Study of a high current arc used for direct lightning effect characterization

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STUDY OF A HIGH CURRENT ARC USED FOR DIRECT LIGHTNING EFFECT CHARACTERIZATION

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ABSTRACT

Composite materials are used in aeronautics for their mechanical properties and their lightness. Unfortunately, their conductivity is not isotropic and is lower than Aluminum, the material previously used. When a lightning event occurs, if the material resistance is too high, the current flowing in the structure may induce damage. To prevent this, new aeronautic materials are tested according to the following test procedure: a 100 kA impulse current flows in the material through a 10 cm arc. As our team develops codes on this problematic [1] to model and simulate the effect of such high current on new materials, we built a test bench producing a 10 cm arc of 100 kA with a biexponential current curve as defined by the aeronautic standard. The measurements obtained with this system will provide necessary data to validate our MHD simulation code.

This work presents the test bench, the current associated diagnostics and the preliminary results. Firstly, fast imaging is used with a 500 kfps camera to gather qualitative results such as arc dimensions and arc turbulence observation. Secondly, emission spectroscopy provides quantitative data on plasma temperature and pressure by solving the equation of radiative transfer on two positions across the plasma channel and for different timing.

1. INTRODUCTION

Electrical arcs are widely used in the industry for welding, cutting, waste treatment and spraying. In the later two applications, the arc is unsteady and investigation is needed to fill the lack of understanding of their behavior. Lightning is another phenomenon where an uncontrolled and unsteady arc occurs. Lightning induced heat and erosion to the material it strikes. Those damages to the material are especially an issue in the case of aircraft using composite materials for the fuselage. Despite of lower conductivity to disperse the charges induced by lightning compared to aluminum, manufacturers use composite material and have to pass standard tests such as the ones described in SAE ARP5412 [1] to ensure the flying ability of their material.

Standard advises a current waveform and a configuration to certify structures against lightning re-strike. The configuration is composed of two electrodes, one being a sample of aircraft fuselage, in our case a 50 cm large square piece. Current has to flown on the outline of the sample, the arc striking the middle. The other electrode is a tungsten rod with a dielectric piece placed on the tip. This piece is called the ‘jet diverter’ and is used to avoid the direct impact of the jet of plasma towards the sample. The current waveform named D in the case of a re-strike is defined as a 100 kA biexponential lasting 500 µs.

In order to understand this type of discharge, test different materials and validate our MHD code [2], we have designed and built a setup to produce a current D waveform as described by the standard and we have run preliminary tests and measurements. This setup will be used in future works on aeronautic materials, but we limited the current study to aluminum material, thus our samples are made of 1.5 mm thick aluminum plate.

This paper will first describe the test bench and present the electrical characteristic, then fast imaging is presented and radius of the arc channel is deduced. This radius is then used to solve the radiative transfer equation (RTE) and fit our spectra obtained by emission spectroscopy yielding to the pressure and temperature of the arc.

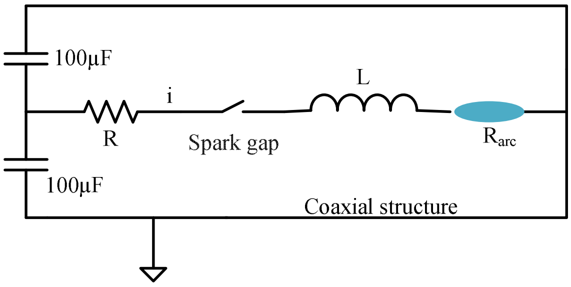

Figure 1: Electrical circuit of the test bench.

2. EXPERIMENTAL SETUP

In order to produce the current waveform D, that is an electrical arc of 100 kA and 10 cm, we use a RLC discharge circuit shown on figure 1. Four 50 µF high voltage capacitors mounted in parallel are charged up to 20 kV storing an energy amount of 40 kJ. They are then discharged through a series of high power resistance into the arc using a spark gap. The resistances with an equivalent value of 0.19 ohms allow controlling the current curve and especially the maximum. As described before, the arc occurs between a tungsten rod and the plate under test. But a charging voltage of 20 kV is not sufficient to discharge across a 10 cm gap, thus a thin wire of 20 µm is connected across the gap using a piece of tape or a knot before each shot. During the first microsecond, this wire is evaporated and its influence is neglected for the current study as copper lines are only observed in spectroscopy measurement during the first 2 µs. In order to trigger the discharge, a high pressure spark gap working in nitrogen is used. This spark gap is able to sustain high current with high dI/dt without drift and with a low jitter of less than 100 ns for more than 50 shots. But the structure of the generator itself induced an inductance that decreases the initial dI/dt. To decrease this inductance as the standard demand a high dI/dt, a coaxial structure is used. The grounding of the test plate goes around the discharge line to the negative side of the capacitors.

