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Electric Arc During Contact Opening at 540 VDC

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Abstract. For several years now, the gradual electrification of aircraft has been one of the levers for the transition in the aeronautical field. Of course, the all-electric aircraft remains a prospect that does not apply to commercial aviation, but the more electric aircraft, and even hybridisation, seem to constitute concrete developments. Under these conditions, an increase in the electrical power of on-board grids seems inevitable. Future voltages are likely to be ± 270 VDC or more. Such a change entails new constraints, including the need to switch off DC grids at such voltages and, moreover, at sub-atmospheric pressures. In this article, we present experimental work concerning the opening (at DC voltage) of a contact under aeronautical pressure conditions. The experimental conditions are as follows: pressure is between 200 hPa and 1000 hPa, supply voltage is 540 VDC, and the current when the contact is closed is 50 A. The change in contact voltage and current are measured. The influence of pressure on these signals and on the arc structure observed in fast cinematography is presented.

Keywords: Electric arcs, Switching, DC.

1. Introduction

For several years now, the trend of utilising direct current (DC) power for low voltage applications is increasing. This can involve a variety of fields, such as photovoltaic power supplies, fuel cells and batteries. This evolution is linked to the increasing electrification observed in many areas involving embedded network such as automotive, aviation and marine industries. In the aeronautical field, the advantages of this transition to more electric power are numerous: easy control of energy generation, distribution and use, less costly maintenance, fuel savings and a reduction in the environmental impact of flights [1]. Figure 1 illustrates the evolution of power consumption in civil aviation over the past few years and provides short - and medium - term forecasts. The increase in power consumption is accompanied by a sharp increase in the distribution voltage to limit the current magnitude levels. Currently, the voltages envisaged are in the order of ± 270 VDC (540 VDC), or even 800 VDC [2], which is much higher than the voltages used to date (28 VDC).

As a result, various issues directly related to the increase in voltage are emerging. One example is the problem of power switching in DC systems operating at voltages of several hundred volts which is more complex than in the AC mode. Indeed, in AC operation, current flowing through zero makes arc extinction easier. In DC mode, the arc can only be extinguished when the voltage required to maintain the arc becomes higher than the supply voltage. Furthermore, it should also be noted that the pressure during flight, which varies from atmospheric pressure (at ground level) to approximately 200 hPa (for a flight altitude of approximately 12,000 m), plays an important role in maintaining the arc and makes it more difficult to break. This article therefore concerns the study of a DC arc under a 540 VDC supply for two pressure values: 1000 hPa and 200 hPa. The main objective of this study is to better understand experimentally the role of pressure both from the point of view of the structure and behaviour of an arc and from the point of view of the associated electrical signals. The rest of the article is organized as follows :

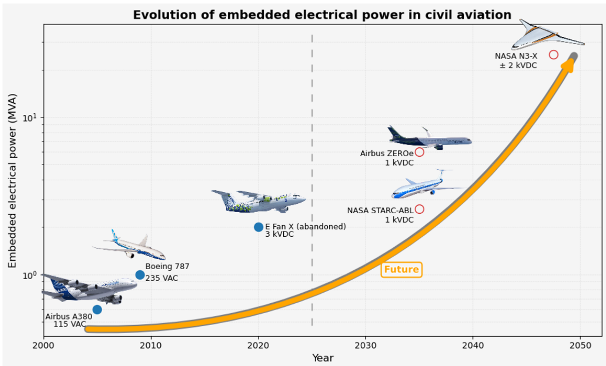


Figure 1. Evolution of embedded electrical power in civil aviation (and evolution of supply voltage) and forecasts.

- ☐ A brief bibliographic review will be provided of studies conducted in recent years on power switching, particularly those concerning the aeronautics sector.
- ☐ The experimental setup used for this study will be briefly described.

- ☐ A few examples of results will be presented to provide a better understanding of how the experiments were conducted. The reproducibility of the results will then be discussed.
- ☐ Results concerning both electrical signals and observation of the arc using high-speed cinematography will then be presented for the two pressures, 200 hPa and 1000 hPa.

