ACTIVE OPTICAL DIAGNOSTICS OF A ‘CURRENT-ZERO-LIKE’ ARC IN AIR IN A MODEL GAS CIRCUIT BREAKER GEOMETRY

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ABSTRACT

We present experimental results of the probing of a ‘current-zero like’ (CZ-like) air arc in a model high voltage gas circuit breaker geometry with active optical diagnostic techniques. Namely, we apply both shadowgraphy and Speckle imaging in an effort to obtain qualitative and quantitative information, respectively, about the physical phenomena involved. With the former technique, the boundary layer between the arc and the imposed gas flow and the transonic flow features can be readily revealed. The latter technique yields quantitative information about the two-dimensional density field with the help of a generalization of the Gladstone-Dale law. Under the assumption of local thermal equilibrium, one may estimate the corresponding temperature distribution along the arc plasma channel and the surrounding gas flow.

1. INTRODUCTION

Research and development in the field of high voltage circuit breakers (HVCBs) has greatly benefitted from advances in CFD (computational fluid dynamics) based models that are able to describe—and thus to a large extent predict—the phenomena occurring during a switching operation [1,2]. Typically, results of such numerical simulations are benchmarked against measurements of relatively easily accessible experimental parameters like the current, arc voltage and pressure build-up. Indeed, these models have been successfully validated in a large number of test cases, yielding good agreement with experiments especially for the so-called high current phase, i.e. for arc currents exceeding about 1 kA [1]. To extend such models towards the description of the ‘current zero’ (CZ) phase, where arc interruption takes place, experimental methods that can access parameters beyond those given above are needed: the probing of thermodynamic quantities could give insight into the current interruption phenomenon and provide significant input to the modelling of the interaction of the gaseous arc with the surrounding transonic gas flow [3].

In order to gain access to thermodynamic field quantities such as gas mass density ρ, several authors [4-8] have reported on active optical diagnostic techniques that rely on the measurement of the index of refraction n and its spatial derivatives: techniques such as interferometry ($\approx n$), Schlieren ($\approx dn/dx$) and Shadowgraphy ($\approx d^2n/dx^2$) have been used in order to probe switching arcs found in HVCBs. Appropriate mathematical treatment of the measurements may then lead via the use of the Gladstone-Dale law $n\text{-}1=K\cdot\rho$ to the reproduction of the density field of the probed object.

The object of this work is to present experimental results, based on active optical diagnostics, obtained when probing a ‘CZ-like’ air arc in a model HVCB. The term ‘CZ-like’ refers to a low current (<20A) DC arc that is sustained for several milliseconds subsequent to high current (>1kA) arcing. Conditions similar to CZ are emulated and sustained for an extended period of time. Here we make use of shadowgraphy and Speckle photography to extract the size of the boundary layer and the arc core, as well as to provide two-dimensional images of thermodynamic properties of a CZ-like arc under two main assumptions: cylindrical symmetry of the probed object and local thermal equilibrium (LTE).

Sections 2 and 3 outline the experimental set-up and measurements: the model HVCB and the electrical circuit used to emulate the CZ conditions are described. Besides standard measurements of blowing gas pressure and arc voltage, the active optical diagnostic techniques that are the focus of this work are described. Furthermore, the necessary post-processing to

obtain quantitative data from the Speckle photography measurements is briefly explained.
Section 4 focuses on the experimental results obtained. We present the arc core and boundary layer sizes as they can be directly estimated from shadowgrams and light intensity videos and then we present the two dimensional field quantities that are obtained via the Speckle technique.
Finally, section 5 summarizes the results obtained and gives proposals for further work.

2. EXPERIMENTAL SETUP

Figure 1 shows a schematic representation of the experimental setup, with the measured electrical signals depicted in grey.

