# Spectroscopic Measurements of Arc Temperatures in a Model HV Circuit Breaker

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Optical emission spectroscopy was applied to determine radial plasma temperature profiles over the arc cross section of an axially blown arc. Two gases are investigated - technical air and $CO_2$. The diagnostics is based on optical emission spectroscopy in appropriate wavelength ranges containing atomic and ionic lines of oxygen as well as nitrogen and carbon, respectively. Radial temperature profiles are obtained from emission coefficients including pressure measurements and calculated plasma compositions.

**Keywords:** optical emission spectroscopy, arc, circuit breaker

## 1 INTRODUCTION

Gas circuit breakers are standard equipment for high voltage switching and protection in electric power transmission systems. They are applied to switch nominal currents in AC networks as well as to switch off fault currents immediately in case of a system failure. Usually, their function is based on the extinction of an arc between separating electrodes supported by blowing gas into the gap to control and cool the arc. Knowledge about plasma parameters like temperatures and partial pressures is one of the crucial issues for comparison with fluid dynamic simulations and device optimization. Optical methods, like laser diagnostics [1] and optical emission spectroscopy (OES) [2], can be utilized to obtain these parameters.

In this paper investigations of a model gas circuit breaker are presented. Optical emission spectroscopy was applied to determine radial plasma temperature profiles of an axially blown arc at the stagnation point of the gas flow. Two gases - technical air and $CO_2$ - are considered.

## 2 EXPERIMENTAL SETUP

The experimental setup is given in Fig. 1. The discharges were driven by sinusoidal current pulses of 30 ms. They were operated vertically between two Cu-W electrodes of 100 mm distance and blown axially by either technical air or $CO_2$. A more detailed description of the discharge geometry, the electric circuit and the pneumatic system of the model circuit breaker can be found elsewhere [1].

OES was carried out at the current maximum of about 1 kA, while the gas pressure in the buffer region was 3.5±0.1 bars at the instant of measurement. A 0.5 m spectrograph equipped with an intensified camera in order to obtain 2D spectra was focused on the area close to the stagnation point of gas flow, nearly 40 mm away from the lower electrode. A long distance microscope was applied resulting in a nominal spatial resolution of the spectroscopic system of less than 10 µm per pixel. The wavelength resolution (FWHM) was about 0.048 nm and 0.64 nm for gratings with 1800 and 150 lines per mm, respectively.

The measurements were accompanied by video imaging using a high-speed camera (Motion Pro Y4, Redlake) with typically 20 frames per millisecond for control of the general discharge behavior.

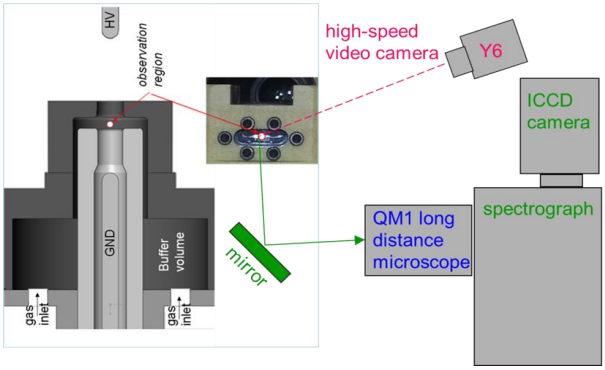


*Fig. 1: Schematic experimental setup of optical emission spectroscopy and video monitoring. The viewport for observation (marked by a white dot) was positioned at the stagnation point of gas flow.*

## 3 RESULTS AND DISCUSSION

An example for a spectrum of a discharge with 3.5 bar in air is shown in the upper part of Fig. 2. The side-on spectra were acquired with the lower spectral resolution and 1 µs exposure time by the ICCD camera, i.e. two-dimensional spectra with one spatial and one spectral dimension. They were corrected concerning the spectral sensitivity of the detection system and the intensity by means of absolute intensity calibration based on a radiance-calibrated tungsten ribbon lamp.

Some prominent groups of lines are labelled in Fig. 2. Obviously, the atomic oxygen lines O I at 777 nm and the atomic nitrogen lines around 745 nm have a broader spatial distribution than the ionic lines of nitrogen N II at 648 nm and 661 nm. Furthermore, their spatial distribution is characterized by two local maxima at side-on positions with considerable distance to the arc center where the maximum intensity of the ionic lines could be observed.