2. Rapid review concerning some properties of electric arc under DC voltage.

Studies on DC electric arcs under aeronautical pressure conditions, particularly at voltages ranging from a few tens to several hundred volts, remain limited. For higher supply voltages — such as 540 VDC — relevant research dates back to the 1950's [3–6] mainly focused on traction systems and avionics. These early works primarily addressed the characterisation of components like contactors and circuit breakers. Among them, Phillips and Mitchel [3] focused on estimating voltage spikes occurring during DC switching as a function of pressure. Quill and Rader [4] investigated how pressure and arc current magnitude influence arc duration. In more recent years, some investigations have looked into the effect of pressure on standard switching devices [7]. However, the majority of contemporary research on DC arcs has centred around the automotive sector, where embedded voltages typically range from 36 V to 42 VDC.

The most straightforward method for studying the spatial extension of an electric arc involves increasing the distance between electrodes and identifying the point at which the arc extinguishes. This distance is influenced by several factors, including the electrode separation dynamics, the type and pressure of the surrounding gas, and the electrical load—particularly the presence or absence of inductance. Several authors have proposed models for estimating the maximum arc length as a function of parameters such as supply voltage, opening speed, and arc current magnitude. Most of these studies have been conducted at atmospheric pressure and in the context of automotive applications, focusing on low-current arcs ($I < 10$ A) and supply voltages between 14 V and 42 VDC [8]. Electrode materials commonly used in these experiments are typical of electrical contact applications, such as gold (Au), silver (Ag), or silver-metal oxides (*e.g.*, Ag-SnO_2 or Ag-CdO) [9, 10]. Under such experimental conditions, arc lengths typically reach a few millimetres and generally increase with arc current magnitude. Only a few studies have investigated copper electrodes under higher voltage and current conditions [11–14]. In these cases, for arc currents exceeding 100 A, it has been observed that the maximum arc length does not necessarily increase with current. Instead, high current levels can induce electromagnetic instabilities that distort the arc column. More recently, academic research [15, 16] has begun to explore electric arc characteristics under pressures ranging from 10^4 to 10^5 Pa, at voltages around 36–42 VDC, and with arc currents of several tens of amperes. Similarly, for higher voltages (540 VDC), the works of R. Landfried [17] and M. Boukhlifa [18] can be cited. They respectively focus on the stability of the arc for various values of pressure (100 hPa – 1000 hPa) and current magnitude (10 A – 100 A) and examine the electrical characterisation in terms of electric field, anodic and cathodic voltage drop, of an arc with a length ranging from 10 mm to several hundred mm.

3. The experimental setup

The experimental device has already been described in [17].and will be briefly recalled. Figure 2 gives a schematic electrical diagram of the experimental system and figure 3 is a photography of the mechanical part of the experiment and of the electrodes.

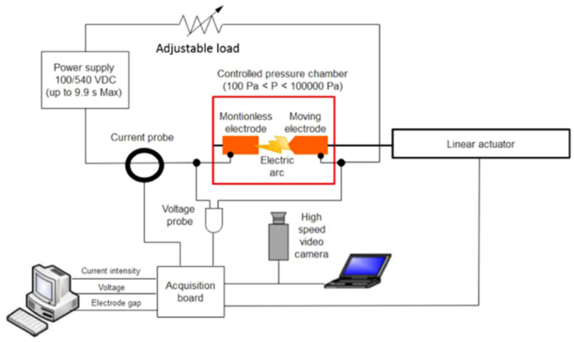


Figure 2. Schematic electrical diagram of the experimental system [17]

