INVESTIGATIONS ON SWITCHING ARCS IN CO_2 BY TIME-RESOLVED OPTICAL EMISSION SPECTROSCOPY AND CFD SIMULATIONS

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ABSTRACT

Despite intensive research work during the last decades, the interruption process in high-voltage circuit breakers is still not fully understood. Especially with regard to the adaption of today's switching technologies for SF_6-substitutes as e.g. CO_2 (carbon dioxide) an improved understanding of the physical processes during current interruption is required. Here optical emission spectroscopy (OES) offers time-resolved access to physical properties, e.g. temperature and pressure, in the nozzle system. Thus OES measurements are performed by means of a circuit breaker model in this contribution. The obtained arc temperature profiles and temperature characteristics are in good agreement with the results of CFD simulations (computational fluid dynamics).

1. INTRODUCTION

In the context of the debate on greenhouse gases and climate change also discussions take place on the replacement of SF_6 by CO_2 for use as quenching gas in high voltage circuit breakers. Despite the fact that prototypes for CO_2-filled circuit breakers have been presented up to nominal voltages of U_m = 145 kV, the arc quenching process is still not fully understood [1, 2]. Optical emission spectroscopy allows access to temperature, pressure and gas composition in the nozzle system of circuit breakers [3]. Thus by OES an improved understanding of the physical processes coming along with the interruption process is gained. Up to now this method has only been applied to single instants during the high current phase in a circuit breaker model [3]. In this contribution a modified OES setup is presented which provides a time-resolved recording of the radiation emission of the switching arc during the high current phase in a circuit breaker model by applying a high-speed camera to the test setup. This allows a detailed analysis of the temperature and pressure developments in the switching arc during the entire current interruption process.

2. EXPERIMENTAL SETUP

The experimental investigations in this contribution are performed with a model circuit breaker (MCB) according to figure 1. The MCB is placed inside a test vessel with a volume of V = 0.07 m³ filled with CO_2 at absolute filling pressure of p_{abs} = 0.5 MPa. For the generation of the high current arc the high current circuit of a synthetic test circuit is used.

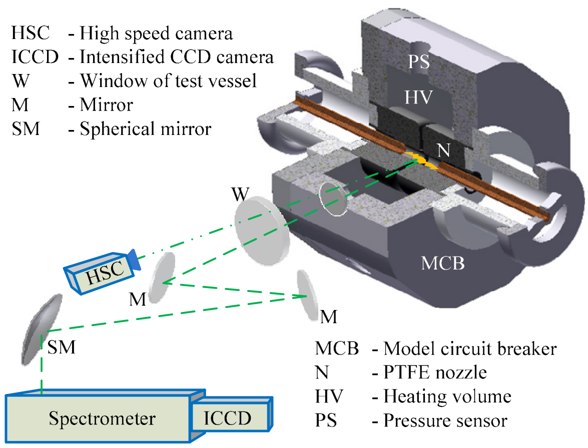

Fig. 1 Experimental setup for OES and high speed imaging of the arc inside the model circuit breaker

The arcing zone can be accessed by the optical measuring system by viewing slots in the MCB housing through the heating channel (see figure 1). The heating channel has a width of w = 4 mm between the two insulating nozzles made of PTFE (polytetrafluorethylene). Due to the self-blast effect a pressure build-up is generated in the heating volume (HV) by ablating nozzle material. Approaching current zero the pressure inside the nozzle system decreases and the arc is quenched by a back-flow of hot gas from the heating volume.

3. PRINCIPLE OF TIME-RESOLVED OES

The optical diagnostic of the arc employs a high-speed camera (HSC) and a spectroscopy system, both arranged as given in figure 1. The former is used to observe the arc dynamics and the latter, consisting of a 0.5 m spectrograph (Acton Research) equipped with either an intensified CCD-camera or another HSC, is used for the determination of the arc temperature and pressure. The absolute calibration of the video OES is performed by comparison of spectra taken with ICCD-camera and those with HSC at same time instances. The HSC frame rate is set to 10000 fps giving approximately 100 spectra during single arcing process.
For the applied line emission analysis, the plasma composition and the Boltzmann distribution of excited states of heavy particles according to the local thermodynamic equilibrium are considered. Line radiation of low optical thickness is chosen. Hence the absorption can be neglected in the line analysis. Based on these assumptions a certain spectral region is chosen where the PTFE plasma radiation is composed mainly of atomic fluorine and ionized carbon lines.
The evaluation procedure similar to that used in [4] comprises Abel inversion and appropriate smoothing. As a result of the evaluation the radial profiles of emission coefficient of excited species (atoms or ions) is obtained. This can be re-calculated in the excited species densities which under assumption of LTE (local thermal equilibrium) can be used for evaluation of the temperature profile across the heating channel. The necessary information about the total pressure is obtained from the Olsen-Richter diagram for line broadening vs. line intensity [3].

