Spectroscopic Study of Arc Temperature Profiles of a Switching-off Process in a Model Chamber

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A model chamber was applied to emulate a switching-off process which is very similar to those in real high-voltage circuit-breakers. The arc between moved W-Cu electrodes through a PTFE nozzle in SF6 was considered. Transparent windows in the chamber wall and a slit in the nozzle enabled an optical investigation of the arc cross section several milliseconds before current zero. The side-on radiance of fluorine atom lines has been measured. Considering rotational symmetry of the arc the corresponding radial emission coefficients have been determined. Radial temperature profiles have been obtained with uncertainties below 10% considering change of window transmission and optical depth of the line radiation. The experimentally determined temperature profiles are used to validate a CFD simulation of the switching-off process in the model chamber.

Keywords: circuit-breaker, arc temperature, spectroscopy

1 INTRODUCTION

The development of modern switching devices, of high-voltage circuit-breakers in particular, suffers from detailed modelling of the processes in the arc chamber and the forecast of the breaking capability. Despite of the increased accuracy of the models and the incoming atomic data, validations by experimental measurements are mandatory. Beside the comparison with pressure and voltage measurements, the control of the calculated plasma properties of the switching arc is one of the most sensitive methods to validate arc simulations including the impact of wall ablation, radiation transport and so on. Optical emission spectroscopy of the arc radiation opens a variety of methods for the spatially resolved determination of the plasma temperature and species densities. It has been applied several times to determine the plasma temperature in arc experiments which have been designed to emulate the typical arc behaviour in switching devices like the ablation dominated arc in self-blast circuit-breakers for example [2]. Only few studies deal with experiments in real geometries of circuit-breaker chambers because of the problem of optical access. Optical fibres in the chamber wall can be used to couple out the arc radiation [3]. However, the determination of spatial profiles of plasma temperatures generally requires the radiation analysis over the arc cross section.

In this paper experiments in a SF_6 self-blast model circuit-breaker are presented where a thin slit in the nozzle is used for optical emission spectroscopy over the arc cross section. The study is focussed on the high-current phase of the ablation dominated arc in the model breaker.

2 EXPERIMENT

The experimental setup consists of a model breaker with an arc chamber very similar to real devices. The electrodes (pin and tulip) are made of W-Cu with pin diameter of 15 mm. The electrodes are separated inside a PTFE nozzle with a narrow part of an inner radius of 9 mm followed by a larger turbulence volume of 25 mm inner radius surrounding the tulip. A slit of 2 mm width perpendicular to the nozzle axis is used for optical investigations. The distance of the pin electrode from the edge of the slit was checked by means of high-speed video monitoring (switching tests without current or plasma) in order to verify the free spectroscopic access to the plasma. The setup is confined in a closed vessel filled with SF_6 at a pressure of 6 bar (absolute). Glass windows at opposite sides of the vessel provide the optical access to the nozzle slit.

The transparency of these windows has been controlled by transmission measurements after every third arc experiment. It turned out that a gas exchange including a complete exhaust of the fume is appropriate for a sufficient transmission of the windows and the vessel volume. The discharges were operated with a sinusoidal current waveform over one half-wave of 50 Hertz frequency and maximum currents of typically about 14 kA (effective current 10 kA) by means of the discharge of a capacitor bank.

The radiation from the slit in the PTFE nozzle is imaged through one of the vessel windows over a distance of about 2 m to the entrance slit of a 0.5 m spectrograph as illustrated in Fig. 1. The spectrograph is equipped with an intensified CCD camera (Pimax2, Roper Scientific) in order to obtain single 2D spectra typically with a wavelength resolution of 0.06 nm FWHM for a wavelength range of about 20 nm. Spatially, a pixel resolution of 0.14 mm/pixel was obtained.

