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# Arc tracking power balance: Method for determining fusion and vaporization power

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## Abstract

The energy balance for fault arcs in aeronautic conditions has been studied for copper and aluminium cables. A method based on high speed observation of melted droplets ejected from the electrodes has been developed for lost mass determination. This allows estimating the power needed for metal fusion and by considering the power transferred to the electrodes, the part responsible for vaporization can be estimated. This leads to more accurate determination of the power balance. In addition, this method allows study of the cables erosion as a function of time. Comparison between aluminium and copper cables has been made for various wire diameters. Results show that while the total power transferred to electrodes is lower in the case of copper, the part available for vaporization is greater. As expected, less metal is vaporized for larger cables at the same power. The droplets ejection shows high fluctuations over time but erosion becomes lower and more stable once the two cables are cut.

## Introduction

The next generations of aircrafts will use increasing electric power, due to replacing of hydraulic or pneumatic network with electrical systems and even development of electric propulsion. However, this increase in electrical power which implies higher voltage presents a number of challenges, the main one being the risk of the appearance of fault arcs. In particular, an arc can ignite between cables and propagate along them. This so-called "arc tracking" phenomenon [1] is a problem known for the past two decades in aeronautic and space applications [2]–[4]. These arcs can occur in parallel to the load when the insulation sheath of the wires is damaged [5] or in serial mode in the case of cut wires or loose connections. In order to get a deeper understanding of this phenomenon and its characteristics, it is necessary to establish an arc power balance. It allows estimating the part responsible to wire degradation, the radiated part and the part lost by conduction and convection.

The power balance considered in this study, which was set up in previous studies [6,7] is presented in Fig. 1. The aim of the present work is to improve some part of it, in particular to reduce the uncertainties on the power required for electrode melting and vaporization. A new method has been developed to estimate the part of electrode vaporization power, instead of using values found in the literature. In addition, the electrode fusion power is obtained with a new measurement procedure. Previously, the power corresponding to cable melting was determined from the ablated mass that was measured by weighting the cable sample before and after a test [6,7]. However, in the case of low intensity arcs, the ablated mass is too low to be measured considering weight measurement uncertainties.

Then the new method is based on high speed observation of the wire melting and droplets quantitative detection.

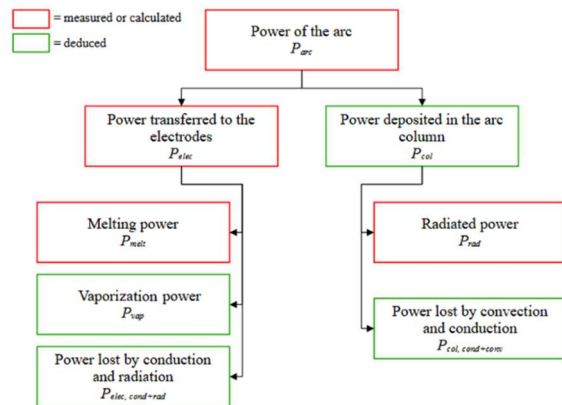


Fig. 1: Power balance of the arc.

## 1. Material and methods

Experiments were performed using a power supply with DC (10-100 A) or AC (35-350 A) output in a chamber allowing to work at ground or reduced pressure (down to 100 millibars). Copper and aluminium aeronautic cables were studied in parallel or serial configuration. In the first case the arc is ignited by powering up the cables and applying droplets of salted water on a part where insulant has been removed on one half of wire diameters for about 1 cm long. In the second case the tips of two cables are placed in contact and the wires are powered up. The ablated mass determination consists in counting the metal droplets ejected during a test using high-speed camera videos. Images are processed using the open-source software ImageJ [8]. On each image of the video, the diameter of each droplet is measured. Only

the droplets within an approximately 4.5 mm thick ring (see Fig. 2c and 2d) surrounding the arc are taken into account, and the images are taken every 5 ms to avoid counting the same droplet multiple times.