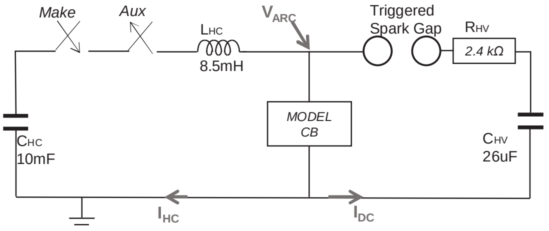

Fig. 1 Schematic representation of the electrical setup

The model circuit breaker is electrically stressed with a single high current (~1.2kA peak) half-wave I_{HC} produced by the discharge of C_{HC} via the coil L_{HC}, controlled by the proper timing of the 'make' and 'aux' switches. Prior to this half-wave's extinction the spark gap is triggered to discharge the C_{HV} capacitor via the R_{HV} resistor, thereby imposing a slowly (time constant several 10 ms) decaying current of 20 A initial amplitude. The idea behind this test circuit, is to generate a low current DC arc subsequent to high current stress, thus emulating CZ conditions occurring in high voltage AC current interruption. As previously mentioned, we refer to this as the 'CZ-like' arc.

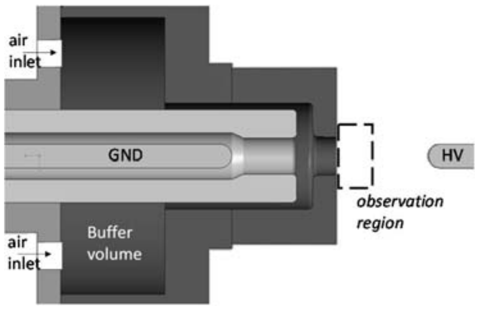

Fig. 2 Cut of the model CB

Figure 2 shows a cross-section through the model CB. It is a double flow device, featuring two plug electrodes initially short-circuited with a thin copper wire to ignite the arc. Technical air is exhausted from a high pressure reservoir (not shown) and after passing through a small buffer volume, where a piezo-electric pressure sensor is placed, blows the arc: the nozzles and the pressure difference ensure sonic flow conditions in the arcing zone. In Figure 2 the observation region for optical diagnostics is shown: it lies at the exit of the nozzle, a region of high gas velocity.

3. OPTICAL DIAGNOSTICS

Figure 3 shows the optical setup for the Speckle diagnostics [9] mainly used in this work for quantitative analysis. The shadowgraphy setup that yields qualitative results is similar to the one shown here with the omission of the ground (Speckle) plate and adjustments in the optical setup.
The spot of a 532nm Nd:YAG laser of 20ns pulse duration is expanded and collimated to create a roughly 50mm diameter beam that propagates through the observation region. A relay lens images the object onto the ground glass plate, which creates the Speckle interference patterns that are recorded by a high speed camera (1MPix, up to 6.6 kfps) placed at a defined defocus distance.

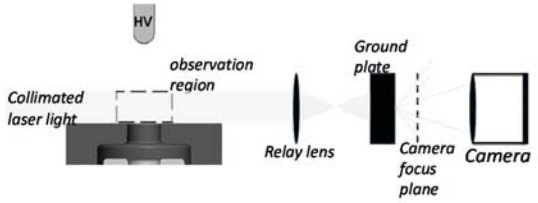

Fig. 3 Schematic of the optical setup for Speckle diagnostics

The cross-correlation between the reference Speckle image (obtained in ambient air in the absence of any arc / gas flow) and the phase object image (acquired in the presence of the CZ-like arc embedded in the sonic flow) yields the displacement of Speckle patterns that is proportional to the line-of-sight integrated light refraction angle, related to the phase object's index of refraction spatial distribution. Thus, under the assumption of cylindrical symmetry of the phase object, the Abel transform is used to reconstruct the two dimensional index of refraction field $n(r,z)$.
For a non-ionized gas the index of refraction n is linearly related to the density ρ via the well know Gladstone-Dale relationship: $n-1=K\rho$, with K being a constant dependent on the light wavelength and the gas used [9]. The aforementioned dependence can be extended to plasma conditions provided the pressure and temperature dependence of the refractive index are known. The refractive index is related to the

sum of the polarizabilities of the plasma species weighted by their density for a given pressure and temperature. Shown in figure 4 is the calculated refractivity (*n-1*) of air as a function of temperature for distinct values of pressure [10].

