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OPTICAL INVESTIGATIONS ON PLASMA TEMPERATURE ESTIMATION IN A MODEL SPARK GAP FOR SURGE CURRENTS

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Abstract. In this experimental investigation optical emission spectroscopy is used to characterize the radiation of the plasma in a spark gap during surge. Different approaches are used, compared and discussed in order to estimate plasma temperatures. The measurements were carried out in a narrow gap arrangement based on spark gap technology. This model is tested using 8/20 µs surge currents according to the IEC 62475 with amplitudes of 5 kA and 11 kA.

Keywords: arc, temperature, plasma, spark gap, surge current, surge protective device.

1. Introduction

Class I surge protective devices (SPD) are used in order to protect electrical devices from surge currents caused for example by lightning strikes. Thus following tasks have to be handled by the SPD [1, 2]:

- Plasma ignition caused by occuring surge
- Discharge of the surge to the ground potential
- Ensure of a galvanic isolation

These tasks can be achieved by a SPD based on spark gap technology due to their high energy absorption potential. For the limitation and extinguishing of the follow current in SPDs it is common use to quench the plasma in a narrow gap with gassing chamber walls. The successful extinguishing of the follow current mainly depends on the plasma properties like temperature, pressure and electrical conductivity. Thus one part of understanding the plasma processes and current limitation is the knowledge about temperature behaviour and how to influence it. To investigate the dependence of plasma temperature on different boundary conditions a method has to be found to measure the temperature. In this investigation different methods are presented in order to determine the plasma temperature in a spark gap model at surge currents. Further a comparison of the different results is made to identify the uncertainty of the plasma temperature.

2. Methodology

The measurements are carried out in a narrow gap arrangement based on spark gap technology at surge currents. In order to measure the temperature optical emission spectroscopy (OES) is applied at the spark gap as described in subsection 2.1. Afterwards the different methods to determine the temperature are described in subsections 2.2 to 2.4.

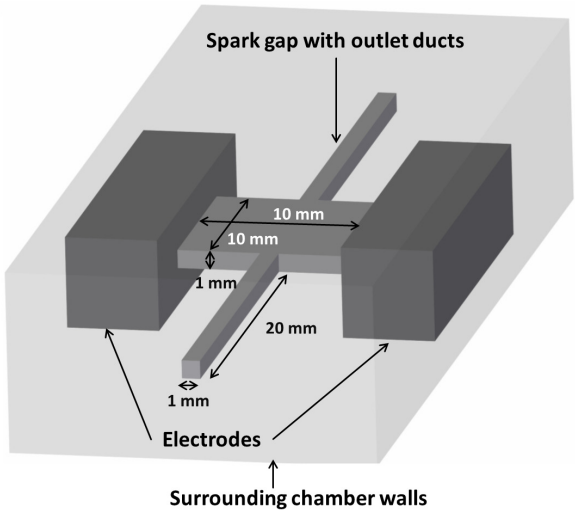

Figure 1. 3-D model of the used spark gap model without SDD [4].

2.1. Experimental Setup

The used spark gap model is already presented in other publications like [3]. A narrow gap is formed as a box with two outlet ducts by two W-Cu electrodes and a chamber wall. The chamber wall is made of Polyoxymethylen (POM) and Polymethylmethacrylat (PMMA) in order to get an optical access into the spark gap (Fig. 1). Surge currents of the form 8/20 µs are applied according to the IEC 62475 with amplitudes of 5 kA and 11 kA. For the ignition of the spark gap a surface discharge device (SDD) is used connected by a varistor. Afterwards the plasma is spreading in the spark gap and a breakdown occurs leading to a current flow through the plasma. The plasma expands with time and is finally forming a nearly homogeneous discharge in the spark gap [4].