Side-on radiance profiles of the spectral lines confirm this observation. They are obtained by integration over small wavelength ranges as plotted in the lower left part of Fig. 2. It should be mentioned that due to the limited spectral resolution the integration includes also some other lines: In case of O I the integration interval comprises a triplet of atomic oxygen lines at 777 nm plus a weaker N II line at 776 nm, and in case of N II at 661 nm the integration is performed in an interval including two lines of N II. The properties of the single lines were investigated in further measurements with higher spectral resolution. Generally, the ionic radiation mainly results from the arc center and vanishes at side-on positions above 1 mm. The atomic radiation has a broader distribution with maximum at side-on positions around 0.9 mm and a local minimum in the arc center.

Assuming radial symmetry of the arc it is possible to calculate the radial emission coefficient by Abel inversion (lower right plot of Fig. 2). Emission of O I 777 nm mainly originates from a sheath at about 1.1 mm (FWHM of about 0.6 mm). The emission below 0.3 mm is very low and partially caused by contributions of the N II line.

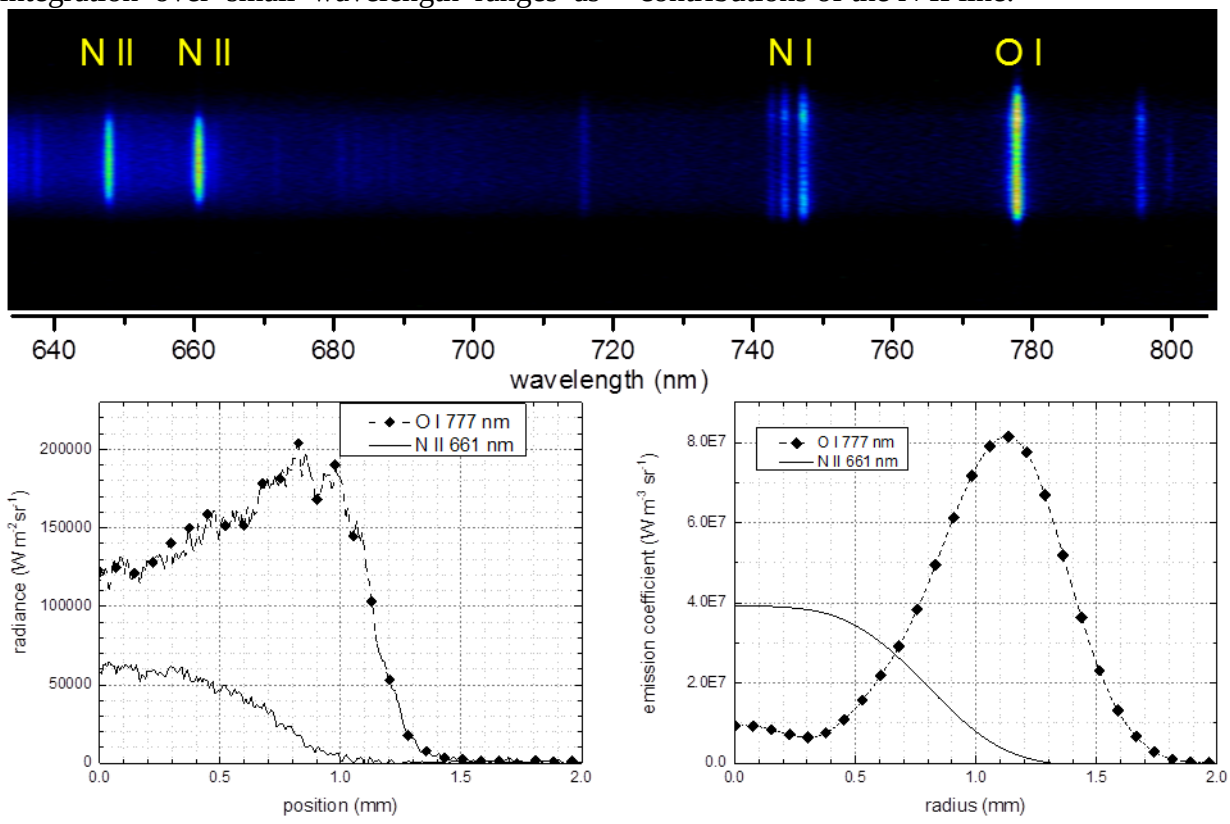


*Fig.2: Overview spectrum of a discharge with 3.5 bar air plasma at 1 kA (top), side-on radiances for atomic oxygen and for ionic nitrogen lines (bottom left) and radial distribution of emission coefficient (bottom right) showing a distinct maximum in the emission of atomic radiation around 1 mm*

The distinct off-axis peak in the radial emission coefficient of the atomic radiation indicates a normal maximum that is caused by an increase of the ionization degree with increasing temperature. Calculation of the temperature dependent emission coefficient yields such a maximum at 17 000 K for an air plasma of 3.5 bar. The pressure dependence is rather weak, even doubling of the pressure causes a shift towards 18 000 K only. Thus, the temperature at which the normal maximum occurred is known quite exactly and could be used as a fix point for temperature determination (Fowler-Milne method). Comparison with calculated emission coefficients shows that the experimentally determined