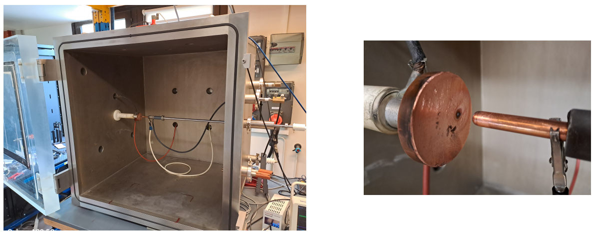


Figure 3. Photograph of the experimental set-up and zoom on the contact electrodes

On the one hand, the experimental setup consists of a mechanical device for opening a contact consisting of two electrodes, one of which is fixed, while the other can be set in motion by a controlled electric actuator. In this study, the average opening speed is of the order of 100 mm/s. The maximum inter-electrode distance (denoted d) is 10 mm. The electrodes are made of OFHC copper. The assembly is placed in a vacuum chamber with a polycarbonate door, enabling the opening arc to be observed. Figure 4 shows the evolution of the inter-electrode distance during opening for two values of pressure in the chamber (1000 hPa and 200 hPa). d does not really vary linearly with time. However, it is reproducible over the course of the tests, independently of the pressure in the chamber.

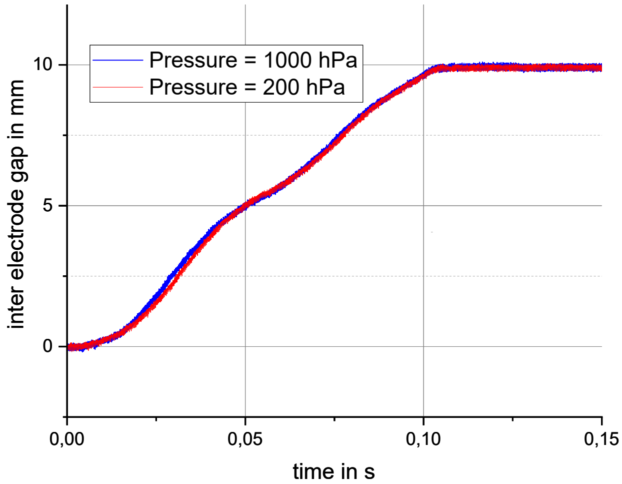


Figure 4. Evolution of the inter-electrode gap for two different pressures

On the other hand, a DC power supply composed of a bank of super capacitors is able to deliver a set DC current. In this study, we set it to 540 VDC, which does not mean the arc voltage will reach this value, since the the maximum gap is 10 mm. The load in the circuit is used to set the value of the current magnitude when the circuit is closed (noted Icc). The current magnitude and the electrode voltage evolutions are measured during the arc. The electrode gap is measured using a potentiometric transducer with an accuracy of 100 µm. The arc is observed with the help of two high speed cinematography cameras Fastcam MiniUX50. One of the cameras is used with a filter centered on one of the lines emitted by the copper vapor in the arc plasma at 521 nm ; the second one is used without any filter.

4. Experimental results

4.1. An example of electrical signal during the opening phase

In figure 5 we present a typical example of electrical characteristics in the following case: the current in the closed contact (denoted I_{cc}) is approximately 50 A and the pressure equal to 1000 hPa. Three stages can be distinguished:

- ☐ a first stage when the contact is closed. The current is then constant in the contact.
- ☐ A second one, the opening stage, which begins with the arc ignition when the electrodes separate. The opening stage can be divided into two phases. The first phase lasts for about 5 to 10 ms and is characterised by a rapid voltage rise to a value corresponding to the sum of the anodic and cathodic drops, while a slight decrease in current magnitude, due to the high voltage supply value, can be observed. This is followed by a second phase, during which the voltage continues to increase but at a slower rate. For about 30 to 40 ms, corresponding to a contact separation of around 5 mm, the arc voltage rises steadily, indicating a stable arc. After that, voltage peaks appear, associated with arc instabilities captured by the high-speed camera, such as column distortions or motions of the arc roots on the electrodes. Since the contact separation is directly linked to the opening speed, these two phases can be correlated respectively with a strong electric field in the arc column during the first phase and a weaker field during the second.
- ☐ After 100 ms, opening is complete, current magnitude is almost constant, and a few instabilities in arc voltage can be observed. The arc is then extinguished as the power supply limits the duration of the current pulse.