For the optical emission spectroscopy two different setups are used. The first one consists of a

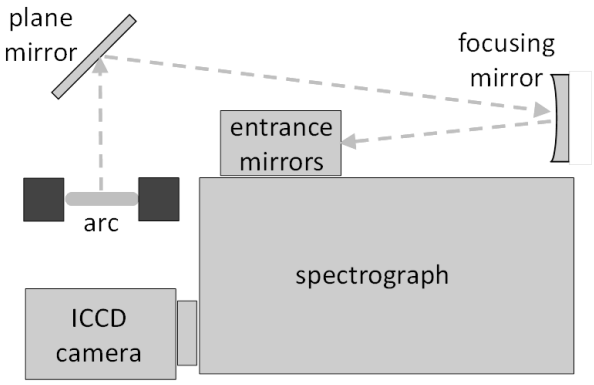

Figure 2. Setup for optical emission spectroscopy of SPD.

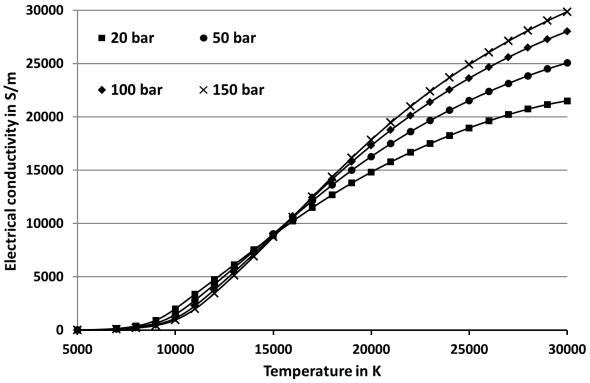

Figure 3. Electrical conductivity of air in dependence of temperature and pressure [6].

compact spectrometer (Avantes AcvaSpec 2048XL) with an entrance slit of 25 µm and a grating with 300 lines per mm on a 75 mm optical bench. Thus a spectrum from 250 nm up to 1000 nm can be recorded with a spectral resolution of about 1.5 nm full width at half maximum. The spectrometer is triggerable and the exposure time is set to 2 µs. To collect the radiation of the plasma a bare fibre with 200 µm diameter is used.

The second spectroscopic setup consists of an imaging spectrograph with 0.5 m focal length (Roper Acton SpectraPro SP2500i) equipped with an intensified CCD camera (Princeton Instruments PI-MAX) to record one image per shot at exposure times of about 1 µs (see Fig. 2). For this purpose the arc is imaged on the entrance slit of the spectrograph (40 µm slit width) by a focusing mirror. Deflecting mirrors are used to guide the radiation. Making use of a grating with 150 lines per mm, a spectral range of about 150 nm can be recorded by the triggered ICCD camera with a spectral resolution of about 0.3 nm full width at half maximum.

The trigger delay was adjusted to 13 µs for the first and 14 µs for the second setup to obtain spectra around current maximum. In both setups an absolute calibration of side-on spectra in units of spectral radiance are performed placing a calibrated tungsten strip lamp (OSRAM Wi 17/G) at the arc position.

2.2. Method I

The presented method I is not based on optical emission spectroscopy. In this case measurements of the electrical conductivity and plasma pressure are used as done in [4] and [5]. Together with data from [6] (Fig. 3) the electrical conductivity and pressure are used to determine the temperature. In this case data for air are used. This assumption can be made due to the negligible influence of POM and PMMA on the electrical conductivity compared to air plasma [7, 8].

2.3. Method II

From spatially and spectrally resolved OES the volume emission coefficient of a spectral line can be observed. In this investigation H_α at 656.279 nm as most marked spectral line in the observed spectrum is used. The so-called single line method makes use of this volume emission coefficient which can also be calculated from the following equation:

$$\varepsilon(T) = \frac{hc_0}{4\pi\lambda_0} \cdot \frac{n_g(T,p)}{Z} \cdot g_u \cdot A_{ul} \cdot \exp\left(-\frac{E_u}{k_b T}\right) \quad (1)$$

with h - Planck constant , c_0 - speed of light in vacuum, λ_0- center wavelength of H_α line, n_g - density of atomic hydrogen, Z - partition function of atomic hydrogen, g_u - statistical weight of the upper level of the transition, A_{ul} - transition probability, E_u - energy of the upper level, k_B - Boltzmann constant, and T - plasma temperature. The hydrogen density n_g can be obtained from local thermodynamic equilibrium (LTE) plasma composition calculations. The atomic data of the transition are taken from Kurucz database [9]. Now the volume emission coefficient is calculated for a selected temperature range at a given total pressure. From a look-up table the plasma temperature is deduced for the experimental emission coefficient.