values are lower than expected, probably due to self-absorption of the atomic radiation. Therefore, the experimental values are normalized to avoid non-physical discontinuities in the temperature profile. For temperature determination one has to differ between emission coefficients obtained for temperatures below the normal maximum (corresponding to outer radial positions >1.2 mm) and above normal maximum (corresponding to the center of the arc center and radii <1.2 mm).

For the ionic line emission N II at 661 nm a considerably lower optical thickness than for O I is estimated. Thus, absorption has no significant influence on the emission coefficients and the temperature could be derived directly from the emission coefficient (single line method). The normal maximum is not reached, which is around 32 000 K for N II 661 nm.

Results for the temperature determination are shown in the upper part of Fig. 3. The temperature maximum is observed in the center of the arc at about 28 000 K and followed by a slow temperature decrease including a nearly plateau-like behavior within the first 500 µm. 20 000 K are reached at about 1.2 mm according to the ionic line radiation N II. The temperature distribution obtained from atomic radiation O I, however, is found to be about 3 000 K lower in the overlapping range. This is not a general tendency; there are also shots with well overlapping curves or with higher temperature values for O I. Towards outer regions of the arc the temperature decreases down to values around 10 000 K at a radial position of about 1.8 mm, which is the lower detection limit in these experiments.

Although the temperature is quite sensitive to the variation of the emission coefficient over a wide range, it is necessary to set a lower limit for data to be evaluated due to the limited dynamic range of the sensor (down to ~1 % of maximum) corresponding to plasma temperatures of about 9 000 K and 18 000 K for atomic and ionic lines, respectively. Because of increased uncertainties in the arc center with temperatures above normal maximum of O I 777 nm, only emission coefficients down to 50 % of the maximum value are considered here for temperature evaluation from atomic lines corresponding to about 24 000 K.