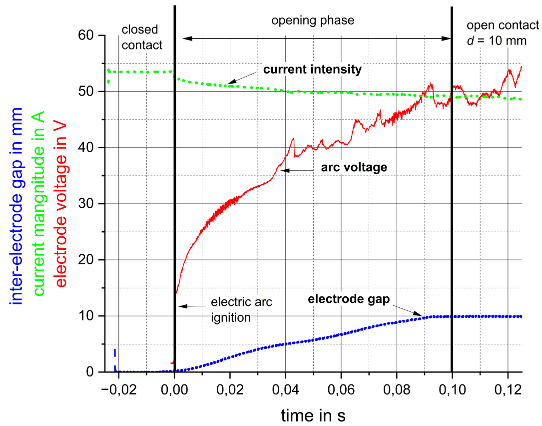


Figure 5. Typical evolution of arc current magnitude, arc voltage and electrode gap for $P = 1000$ hPa.

4.2. Influence of pressure on the electrical characteristics of the opening phase.

Figure 6 shows the minimum, maximum, and average values of the measured voltages obtained from eight tests during the opening stage for two pressure values ($P = 200$ hPa and $P = 1000$ hPa). Each individual test curve lies within the range defined by the minimum and maximum values. A zoom of first 25 ms of the figure 6 opening is shown in figure 7. During the first milliseconds, the curves are almost identical, and differences start to appear after approximately 10–15 ms (equivalent to an inter-electrode distance between 1.2 and 2 mm). Beyond that, the arc voltage measured at $P = 1000$ hPa is higher than at $P = 200$ hPa. One possible interpretation is in line with Gray's [19] work on short arcs. For short distances just after opening, most arcing takes place in the electrode vapour resulting from the explosion of the molten bridge created when the contact opens. At longer inter-electrode distances, plasma gas pressure begins to play a role. It is interesting to note that voltage instabilities appear a few milliseconds after opening for $P = 200\,\text{hPa}$. These voltage instabilities do not appear for $P = 1000\,\text{hPa}$ and seem to exist only for pressures below 200 hPa. They are likely to be linked to specific phenomena that can be significant for these pressures [20].

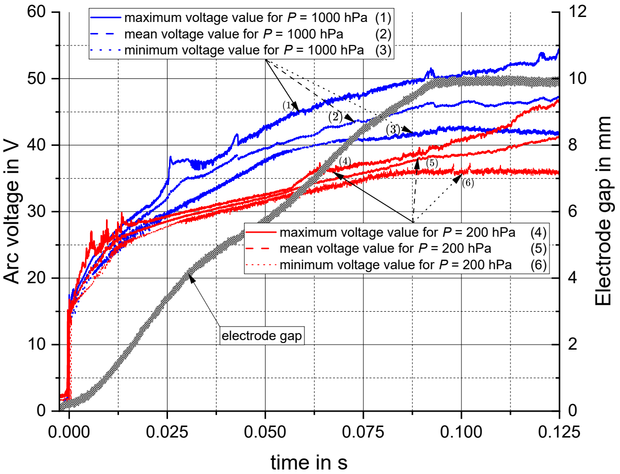


Figure 6. Maximum, minimum and average curves of measured voltage values at 200 hPa and 1000 hPa for 8 tests

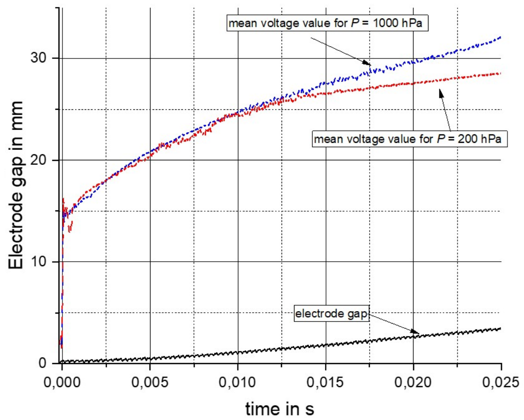


Figure 7. Figure 6 zooms in on the first 25 ms of the opening stage.