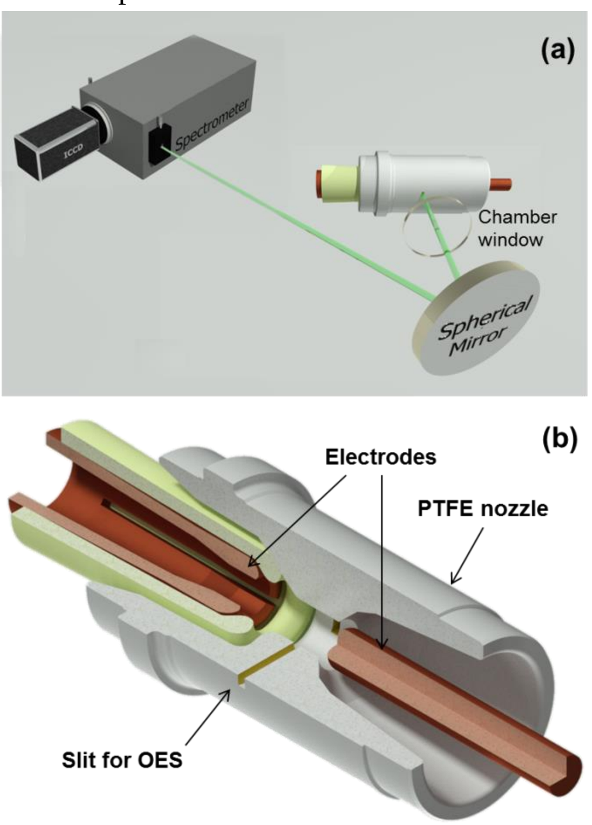

Fig.1: (a) Experimental setup of optical emission spectroscopy. (b) Details of the model chamber showing electrodes and nozzle with 2 mm slit. Spectroscopic measurements are carried out after the moved pin electrode (right) has passed the slit. The outer chamber of the setup is omitted here.

Separate measurements with a tungsten strip lamp were used for absolute intensity calibration of the spectra. Spectra have been measured for several time instants during the falling edge of the current half-wave since the slit is blocked by the pin during the raising edge. The measurements with the CCD camera allow one record during one shot with a typical exposure time of 200 μs.

3 DETERMINATION OF THE PLASMA TEMPERATURE PROFILE

The analysis of the side-on measured radiation intensity of one appropriate spectral line of low optical thickness is used for the determination of the plasma temperature profile of the arc. As in many other works, the plasma composition and the Boltzmann distribution of excited states according to the local thermodynamic equilibrium is assumed. It is expected that the arc radiation is dominated by atomic and ionic line radiation of the species F, C and S because the chamber is filled with SF_6 and the ablation of the PTFE nozzle could be considerable. Depending on the ablation the radiation contribution of C and S at different times during the current half wave can be hardly forecasted. Therefore, the analysis is focused on fluorine atom lines (F I lines) in contrast to former works [2,4] where carbon ion lines were considered. Finally, the F I line at 641 nm has been chosen because the line is well isolated from other spectral lines and atomic data are available. On the one hand, the relatively low energy of the upper state of the corresponding transition has the advantage that a higher population of the upper state leads to sufficient radiation intensity also in the outer regions of the arc and makes the determination of the temperature profile over a larger arc cross section possible. On the other hand, the lower energy of the upper state requires a higher accuracy in the determination of the line emission coefficient from the measurements compared to the analysis of a carbon ion line as considered in [2,4]. Another disadvantage is the higher optical thickness of the F I line as the result of the higher population of the lower state.

The radiation intensity measured in the wavelength range from 640 to 660 nm and for a range of side-on positions of about 18 mm is, in a first step, calibrated with respect to intensity and wavelength. Then, a spectral line profile is integrated to determine the radiance of the F I line at 641 nm for every side-on position. In a next step, Abel inversion is applied to obtain the emission coefficient of the F I line as a function of the radial position in the arc under assumption of low deviations from rotational symmetry of the arc. The radial temperature profile is calculated from the radial course of the emission coefficient according to the relation to the radiator density and the Boltzmann distribution of the excited fluorine atoms. The fluorine atom density is determined from plasma composition calculations either for pure PTFE (CF_4 vapor) or SF_6 vapor dependent on temperature and for pressures measured with a pressure probe at the nozzle wall.

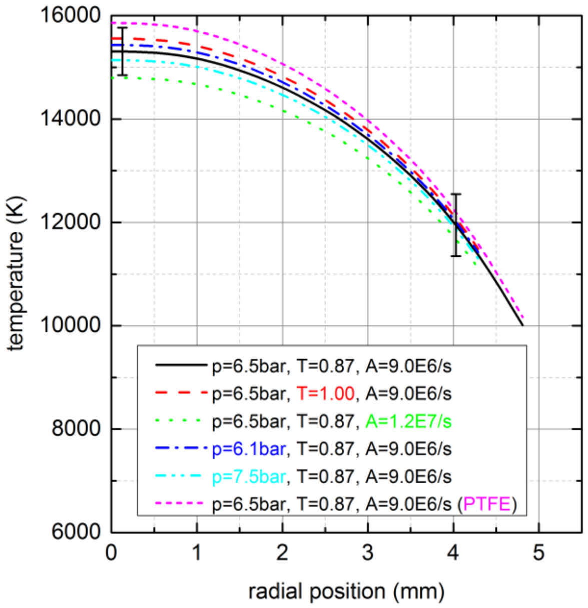

Fig.2: Radial temperature profiles for the current 1.7 kA for different parameters of the radiation analysis as given in the text