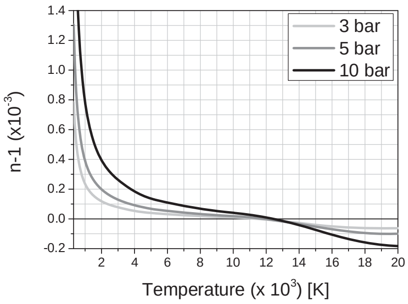

Fig. 4 Refractivity (n-1) of air as a function of temperature for distinct values of pressure

For the low temperature range, below roughly 5000K, one can distinguish the typical Gladstone-Dale law trend. Then, as the temperature increases, one sees the influence initially of atomic and then charged species on the refractivity. For high degrees of ionization at T>12000K the refractivity in fact reaches negative values.

In the following paragraph experimental results probing the CZ-like arc embedded in the high speed gas flow at the nozzle exhaust are discussed. It can be understood that for known pressure and index of refraction, one can estimate from the above figure the temperature, under the LTE assumption. Clearly, this can be estimated rather well for the low temperature range, whereas under plasma conditions it can be seen that small variations in the index of refraction yield rather large differences in temperature. Furthermore, one can observe that there is a rather weak dependence on pressure uncertainties in such a temperature estimation.

It is finally noted that the pressure field is experimentally determined from a cold flow shot (i.e. without arc) using the isentropic relation between pressure and density. This pressure field is used along with the refractivity found in the case of the CZ-like arc to obtain the arc temperature distribution.

4. RESULTS

Figure 5 displays the oscillograms of the electrical and pressure signals acquired during a typical test shot. Upon application of the high current half-wave the arc ignition is denoted by a small peak at the arc voltage. At the same time blowing pressure is established in the buffer volume with the opening of the valve of the high pressure reservoir. A few 10µs prior to the extinction of the high current the spark gap is triggered, discharging the C_{HV} capacitor of figure 2 and sustaining the 'CZ-like' arc during several 10ms. It can be observed that during this period a quasi-constant blowing pressure and current are maintained: suitable conditions to optically investigate the 'CZ-like' arc.

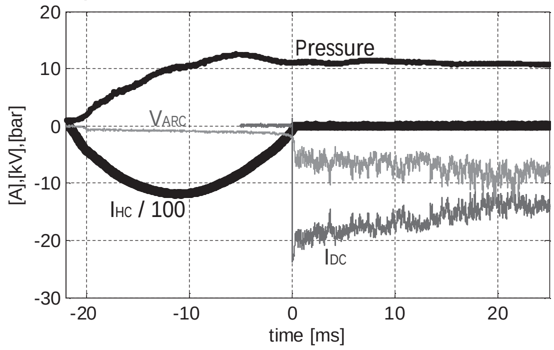

Fig. 5 Oscillograms of buffer volume pressure, high current, DC current and arc voltage recorded for a typical test shot

Figure 6 shows a shadowgram and a light intensity snapshot obtained at the observation region (cf, figure 3) during the 'CZ-like' phase.

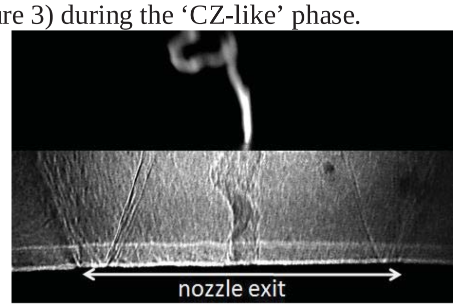

Fig. 6 Light intensity snapshot (top) and shadowgram (bottom) and obtained during the 'CZ-like' phase