With regard to the evolution of the arc current, it seems more appropriate to focus on the quantity ΔI defined by formula 1 than on the evolution of the power supply current magnitude itself, The latter is controlled within approximately ±5%, mainly due to the uncertainty of the supply voltage (±10 V, i.e. about 2%) and to the contact resistance, which is not a reproducible parameter. In our case, the short-circuit current I_{cc} varies between 51 A and 53 A during the tests.

$$\Delta I(t) = I_{cc} - I_{arc}(t) \tag{1}$$

Figure 8 shows the maximum, minimum and average curves of calculated ΔI for 8 tests during contact

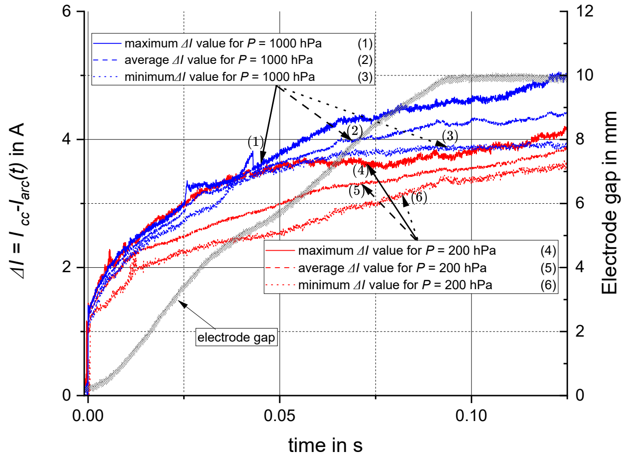


Figure 8. Maximum, minimum and average curves of ΔI, electrode gap evolution during contact opening for 200 hPa and 1000 hPa

opening for the two pressure values. The electrode gap evolution is recalled.

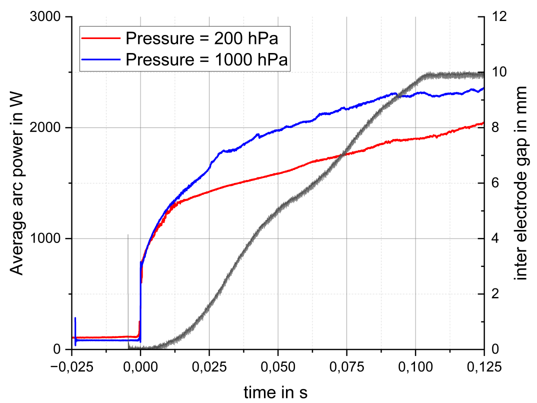
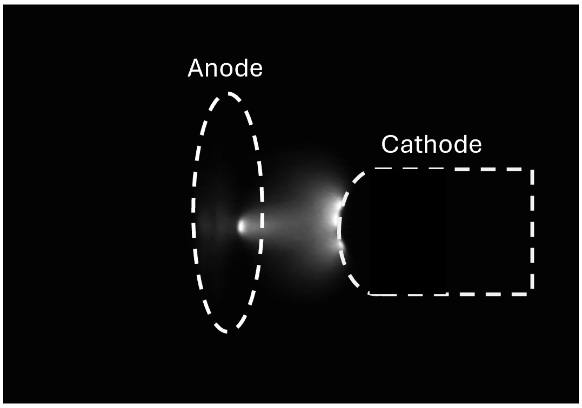


