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OPTICAL DIAGNOSTICS OF SWITCHING ARCS NEAR CURRENT-ZERO: SPECKLE IMAGING AND INTERFEROMETRY

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Abstract. Optical diagnostics can be used to obtain spatially resolved measurements of the density, temperature, conductivity, and electron density of circuit breaker arcs embedded in transonic flows; these can be used to validate the results of simulations, the accuracy of which can currently be assessed in only a limited way. We compare speckle imaging and an interferometric approach. Both use a pulsed nanosecond laser. The speckle imaging setup does not require a reference beam, but only yields information about the gradient of the refractive index. Its accuracy is sensitive to the alignment of the optical components. Interferometry directly yields high resolution images of the index of refraction, from which the density can be calculated using the Gladstone-Dale relation. By using two laser beams, interferometry provides spatially resolved information about the electron density. Such measurements are a significant step towards more accurate CFD models.

Keywords: circuit breaker, current-zero, interferometry, imaging, density, temperature.

1. Introduction

High voltage circuit breakers are used to switch the currents that flow under normal conditions in different sections of the power grid on and off. They must also be able to interrupt short circuit currents that arise when a fault occurs; these currents can be an order of magnitude higher than the typical load currents that flow during normal operation. The current is interrupted by drawing an arc between two contacts. Nozzles surrounding these contacts are used to guide a transsonic flow that cools the arc and interrupts it at a current-zero crossing of the alternating current. The design of more effective and efficient circuit breakers depends on a detailed understanding of the arc physics relevant during the roughly 100 µs before and after the zero-crossing. Information about the arc and the gas flow used to cool it is typically obtained indirectly via measurements of the arc voltage, the current, and the pressure (at specific locations in the arc zone of the circuit breaker). These integral measurements do not give sufficient insight into the structure of the arc to allow a detailed understanding of the processes involved in interrupting it. Such information can be obtained from computational fluid dynamics (CFD) simulations [1], but such models often lack experimental validation (aside from comparison with the measured current, voltage, and pressure). For this reason, several spatially resolved optical diagnostic methods based on well-established techniques that measure the index of refraction (or its gradient) were recently developed or adapted to image circuit breaker arcs near current zero [2–5]. The advantages and disadvantages of interferometric techniques compared to other optical methods (such as emission spectroscopy) are discussed in detail in those studies. Here we seek to briefly outline and compare two of these approaches, speckle imaging and interferometry. Section 2 describes the experimental approaches used. Results of measurements with the two techniques are presented in Section 3, while Section 4 discusses the differences between the two techniques.

2. Experimental techniques

The speckle and interferometry experimental setups are described in detail in [3] and [4], respectively. Here we only briefly present the two techniques; a schematic of the speckle imaging setup is provided in Figure 1; the experimental setup for interferometry is given in Figure 2. In both cases a 532 nm CrystaLaser CRL-QL532-100-YG pulsed, Q-switched laser with a nominal pulse duration of 12 ns was used. To provide an additional wavelength for the interferometry measurements to measure directly the electron density, a 671 nm CNI AO-V-671 pulsed, Q-switched laser with a nominal pulse duration of 16 ns was employed. The laser beam(s) were passed through a beam expander to increase the beam diameter to match the size of the region imaged. In the case of the speckle setup, the arc zone was imaged onto a glass diffuser using a relay lens. A scientific camera (Phantom V7100 or ProSilica GT4905) was focused a defined displacement distance behind the glass diffuser. Shifts in the speckle pattern produced by scattering from the diffuser and observed on the camera (with respect to a reference image in the absence of an arc and/or gas flow) were used to determine the line-of-sight integrated gradient in the refractive index at each point. The approach used to calculate the density and temperature from such measurements is given in [3]. For the interferometry measurements, a reference beam was added to the experimental setup and the probe beam and the reference beam were re-combined at a slight angle using a beam-splitter and recorded by a ProSilica GT4905 or GT2300 camera. The resulting interference patterns were analyzed using Fourier techniques to obtain the line-of-sight integrated refractive index (again making use of a reference image). The procedure employed is detailed in [4].

