reduction of the copper line emission). Particularly, strong emission of the hydrogen Balmer-alpha and beta peaks has been detected, which can be related to the reaction of ablation products of the PA6 and PMMA walls with the high temperature plasma. Rough estimates of the average arc temperature show that it is only slightly reduced in the case of ablating walls. However, photographs clearly show the reduction of the arc column volume by the ablation of the polymer walls. Such reduction leads to the decrease of the emission intensity detected by the spectrometer compared with the case of Al$_2$O$_3$ walls.

Acknowledgment

The authors would like to thank Prof. Aubrecht for letting us use his absorption coefficient code. M.B. would like to acknowledge the financial support of ABB AB, the Swedish strategic research program StandUp for Energy and EIT KIC InnoEnergy.

References