4. CFD SIMULATION RESULTS

By means of CFD simulations the calculation of time dependent arc temperature profiles is possible (cf. [5]). In addition the amount of ablated nozzle material inside the nozzle system can be determined by these simulations. The results are depicted in figure 2. From these it is observed that the nozzle is fully filled with ablated PTFE during the high current phase. Approaching the current zero crossing of the test current the PTFE percentage reduces due to the clearing of the nozzle by the blow gas flow from the heating volume. At the same time a remaining PTFE percentage of approximately 10% is observed in this time region which could e.g. affect the dielectric recovery after current zero due to the changed gas composition.

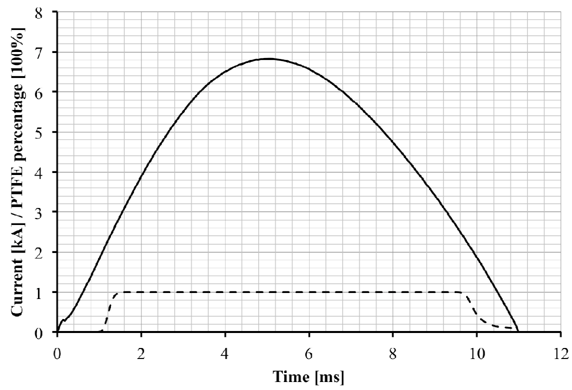

Fig. 2 PTFE percentage (dashed line) inside the nozzle system of the circuit breaker model during the high current phase (solid line)

5. TIME-RESOLVED OES-RESULTS

At distinct instants during the high current phase emission spectra are recorded. As the result of evaluation the absolute intensity of carbon ion line is shown in figure 3.

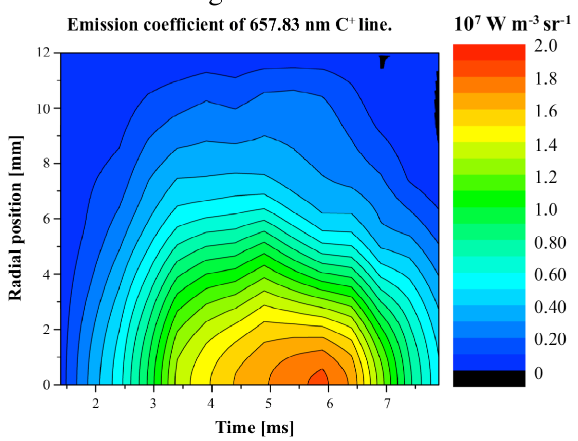

Fig. 3 Intensity of CII 657.83 nm line after Abel inversion for different time instances and radial positions

During the high current phase an increase of the pressure at the position of the heating channel is observed resulting from ablation of material from the insulating nozzles as depicted in figure 4.

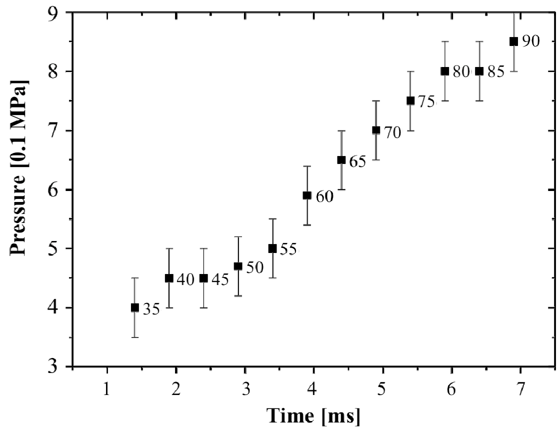

Fig. 4 Result of the pressure determination from Olsen-Richter diagrams. Numbers at the data points denote the spectrum number.

In addition the arc temperature is important as it is directly linked to the cooling of the arc and therefore the current interruption. Thus time-resolved radial arc temperature profiles are determined from the OES measurements at the spatial position of the heating channel.

In figure 5 two exemplary temperature profiles (from spectra number 70 and 90 corresponding to 4.9 ms and 6.9 ms in figure 4) during the high current phase are presented (cf. [5]).

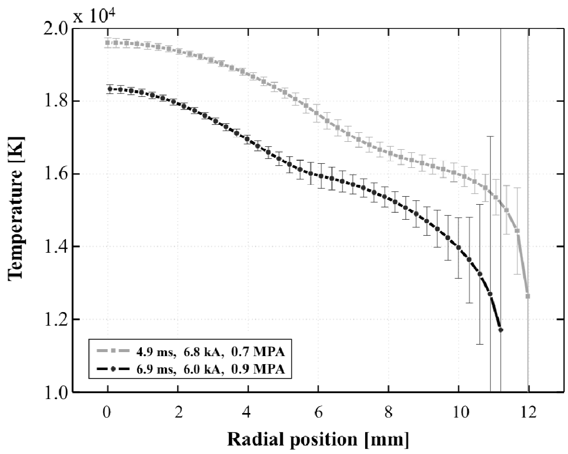

Fig. 5 Radial arc temperature profiles determined from the OES spectra 70 and 90 (cf. [5])

A temperature decrease from the arc centre to the outer arc boundary is observed for both instants. In addition increased scatter occurs at the arc boundary layer at 11 mm or 12 mm caused by a decreasing signal to noise ratio at the arc boundary. From the temperature profiles it is determined that the arc temperature decreases with decreasing current amplitude. Furthermore the arc quenching process can be observed comparing the maximum arc radius at 4.9 ms and 6.9 ms as depicted in figure 5. This effect also results from the decreasing energy input with decreasing test current.