Figure 9. Evolution of average arc powers for P = 1000 hPa and P = 200 hPa

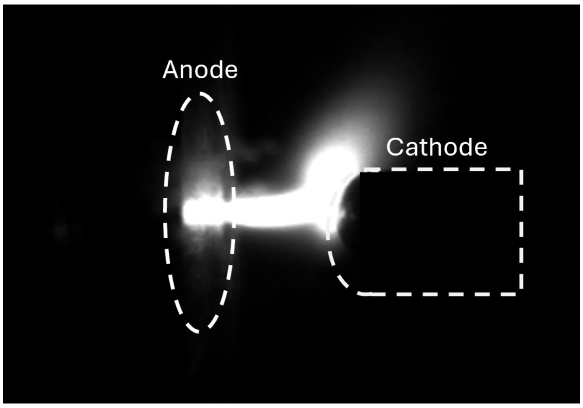
We then looked at the power dissipated at these pressures. Figure 9 shows the evolution of average powers over 8 tests for both pressures. The powers dissipated in the arc remain similar for both pressures during the first ms after opening. Thereafter, they exhibit similar behaviour to the arc voltage. The power dissipated at 1000 hPa becomes around 20% higher than the power dissipated at 200 hPa.

4.3. Observation of arcs using fast cinematography

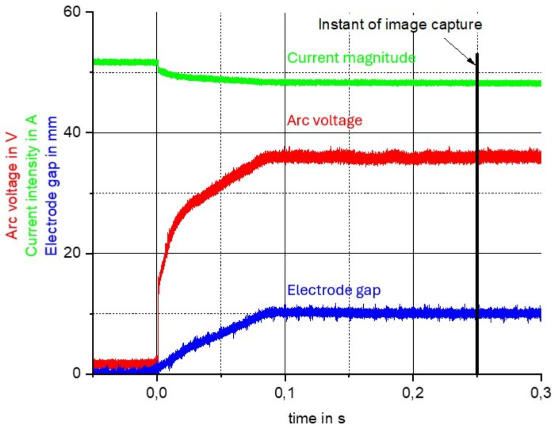
To observe potential differences in behaviour as a function of pressure, films were made at several pressures with two synchronised cameras (recording speed = 5000 frames/s) filming the same arc, with a resolution of about 150 µm/pixel. One of the cameras was equipped with an interference filter centred on one of the copper emission lines (521 nm). In figure 10 we present images extracted from films made with the same camera settings and the respective electrical signals in the case of an electric arc at 200 hPa (fig-



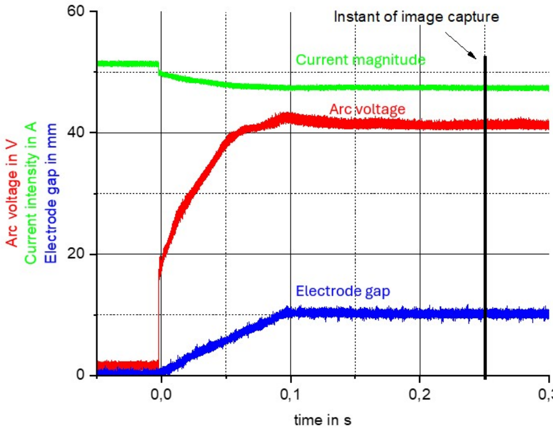
(a) . Image extracted from a fast cinematography film for $P = 200\,hPa$



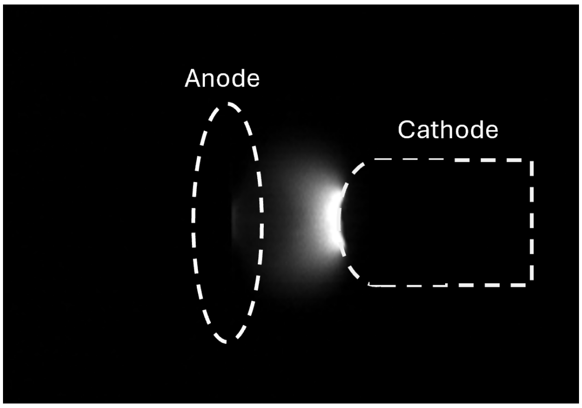
(b) . Image extracted from a fast cinematography film for $P = 1000\,hPa$