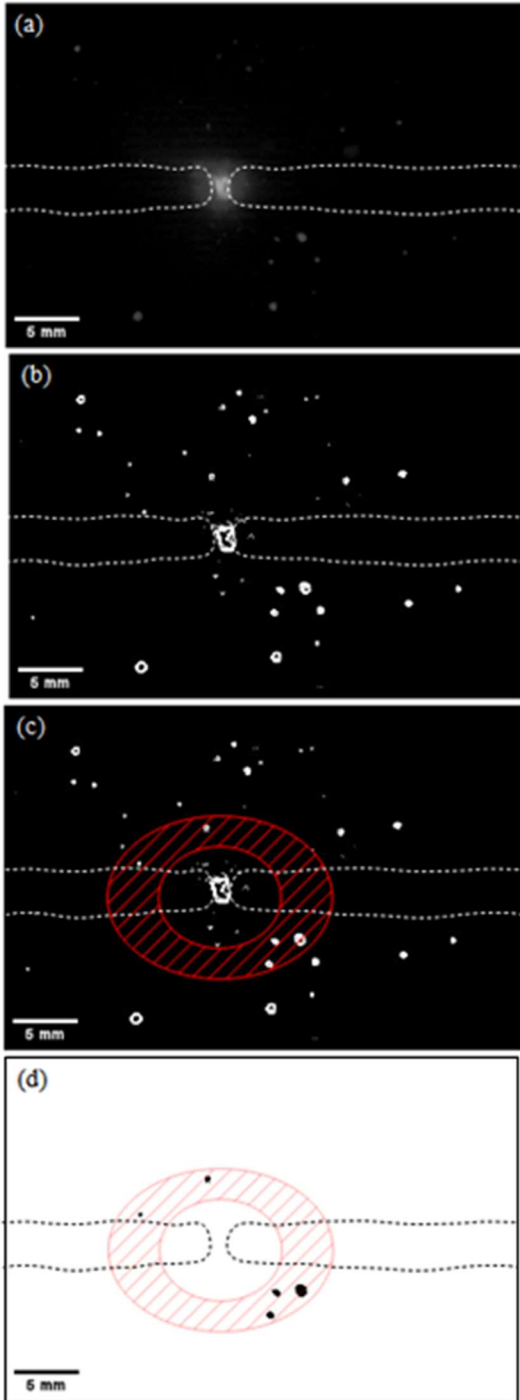


Fig. 2: Method of processing videos on ImageJ: (a) base image (256 grey levels) (b) black and white image (c) counting ring (d) droplets counted by software [Example for a 10A 1atm AD10 serial arc].

By assuming the droplets are spheres, it's possible to determine their volume and the corresponding melted mass. Considering thermodynamic data [9] the power needed for causing this fusion can be estimated. Furthermore, this can allow a temporal study of the

melted mass during the arc lifetime. Some droplets remain attached to the cables and are not expelled, so they are not counted in the videos. This can lead to underestimation of the power required for cable fusion. To take into account this mass, each cable is photographed after the test to estimate the volume of the droplet and deducing the mass, considering its porosity [10].

Finally, the vaporization power is calculated according to Eq. 1, by subtracting the melting power from the power transmitted to the electrodes (which is calculated from current and electrode voltage drop).

$$P_{elec} = P_{melt} + P_{vap} + P_{elec, cond+rad} \quad (1)$$

All power transmitted to the electrodes is assumed to cause cable fusion and vaporization. The power lost through conduction and radiation at the electrodes is neglected, which is an assumption that has been made in other studies [6], [11]. This leads to overestimation of the vaporized mass, but the impact is moderate considering other uncertainties.