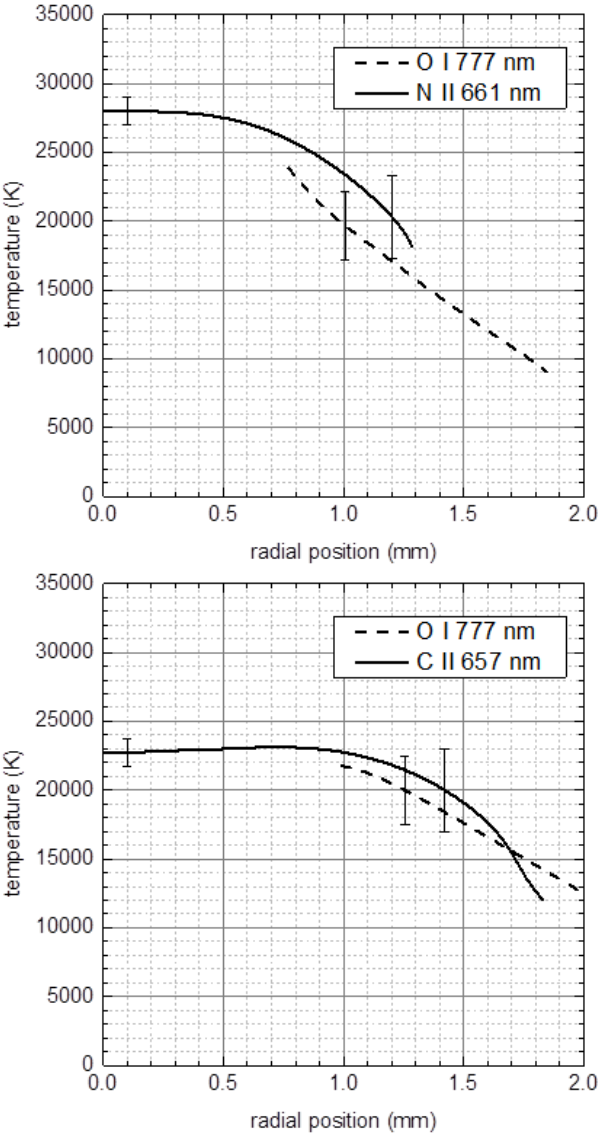


*Fig.3: Temperature profiles for discharges of air (top) and $CO_2$ (bottom) of 3.5 bar at 1 kA*

A similar procedure is carried out for discharges with $CO_2$ gas instead of air. Here, the same spectral range and the oxygen triplet O I at 777 nm is used for the temperature determination of the outer region of the arc based on Fowler-Milne method. Once again, the single line method based on ionic line emission could be applied for higher temperatures, i.e. in the center region of the arc. Here, a collection of two strong ionic lines and nine much weaker atomic lines of carbon between 656 nm and 661 nm is used that are summarized and labelled as C II at 657 nm.

The radial temperature distribution for discharges with $CO_2$ is shown in the lower plot of Fig. 3. Although the principal behavior was comparable to the case with air plasma, the maximum temperature in the arc center is about 4 000 K lower (around 23 000 K) and the temperature profile is considerably broader for $CO_2$.

The main sources of uncertainty and ambiguity can be named as follows:

- Shot to shot variation of arc emission
- Strong arc dynamics within one shot (arc width variation)
- Dynamics of the arc during OES acquisition (arc movement)
- Deviation from rotational symmetry
- Optical thickness of the plasma

The uncertainty of temperature determination from the ionic lines could be as low as ±1 000 K in the arc center. This is valid under the idealized condition of perfect rotational symmetry only. Towards the outer region of the arc, the intensity of the ionic lines decreases. Thus, the ambiguity due to noise will be increased resulting in an additional effect on temperature determination summing up to an uncertainty of about ±3 000 K. The shot-to shot variation depends on the conditions set for (pre-) selection of the spectra and is estimated to be ±2 000 K in the arc center.

Concerning the atomic lines the accuracy can be higher, at least at the normal maximum. The temperature of the normal maximum is quite well known and has only weak dependence on gas pressure. Thus, the ambiguity of plasma temperature at the position of normal maximum is below 1 000 K – assuming perfect rotational symmetry of the arc. The temperature rise around normal maximum, i.e. at the edge of the plasma, depends on the steepness of the side-on radiance and thus, again on its symmetry. As a consequence, the temperature at a certain radial position can vary by 2 000-3 000 K depending on which part of the side-on profile is chosen for one shot.

To summarize the overall uncertainty in temperature determination is about ±2 000 K (10%) for selected shots in the arc center. The poor rotational symmetry has to be considered as additional source of uncertainty, which can hardly be quantified.

## 4 SUMMARY AND OUTLOOK

Radial temperatures profiles of the arc have been obtained in an experiment using a model circuit breaker. Switching arcs with 3.5 bar of either technical air or $CO_2$ were investigated at a maximum current of about 1 kA. Maximum temperatures of 28 000 K for air and 24 000 K for $CO_2$ are obtained. Furthermore, the temperature profiles for $CO_2$ are considerably broader.

Our results complement recent Speckle measurements [1]. Next steps will include an analysis of gas pressure dependence, application of high-speed video monitoring with narrow band-pass filters for the observation of atomic and ionic lines, and spectroscopy at different time instants of the discharge, i.e. closer to current zero.

## REFERENCES

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