It is important to note that the circuit breaker test devices used to obtain speckle and interferometric images differed considerably. The test device used in the former tests, described in detail in [3] is shown in Figure 3. Briefly, this test device consisted of two fixed contacts (a hollow contact and a solid contact) and a nozzle system used to guide the flow of gas (synthetic air in the case of the tests discussed in this work) from a high pressure tank through the arc zone. Optical measurements could be performed in the stagnation region (through a window in the nozzle) and at the nozzle exit. This test device provided more direct optical access to the arc (at the nozzle exit), but had the disadvantage that the arc was not well-stabilized by the gas flow (which accelerated out of an intermediate volume between the arc zone and the high pressure tank). This led to an arc that moved within the arc zone and did not always remain parallel to the axis of the test device. As discussed in detail in [3] the instability and asymmetry in the arc sometimes prevented reconstruction of the index of refraction profile from the measured line-integrated deflection angles (corresponding to the line integrated refractive index). This is because a three-dimensional reconstruction based on a single projection is only possible for an object with defined symmetry, such as axi-symmetry (temporal and spatial fluctuations can also wash out features, but this effect is negligible for single, nanosecond laser pulses). One approach to overcome this problem (using almost the same circuit breaker test device) is described in [5]. In that work, multiple beams were used to probe the index of refraction distribution, permitting, in principle, a three-dimensional reconstruction from the line integrated measurements even in the absence of axi-symmetry. However, it likely that at least eight beams are required to achieve a reasonable reconstruction.

The test device used in the interferometry experiments is illustrated in Figure 4. It was designed specifically to ensure a stable, axi-symmetric arc by allowing the gas (argon in the case of the tests discussed in this work) that cools and interrupts the arc to accelerate from rest in the arc zone. The three-dimensional index of refraction and density distribution in this arc and surrounding gas flow can be re-constructed from a single projection. This test device is described in detail in [4].

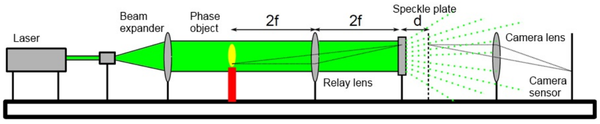


Figure 1. Illustration of the optical setup used for speckle imaging.

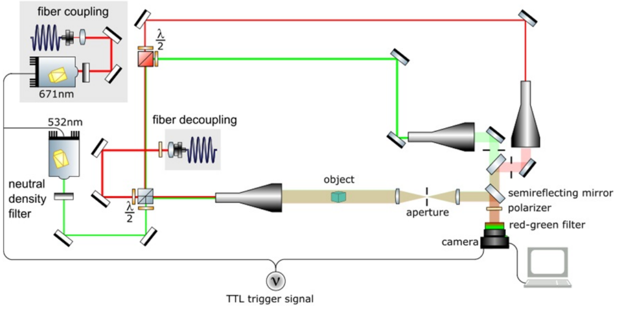


Figure 2. Sketch of the optical setup used for interferometry.

3. Results

The speckle technique was used to image the index of refraction distribution in the stagnation region of the test device described in the previous section. The density was determined from the measured index of refraction using the approach presented in [3]. Assuming that the pressure distribution is the same as the one obtained from measurements in the absence of an arc (an assumption explained in [3]), the temperature can also be calculated. These results are presented in Figure 5 for illustration; additional results are given in [3]. Figure 5 shows the results for six different measurements and illustrates the scatter (twice the standard deviation). This scatter does not represent the uncertainty in the measurement; instead, it demonstrates that there are fluctuations in the arc from test shot to test shot. The largest variation can be seen in the temperature at the arc boundary; the gradients are very steep, and a large change in temperature corresponds to only a small difference in the refractive index.

Similar measurements were performed with the interferometric technique, although it should be noted that the test device, the gas, and other aspects of the experiment differed. An example of such a measurement for a 100 A quasi-direct-current arc and a stagnation pressure of 1560 kPa are shown in Figure 6. The measurements were also performed in the stagnation point, but in the test device that was optimized to achieve a stable, axi-symmetric arc (Figure 4). The variation in the arc density profile observed from shot to shot with the test device shown in 3 cannot be seen in the measurements made on the stable arc; the results are consistent from test shot to test shot.