2.4. Method III

In this method it is assumed that the plasma behaves like a black-body radiator due to a high optical depth caused by a high plasma pressure. With this assumption the temperature can be determined by comparing the measured intensity ratio L_2/L_1 of two wavelengths λ_1 and λ_2 with the intensity ratio of a black-body radiator at the same wavelengths as given in Eqn. (2).

$$\frac{L(\lambda_2,T)}{L(\lambda_1,T)} = \frac{\lambda_1^2 \cdot [\exp\left(-\frac{hc_0}{\lambda_1 k_b T}\right) - 1]}{\lambda_2^2 \cdot \left[\exp\left(-\frac{hc_0}{\lambda_2 k_b T}\right) - 1\right]} \quad (2)$$

3. Results and Comparison

This section is divided into three subsections: Firstly the calculation of temperatures by the use of measured pressure and electrical conductivity (method I), secondly the determination of temperatures using OES

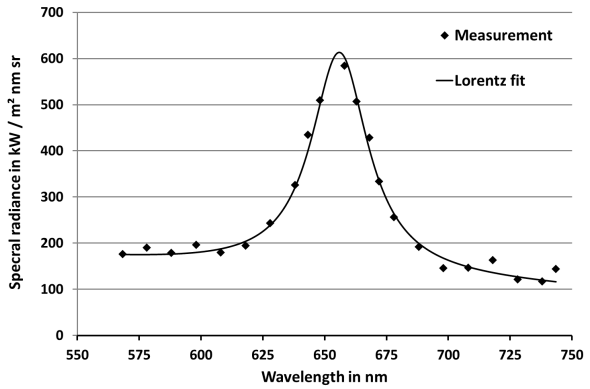

Figure 4. Side-on intensity of H_α line and Lorentz fit including linear offset for current amplitude of 5 kA.

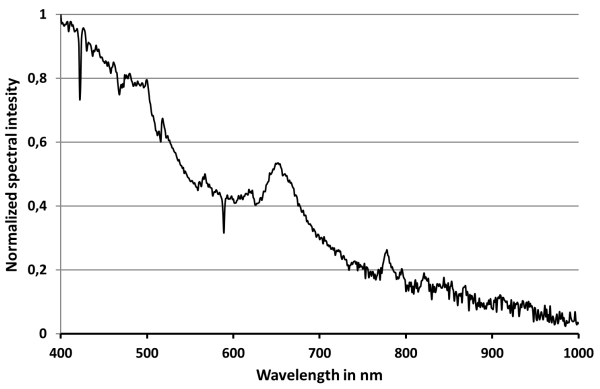

Figure 5. Normalized spectral intensity at a current amplitude of 11 kA.

(method II and III) and thirdly the comparison of the different results.

3.1. Results using method I

In this subsection the estimated temperature is presented using method I. Thus the measured electrical conductivity and pressure are used together with the data of [6] in order to determine the temperature. The measured pressure and electrical conductivity are shown in Tab. 1 together with the calculated temperature for different current amplitudes. They are representing the maximum temperature during surge occurring at current maximum. Next to the calculated temperature an uncertainty of these results are given. This uncertainty is arising from the uncertainties in the measurements of pressure with 10 % and electrical conductivity with 15 % [4, 5].

3.2. Results using method II and III

In order to determine the plasma temperature by OES two different methods are used. For the temperature at a current amplitude of 5 kA method II and for 11 kA method III is applied. Caused by the absorption in the PMMA at wavelengths below 400 nm only the spectral radiance between 400 nm and 1000 nm can be used. Fig. 4 presents the spectral radiance of the plasma at a current amplitude of 5 kA. The detected radiation originates from a region in the center of the chamber of about 1 mm lateral dimension. There appears a strongly broadened H_α spectral line at 656.279 nm with a full width at half maximum of 28 nm, which can be fitted by a Lorentz profile. Assuming a homogeneous plasma along the 1 mm line of sight and integrating over the spectral line profile, taking account of linear background signal, one yields a volume emission coefficient of $2.2 \cdot 10^{10}\,\mathrm{W/m^3\,sr}$.