With this scheme and based on current measurement using a Pearson probe and shown on figure 2, we can deduced an inductance of 1 µH and an initial dI/dt of 2.10^{10} A/s. The maximum current is 90 kA for a charging voltage of 20 kV, using 23 kV gives a higher current and validates a D waveform each shot. For this preliminary study, we have limited the charging voltage to 20 kV to avoid cleaning the spark gap too often. After several shots, the current is reproducible in the order of the current probe error.

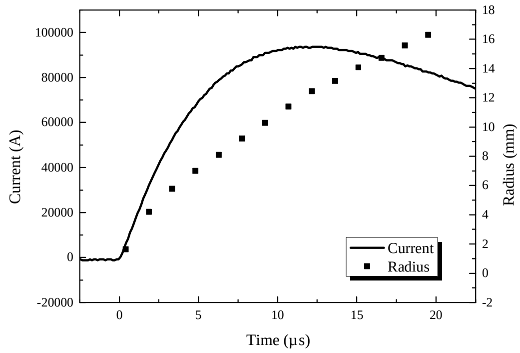

Figure 2: Current and arc channel radius of a typical shot.

3. HIGH SPEED IMAGING

The current of this arc discharge lasts several tenth of microsecond and the emitted intensity is high. Thus we can use high speed camera such as a Phantom V711 from Vision Research with sufficient signal. Several pictures per shot are obtained with each video but to increase the number of pictures/s, one need to reduce the size of the picture. Several videos were obtained using two configurations. The first one is a high resolution picture but with long exposure time (70 µs) and long delay time between pictures (70 µs). The result is shown on figure 3 with the four first pictures of the video. The tungsten rod is on the left side and the plate on the right side. The arc is very dense and the emitted intensity is high. The arc starts around the ignition wire and then extends to a radius of a few cm. After 70 µs, turbulence between the hot air and the surrounding gas is observed.
The second configuration is a low resolution 8x128 pixels perpendicular to the plasma channel. A delay of 1.5 µs between each pictures is achieved and the result is presented on figure 2. The channel radius quickly increases during the first microseconds. It provides limits to the temperature and pressure profile used in the next part of this paper.

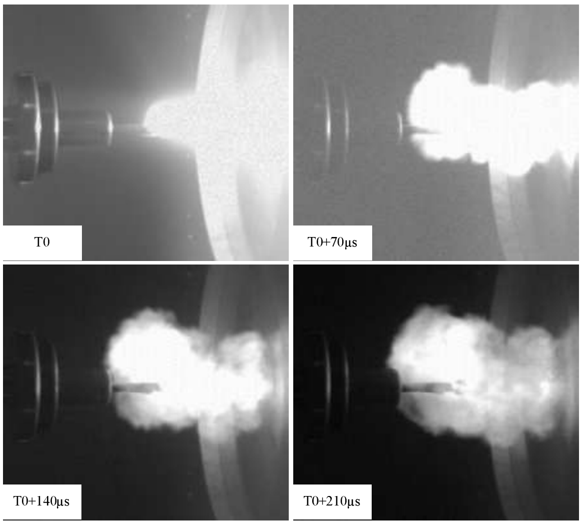

Figure 3: Pictures of a shot with an exposure time of 70 µs.

4. EMISSION SPECTROSCOPY

Emission spectroscopy has been used to retrieve the pressure and temperature of a few points inside the plasma channel. An optical design presented on figure 4 gather the light along a direction perpendicular to the plasma channel. A 16 fibers bundle with an chromatic lens collects the light emitted by the plasma at the middle distance between the electrodes. Each spot observed by an optical fiber through this lens has a 2 mm diameter and there is a distance of 6 mm between each spot. Since the test bench emits a lot of electromagnetic noise, the spectrometer (ACTON SP2750) and the ICCD camera (PI-MAX 2) are placed in another room using the 20 meter long bundle.

After 20 µs, the arc radius is 16 mm so 7 fibers are enlightened. In order to avoid the arc moving between each shot, a careful positioning of the ignition wire using a laser is performed for each shot. Thus the emission by the center of the arc is always collected by the same fiber.

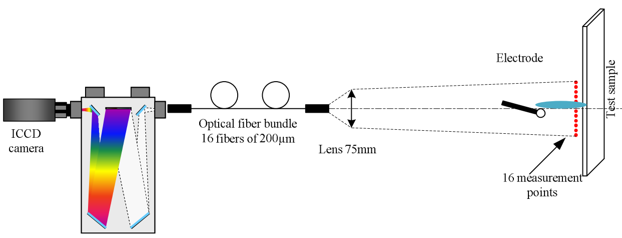

Figure 4: Experimental setup for the spectroscopy measurement using a 16 optical fiber bundle.