6. DISCUSSION

The radial arc temperature profiles resulting from the OES measurements and the CFD simulation are depicted in figure 6. From both investigations methods a decrease of the arc temperature with decreasing arc current as well as an expansion of the arc plasma into the heating channel (inner nozzle radius r = 6 mm) are observed. At the same time the results of the CFD simulation yield a stronger temperature decrease in of approximately 5000 K in the heating channel (r = 6…12 mm). A possible explanation for these effects is the deviation of the real arc behaviour inside the nozzle system from the ideal rotationally symmetry assumed for the simulations.

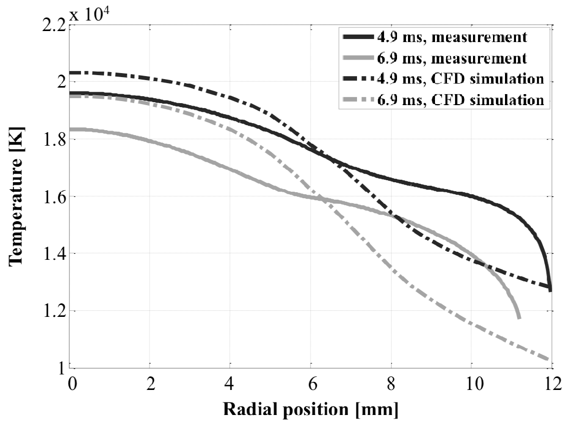

Fig. 6 Comparison of the measured and simulated radial arc temperature profiles for increased filling pressure (cf. [5])

Comparing the pressure characteristics at the position of the heating channel with the pressure measurement in the heating volume of the test vessel, deviations are found. The observed absolute values of the OES pressure reconstruction start from p_{abs} = 0.4 MPa which is 20% below the filling pressure (see figure 7). The reason for this discrepancy may lie in the method of OES pressure determination. The Olsen-Richter diagrams were computed for the radiation of LTE (local thermal equilibrium) plasma of the pure PTFE arc at different pressures. In the beginning of the current pulse the plasma does not consist entirely of PTFE what can result in the pressure underestimation. Nevertheless the results of CFD simulations (see figure 2) a PTFE percentage of 100% is observed in the nozzle system. Despite this fact, the results of the OES measurements indicate deviations between real ablation in the nozzle system and the simulation model which should be covered by further investigations. Comparing the general characteristics of the measured pressure curve and the pressure values determined from the OES measurements fair agreement is achieved.

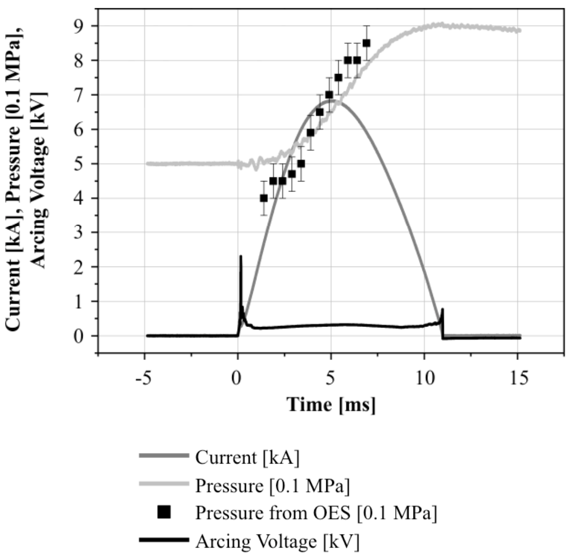

Fig 7 Comparison of the measured and estimated pressures. The measurement of the pressure was performed at the outer vessel wall. The pressure estimation from diagrams (symbols) was performed for the position of the spectroscopic measurements (heating channel).

7. SUMMARY AND OUTLOOK

In this contribution the temperature and pressure characteristics of a switching arc burning in the quenching gas CO_2 were investigated by means of optical emission spectroscopy as well as CFD simulations. For the temperature profiles sufficient agreement between measurement and simulation was observed. Nevertheless the accuracy of the simulation model has to be improved with regard to asymmetric behaviour of the investigated arc. The determination of the time-dependent pressure characteristics was possible with an accuracy of 20%. Deviations may arise from differences between the ablation modelling in the simulation and the ablation process at low current densities. This effect becomes even more relevant approaching the current zero region of the interruption process coming along with a reduction of the current density and a change of the ablation mechanism from photodegradation to pyrolysis [6]. Therefore this phase of the interruption process should be subject of future experimental and simulative investigations.

ACKNOWLEDGEMENT

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