4 RESULTS AND ERROR ESTIMATION

Figure 2 presents results for the radial temperature profile obtained from one and the same spectral measurement at the current 1.7 kA (0.4-0.2 ms before CZ). The results belong to different values of pressure *p*, window transmission factor *T* and transition probability *A* to demonstrate the influence of variations of these parameters. The black curve corresponds to the measured values of *p* and *T* and the tabulated value of *A* (NIST database). For all curves expect the last one plasma composition for SF_6 is considered. It becomes obvious that expected uncertainties of pressure and transmission measurements lead to errors less than 3 % (blue and red curves). Using *A* from Kurucz data base the temperature is decreased by about 5% (green). Considering PTFE composition yields larger values by about 5 % (magenta). All these errors are lower than the expected maximum error which could result from Abel inversion at larger radial positions – about ±700 K – cf. the error bar in Fig. 2.

An additional significant source of errors is the optical thickness of the F I line. For an estimation of the influence on the temperature values the optical depth has been calculated from the integral of the absorption coefficient (considered as the emission coefficient divided by the Planck function for the given temperature profile) over the radial position for the center of the F I line. Then, the measured line intensity is corrected by the optical depth, and the approach of the temperature determination is applied again. This procedure is repeated until sufficient convergence. It results in a temperature profile which is about 7 % larger. Since the optical depth has been calculated for simplicity only for the line center and not for all wavelength values separately, the result gives an upper limit.

Table 1: Parameters of the measurements for three different currents together with the determined maximum temperature

I_{mom} (kA)	p_{tot} (bar)	t_{CZ} (ms)	d (mm)	T_{max} (kK)
3.5	6.8	0.7-0.5	1.80-2.50	14.0
3.3	6.8	0.7-0.5	0.68-1,42	14.6
1.7	6.5	0.4-0.2	2.81-3,74	15.3

Results for three different currents are presented in Fig. 3. The corresponding parameters at the instant of spectroscopy (measured current I_{mom}, measured pressure p_{tot}, time t_{CZ} before current zero, and electrode distance *d*) are given in table 1 together with the temperature in the arc center. The positive distance of the pin electrode from the utmost edge of the slit verifies that free spectroscopic access to the plasma was guaranteed. These results have been obtained using *A* from NIST data base and SF_6 composition without a correction with respect to the optical depth. With decreasing current the temperature profile becomes narrower whereas the maximum temperature increases.

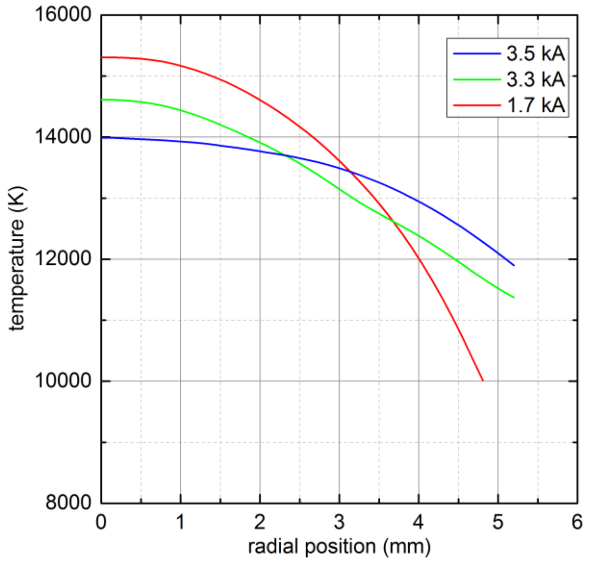

Fig.3: Radial temperature profiles for three different currents corresponding to the parameters given in Table 1

A further question is the possible influence of eroded electrode material on the plasma properties in the vicinity of the electrode. A certain cooling effect would be expected mainly due to the radiation of copper. From the spectroscopic measurements used for temperature determination no information can be deduced about this effect since there are no significant copper lines in the wavelength range around the F I line at 641 nm. However, additional measurements reveal that copper line radiation around 510 nm is always present but with a weak contribution to the overall emission. Furthermore, no dependence between the pin electrode distance *d* and the calculated plasma temperature *T* can be deduced from the experimental data.

5 SUMMARY AND OULOOK

Radial temperatures profiles of the switching arc have been obtained in an experiment with a model chamber during the falling edge of the current. With the spectral recording and analysis of the radiation of a fluorine atom line at 641 nm the temperature profiles could be determined with an accuracy better than 10 % despite of relatively high optical depth of this line. These results are appropriate for the validation of results of a corresponding CFD model of the arc in the model chamber [1]. Next steps will include a more detailed study of the changes of the composition during the current half wave and a more sophisticated consideration of the optical depth in the analysis of the F I line radiation.

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