## 2. Melted and vaporized mass measurements

The results obtained at high current (350 A) for AC parallel arc at atmospheric pressure show that the vaporization part is about 1% of power transferred to the electrodes. This confirms the previous estimations (1 to 10% were considered). In the case of low current serial arcs (10 A), one can see (in Fig. 3) that the vaporization part decreases when increasing diameter (from AD10 to AD8 aluminium cables).

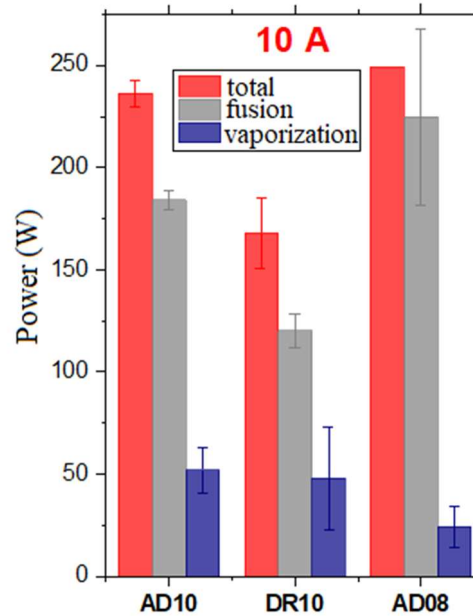


Fig. 3: Power repartition: total transferred at electrodes, melting, and vaporization power.

This can be explained as follows: for the same power and larger cables more energy is first needed for

melting the cables and less power remains for vaporization. When comparing copper (DR) and aluminium cables (AD) for the same diameter (AWG 10), the proportion of power corresponding for vaporization is greater in the case of copper. This trend is even more strong when comparing result for the same nominal current (35 A) with AWG 10 for copper and AWG 8 for aluminium. One has to note that the total power transferred to the electrodes is smaller in the case of copper due to lower voltage drop.

### 3. Ablation over time

In the case of a parallel AC arc at 350 A, the time needed to cut the wires is about 300 ms. The temporal study of droplet ejection shows that the ejected droplets mass decreases after that time as one can see in Fig. 4. This can be explained by the fact that during the first phase of the arc lifetime, the arc is attached on the lateral part of the wires where insulating coating was removed for arc initiation. Once the cables are cut the arc is attached on their extremity, that is to say on a smaller area corresponding to wire cross-section not protected by the insulant. Then even if the power is concentrated on a smaller surface the protective effect of the PTFE coating limits the wire erosion. One can also see that the erosion is a very erratic phenomenon with strong variation of melted mass over time. Again once the wires are cut the fluctuations tend to be smaller. During this second phase of the arc lifetime, the erosion seems to be smaller in the case of reduced pressure.

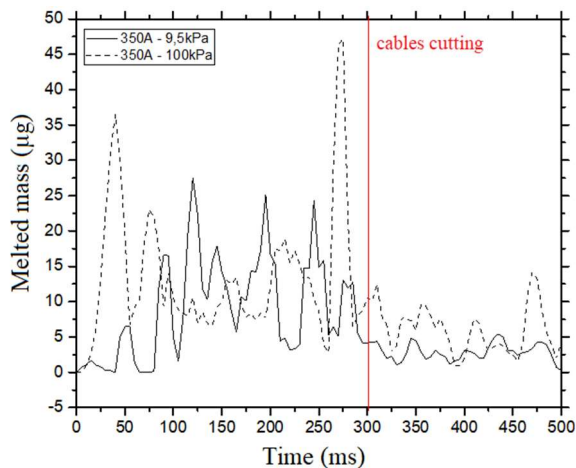


Fig. 4: Melted mass over time for aluminium cables (AWG 8),  $I=350$  A, AC parallel arc

### Conclusions

The method proposed in this work makes it possible to calculate the power required for electrode melting during an arc, while direct measurements by weighing were not possible in our case. This also allows to obtain first values for the power required for vaporization. Results show that with smaller power transferred to the electrodes in the case of copper wires, the part corresponding to vaporization is greater than with aluminium.

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