The interferometric technique was carried out with two laser wavelengths, permitting the measurement of the electron density in addition to the neutral particle density. Two laser wavelengths allow the measurement of the electron density because the contribution of the electrons to the index of refraction is strongly wavelength dependent, while the contribution of the heavy particles is not. The details of this approach are described in detail in [2, 4]. An example of a

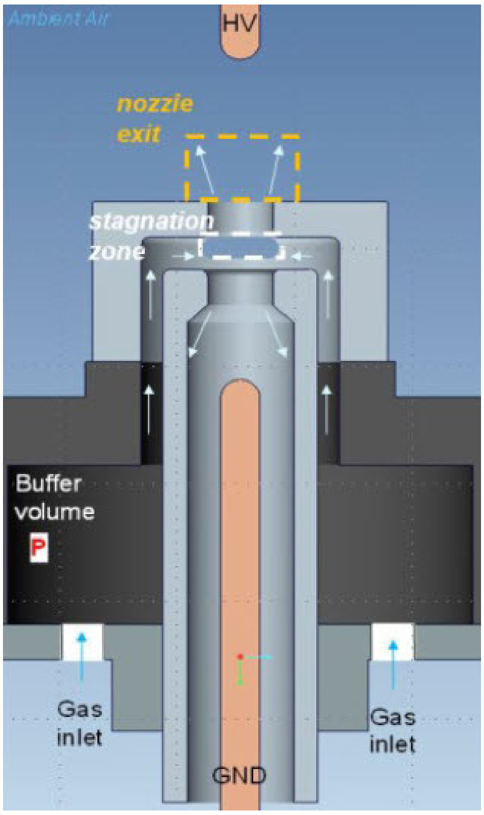
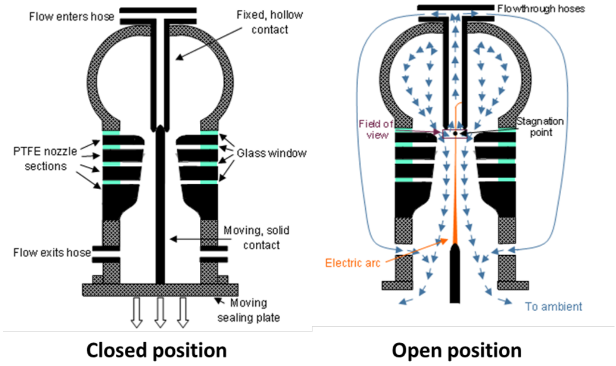


Figure 3. Sketch of the circuit breaker test device used for speckle imaging.



Closed position **Open position**

Figure 4. Sketch of the circuit breaker test device used for interferometric imaging.

measurement of the electron density in the stagnation point of the arc zone is given in Figure 6. Assuming local thermodynamic equilibrium, the temperature of the arc core can be determined from the electron density measurement [4].

4. Comparison of techniques

The measurements made with the speckle and the interferometric experimental setup allow the two approaches to obtaining spatially resolved information about a circuit breaker arc near current-zero to be compared. It is important to note that both the optical techniques and the test devices used differ. The main difference that stems from the test device is the much more stable arc observed when the gas flow in the arc zone accelerates from rest. In principle, speckle measurements made on such an arc would also show less shot to shot scatter. In other words, this difference is due to the test device and not the measurement technique.

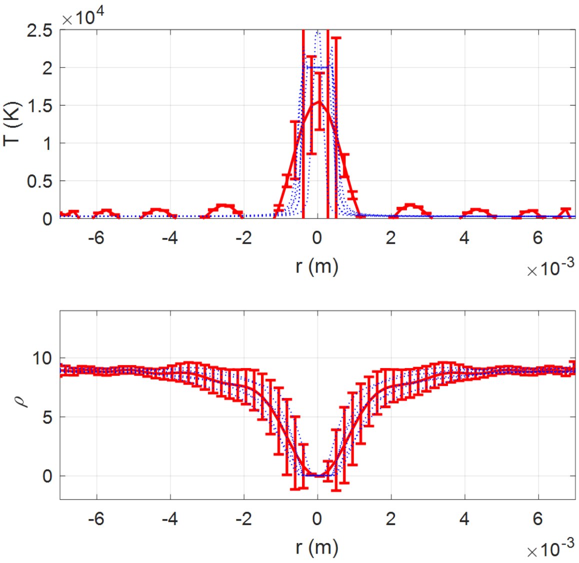


Figure 5. Speckle measurements of the temperature and density in the stagnation zone of the test device shown in Figure 3 illustrating the variation in the measurement. The stagnation pressure was 750 kPa and the current was 12 A. The density is given in units of kg/m^3.