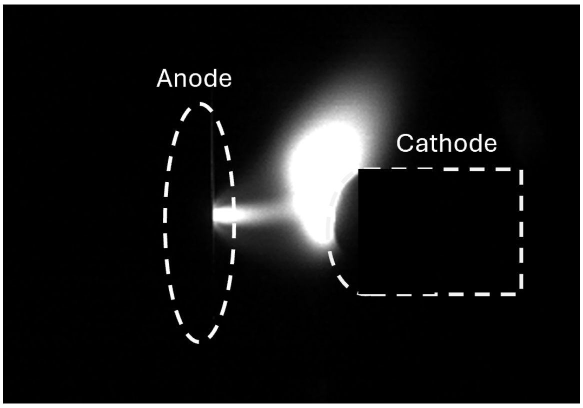
(c) . Electrical signals (current magnitude, arc voltage and inter-electrode distance) for $P = 200\,hPa$



(d) . Electrical signals (current magnitude, arc voltage and inter-electrode distance) for $P = 1000\,hPa$



(e) . Image extracted from a fast cinematography film realized with a filter centred on line 521 nm for P = 200 hPa.



(f) . Image extracted from a fast cinematography film realized with a filter centred on line 521 nm for P = 1000 hPa

Figure 10. Fast cinematography results and electrical signals

ures 10a, 10c and 10e) and an arc at 1000 hPa (figures 10b, 10d and 10f).

Images were taken in both cases 250 ms after opening. In order to understand the images, the shooting conditions for the two pressure values are identical (number of frames per second, exposure time, lens aperture setting). Images 10a and 10b were acquired without filter (f/16, 20 µs exposure), while images 10e and 10f were acquired with filter (f/2.8, 200 µs). The corresponding electrical signals are presented in Figures 10c and 10d. In the various images, the outline of the electrodes has been added in white dotted lines.

Observations made without a filter show that the arc at 1000 hPa is much brighter than at 200 hPa. Moreover, at lower pressure, with the filter, only the cathode zone remains bright. This seems to give insight into the qualitative distribution of copper vapour between the anode and the cathode at the two pressures, as seen in [21]. Optical emission spectroscopy measurement would be then necessary to quantify the copper vapour concentration, provided that local thermodynamic equilibrium is satisfied.

5. Conclusion and perspectives

Voltage and current evolutions were presented for opening arcs in air under a 540 VDC supply, at 200 hPa and 1000 hPa, with copper electrodes. The influence of air pressure on the structure of the arcs has been addressed through high-speed imaging.

This study will be extended in order to cover a broader range of pressures between 200 hPa to 1000 hPa, and to try to quantify copper vapour concentration at the electrodes with respect to gas pressure.

References

[1] G. Buticchi, P. Wheeler, and D. Boroyevich. The more-electric aircraft and beyond. *Proceedings of the IEEE*, 111(4):356–370, 2023. doi:10.1109/JPROC.2022.3152995.

[2] S. Ngo Bui Hung, C. Gautier, L. Pniak, et al. Dimensionnement d'un convertisseur mmc pour la génération électrique d'un réseau de bord aéronautique. In *Proceedings of Symposium de Génie Électrique*, July 2025.

[3] V. E. Phillips and W. P. Mitchel. Peak voltages with d-c arc interruption for aircraft. *Electrical Engineering*, 63(12):944–949, 1944. doi:10.1109/EE.1944.6440632.

[4] J. S. Quill and L. T. Rader. D-c arc interruption for aircraft. *Transactions of the American Institute of Electrical Engineers*, 63(12):883–888, 1944. doi:10.1109/T-AIEE.1944.5058820.

[5] T. R. Stuelpnagel. An environment-free 120-volt d-c limit switch. *Electrical Engineering*, 69(12):1070–1070, 1950. doi:10.1109/EE.1950.6437145.

[6] B. S. Beall and P. J. Reifschneider. New circuit breaker for aircraft electric systems. *Electrical Engineering*, 71, 1952. doi:10.1109/TAI.1952.6371253.