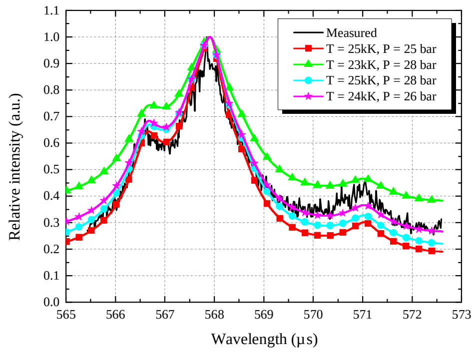

Figure 5: Fit example for a distance of 12mm from the center of the arc and 12 µs after T0.

The calibration of the setup was performed using a mercury lamp for wavelength and an halogen lamp for relative intensity.

In order to retrieve pressure and temperature value from emission spectra, we solved the RTE. A measured spectrum is compared to one obtained from RTE simulation using the absorption coefficient of an air plasma and temperature and pressure profile. The absorption coefficient is given by a database developed in the EM2C laboratory in previous studies [3, 4]. This database has been extended up to 35000 K and 100 Bar as described by Peyrou *et al* [5]. The arc channel is supposed at the local thermal equilibrium and supposed to be axisymmetric. We integrate along one direction, corresponding to our optical setup, the light emitted by the arc. Since we have the arc radius and if we suppose a gaussian pressure profile and a smooth step profile for the temperature, we can get a simulated spectrum to be compared with the measured one.

With our setup, we focused on spectral domain composed of several lines to help the fitting of our simulated spectra to the measured one. We concentrated our first results on the NII lines around 567.9 nm. At 6 mm and 12 mm distance from the center, NII lines were observed above the continuum but it was not the case on the central fiber composed mainly of continuum emission. A fit example is shown on figure 5. This method needs improvement but it allows getting temperature and pressure data with respectively 2 kK and 2 bars error.

The same method was applied to four position in time from 6 µs to 12 µs when the current reach its maximum. The results are shown on figure 6 for two positions, 6 mm and 12 mm away from the center of the arc channel.

The pressure is decreasing versus time and distance but the temperature is constant in the plasma channel. Value of temperature above 25 kK and pressure above 30 bars are coherent with the black body emission observed at several wavelengths in the visible and especially through the central fiber. More comparison with measured spectra will be realized in the near future to validate those first results. Moreover the optical setup will be modified to get more point along the channel radius.

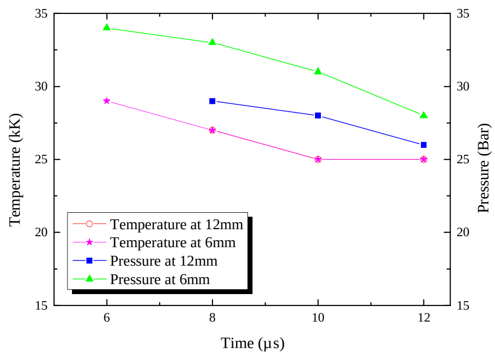

Figure 6: Pressure and Temperature as a function of time for a distance of 6 and 12 mm from the center of the arc.

CONCLUSION

In order to understand the behaviour of a high intensity arc used to simulate direct lightning effect on a material sample, a test bench able to produce a current waveform D has been built and tested. Current measurements were used to validate the current waveform. Fast imaging was used to observe the arc channel and deduced its radius versus time. Emission spectroscopy was performed around 569 nm on the NII lines yielding with ETL hypothesis and a database from EM2C laboratory to the pressure and temperature of the arc at two distances from the channel center and for different timing. Those results show that with increasing time and increasing radius of the channel, the pressure decrease spatially and temporally while the temperature decrease mainly temporally.

Those preliminary results will serve as a basis for a complete study of the beginning of the current impulse with different material and providing the temperature and pressure along the channel. Moreover, another test bench already built and tested and delivering a current waveform BC* (400 A during 50 ms) will be connected to the generator described here. Both generator will deliver a current waveform DBC* of interest for aircraft application.

REFERENCES

[1] Standard ARP5412, Aircraft lightning environment and related test waveforms, SAE International.

[2] L. Chemartin, P. Lalande, C. Delalondre, B. Cheron and F. Lago, *J. Phys, D: Appl. Phys.*, **44**, 194003, 2011.

[3] S Chauveau, M-Y Perrin, Ph. Riviere and A Soufiani, *J. Quant. Spectrosc. Radiat. Transfer*, **72,** 503–530, 2002.

[4] S. Chauveau, Ch. Deron, M-Y. Perrin, Ph. Riviere and A. Soufiani, *J. Quant. Spectrosc. Radiat. Transfer*, **77**, 113–130, 2003.

[5] B. Peyrou, L. Chemartin, P. Lalande, B. Cheron, Ph. Riviere, M-Y. Perrin and A. Soufiani, *J. Phys, D: Appl. Phys.*, **45**, 455203, 2012.