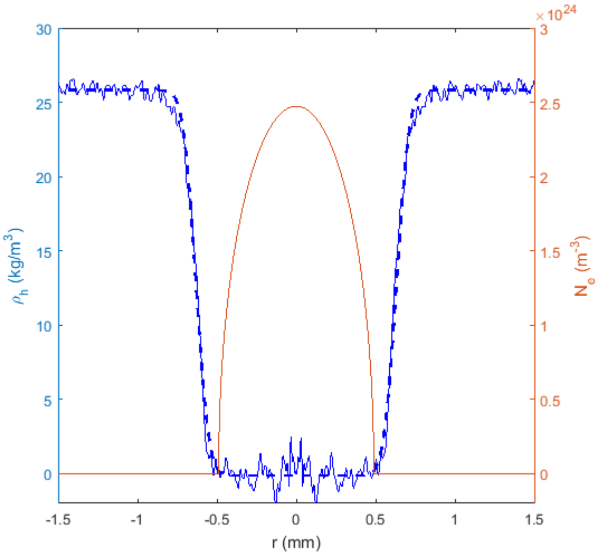


Figure 6. Interferometry measurement of the density and the electron density distribution in the stagnation zone of the test device shown in Figure 4. The stagnation pressure was 1560 kPa and the current was 100 A. Note that noise in the density measurement amplified by Abel inversion results in unphysical dips below zero in the arc core. These unphysical dips are removed by performing a fit to an analytical function [4].

Although the speckle and interferometry techniques are both based on measuring the change in index of refraction between conditions with and without an axially blown arc, there are key differences. The former technique requires a less complex experimental setup. Only a single beam path is required in that case, while the latter approach requires the use of two beam paths, one of which bypasses the test device. The advantage of using a reference beam is that the line-integrated difference in refractive index is measured directly. The speckle technique (similar to schlieren imaging and Hartmann-Schack inteferometry) only allows measurement of the gradient of the refractive index. On the other hand, unlike in the case of speckle imaging, interferometry requires that the coherence length of the laser be sufficient for the reference and probe beams to interfere.

Correct measurement of the distance the diffuser (or speckle plate) is placed out of the focal plane of the camera lens is crucial to accurate speckle measurements and can in some cases limit their accuracy. In the case of interferometry, only the magnification of the imaging optics must be determined accurately, but this is generally straightforward.

The inteferometric technique can also makes better use of the available resolution of the camera, as discussed in [4]. To summarize, the somewhat more complex optical setup required to perform interferometry is justified by its ability to directly determine the index of refraction and by the improved resolution it can provide.

5. Conclusion and outlook

Both speckle and interferometric imaging can be used to obtain information about the density distribution in the arc zone of a circuit breaker during the important current interruption phase. The speckle technique requires a somewhat simpler experimental setup—a reference beam is not needed and the coherence length of the laser does not need to be considered. In addition, the sensitivity of the speckle technique can be tuned by simply shifting the location of the diffuser plate used to generate the speckle pattern. On the other hand, using only a few additional optical elements, the interferometric technique permits direct measurement of the index of refraction (rather than of its gradient) and does not require determination of the diffuser plate defocus distance (the accuracy of which can limit the accuracy of the overall measurement). Thus, while both experimental approaches can be used to study the arc in a circuit breaker near current zero, the interferometric approach is generally to be preferred.

In general, index of refraction based optical diagnostic techniques provide spatially resolved information about the arc and the surrounding gas flow related to the density, arc radius, temperature, conductivity, and electron density that cannot be obtained from conventional measurements of the arc voltage and current. Thus, these methods provide new data that can be used to validate and further develop arc models used in the simulation and design of circuit breakers.

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