[7] T. Klonowski, F. Mercier-Calvairac, F. Etchenique, et al. Characterization of hvdc contactors in depressurized environment. In *More Electrical Aircraft*, February 2019.

[8] J. Swingler, A. Sumption, and J. McBride. The evolution of contact erosion during an opening operation at 42v. In *Proceedings of the Fifty-First IEEE Holm Conference on Electrical Contacts, 2005.*, pages 346–351, 2005. doi:10.1109/HOLM.2005.1518268.

[9] T. J. Schoepf. Electrical contacts in the automotive 42 v dc powernet. In *Proceedings of the 21th International Conference on Electrical Contact*, 2002.

[10] L. Doublet, N. Jemaa, F. Hauner, and D. Jeannot. "electrical arc phenomena and its interaction on contact material at 42 volts dc for automotive applications". In *Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts Electrical Contacts, 2004.*, pages 8–14, 2004. doi:10.1109/HOLM.2004.1353087.

[11] P. Colombo, M. Bigliati, and C. Lonzar. Arcing study in high current electromechanical switching for future 14-42v dual voltage systems. *SAE Transactions*, 111:265–272, 2002. URL: http://www.jstor.org/stable/44699422.

[12] P. Teste, T. Klonowski, R. Andlauer, and T. Leblanc. Study of the properties of high intensity switchingunder 36 vdc. influence of the contact material. *The European Physical Journal - Applied Physics*, 41(3):251–264, 2008. doi:10.1051/epjap:2008028.

[13] K. Yoshida, K. Sawa, K. Suzuki, and K. Takaya. Influence of opening velocity on various characteristics in dc high voltage ag break arc. In *2015 IEEE 61st Holm Conference on Electrical Contacts (Holm)*, pages 111–116, 2015. doi:10.1109/HOLM.2015.7355083.

[14] W. Kim, Y.-J. Kim, and H. Kim. Arc voltage and current characteristics in low-voltage direct current. *Energies*, 11:2511, 09 2018. doi:10.3390/en11102511.

[15] R. Boukadoum, R. Landfried, T. Leblanc, et al. Role of the pressure in the dc electric arc characteristics application: case of the more electrical aircraft. 06 2016.

[16] R. Landfried, L. Savi, T. Leblanc, and P. Testé. Parametric study of electric arcs in aeronautical condition of pressure. *The European Physical Journal Applied Physics*, 67:20802, 08 2014. doi:10.1051/epjap/2014140065.

[17] R. Landfried, M. Boukhlifa, T. Leblanc, et al. Stability, spatial extension and extinction of an electric arc in aeronautical conditions of pressure under 540 vdc. *The European Physical Journal Applied Physics*, 87, 09 2019. doi:10.1051/epjap/2019190029.

[18] M. Boukhlifa. *Contribution à l'étude des arcs électriques sur réseau HVDC (540 VDC) en conditions aéronautiques*. PhD thesis, Université Paris-Saclay, 2021. Thèse de doctorat dirigée par Testé, Philippe et Landfried, Romaric Génie électrique université Paris-Saclay 2021. URL: http://www.theses.fr/2021UPAST013.

[19] E. W. Gray. Some spectroscopic observations of the two regions (metallic vapor and gaseous) in break arcs. *IEEE Transactions on Plasma Science*, 1(1):30–33, 1973. doi:10.1109/TPS.1973.4316076.

[20] C. Pietri, R. Landfried, T. Leblanc, and P. Testé. Voltage evolution in low pressure free electric arcs in air. To be published in ICPIG 2025 Proceedings.

[21] F. Valensi, P. Ratovoson, M. Razafinimanana, and A. Gleizes. Anode energy transfer in a transient arc. *Journal of Physics: Conference Series*, 825(1):012018, mar 2017. URL: https://doi.org/10.1088/1742-6596/825/1/012018, doi:10.1088/1742-6596/825/1/012018.