The two snapshots, though not taken simultaneously, correspond to very similar experimental conditions. In the shadowgram, one can observe, symmetrically about the flow propagation axis, two diverging structures that correspond to the jet's boundary, whereas the two converging structures denote the oblique shock impinging from the nozzle exit. Most interestingly, in the middle of these cold flow structures one observes the mantle of the 'CZ-like' arc, i.e. the boundary layer between the arc core and the surrounding cold gas flow. From the shadowgram its size is estimated at roughly 2mm. The light intensity image depicts the arc core. It can be observed that its size is smaller than the mantle and can be estimated to be roughly 0.5-1mm. Both the shadowgram and light intensity images show that the 'CZ-like' arc exhibits rotational symmetry (i.e. can be approximated by a cylinder) in the first few mm downstream of the nozzle exit, while farther away three dimensional effects, denoted by the arc's 'bending', seem to destroy the axi-symmetry necessary for quantitative Speckle analysis (cf. paragraph 3).

Figure 7 displays the reconstructed two dimensional mass density field of the CZ-like arc embedded in the cold gas flow, obtained with the help of Speckle imaging at the observation region (cf. figure 3). In this figure (0,0) corresponds to the middle of the nozzle exit and z is the flow axis.

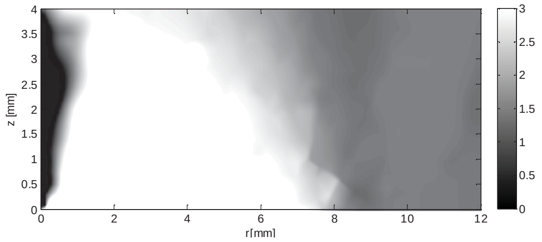

Fig. 7 Reconstructed 2D density field ρ(r,z) in kg/m³of the observation region at the nozzle exit during the 'CZ-like' phase

In this figure one may observe the cold flow structures (jet boundary, oblique shock) earlier discussed with the help of the shadowgram (figure 6 - bottom). Furthermore, the density minimum at the vicinity of the flow axis *z* corresponds to the CZ-like arc core and the surrounding boundary layer.

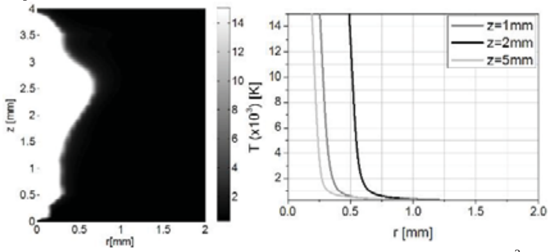

Fig. 8 (Left) Reconstructed 2D temperature field T(r,z) in (x10³)K and radial plots of temperature for distinct z-positions

This is better illustrated with the help of figure 8, which depicts the corresponding two dimensional temperature field of the CZ-like arc as well as a plot of the radial temperature distribution at distinct positions along the flow axis *z*. On the left panel, one can distinguish the arc core as the high temperature region in the vicinity of the flow axis. It can be observed that the core's radius is fluctuating around a value of approximately 0.3mm as we move downstream from the nozzle exit. The right hand panel permits the radial extension of the boundary layer to be determined; it is denoted by the exponential decay of the temperature from that in the arc core to that of the cold gas. The boundary layer extends out to roughly r=1mm.

4. CONCLUSIONS / OUTLOOK

This work aimed to illustrate, with the help of active optical diagnostics, the structure of a 'CZ-like' air arc embedded in the imposed cold gas flow in a model CB. Information on the arc boundary layer and cold flow structure can be readily obtained via shadowgraphy, whereas quantitative results for density and temperature fields are accessed via the Speckle imaging technique. In the conditions investigated here, which mimic the high voltage AC thermal interruption process, the 'CZ-like' arc core has a high temperature exceeding 15kK and a radius of roughly 0.3-0.5mm. The surrounding mantle is found to have a radial extent of up to 1mm.

These results can be used to benchmark computational models that aim to describe the thermal interruption process.

Possible extension of the Speckle technique presented here may include multi-beam probing to account for 3D effects in an effort to avoid having to make the axi-symmetric approximation.

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