Before application of Eqn. (1) the hydrogen density n_g has to be determined from plasma composition calculations for pure POM and pure PMMA plasmas at a given total pressure of 90 bar (see Tab. 1). This yields a temperature of 18 600 K in case of a pure POM plasma and a temperature of 18 400 K for a pure PMMA plasma. The experimental uncertainty of the emission coefficient is estimated to be better than $\pm 40\,\%$ leading to an uncertainty in the temperature of less than $\pm 4\,\%$ (± 750 K).

At a current amplitude of 11 kA the H_α spectral line becomes less marked and the spectrum becomes more and more Planck like, as can be seen in Fig. 5. Thus the ratio of measured intensities at different wavelengths L_2/L_1 as given in Eqn. 2 is used to determine the plasma temperature in this case (method III). The ratio of intensities depends on the temperature and the chosen wavelengths. At the use of this method it is important that no marked spectral line is located at the choosen wavelengths. Further two wavelength with a high distance have to be used to get a higher slope in the ratio over temperature and therefore a better resolution. Here the ratio is determined for 525 nm and 900 nm. Due to the signal noise, spectral intervals of ± 5 nm are averaged at the given wavelengths. This yields a measured ratio of 6.5 ± 0.75. A comparison with the calculated ratio using Eqn. (2) is presented in Fig. 6. Thus the temperature is determined to be 23 200 K with a lower boundary of 17 000 K and upper boundary of 36 000 K caused by the uncertainty of the measured ratio. For the comparison in the next subsection the uncertainty is determined by the average of difference between 23 200 K and lower and upper boundary which yields in 9 500 K.

3.3. Comparison of Temperatures

The comparison of the different results for plasma temperature at current amplitude of 5 kA and 11 kA are shown in Tab. 2.

At a current amplitude of 5 kA method I and II are in good accordance among themselves with an acceptable uncertainty. In case of 11 kA current amplitude the results using method I and III differ more. Especially the uncertainty of method III is too high in order to have an informative character.

Current Amplitude	Pressure	Conductivity	Temperature
5 kA	90 bar	15 250 S/m	18 750 ± 1 875 K
11 kA	250 bar	31 815 S/m	29 500 ± 5 900 K

Table 1. Estimated plasma temperature determined by method I.

Current Amplitude	Method I	Method II	Method III
5 kA	18 750 ± 1 875 K	18 500 ± 750 K	—
11 kA	29 500 ± 5 900 K	—	23 200 ± 9 500 K

Table 2. Comparison of plasma temperature using different evaluation methods.

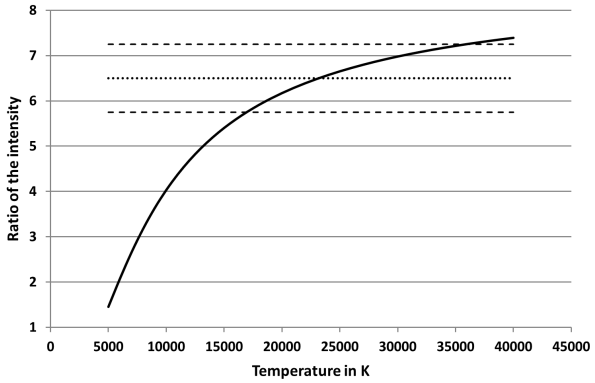

Figure 6. Comparison of the calculated intensity ratio (solid line) with measured intensity ratio (dotted lines) within given uncertainty (dashed lines).

4. Conclusion and Outlook

Different methods are used in order to determine plasma temperatures in a model spark gap at 8/20 µs surge currents according to the IEC 62475 with amplitudes of 5 kA and 11 kA. Method I based on measurements of plasma pressure and electrical conductivity, method II on OES using the volume emission coefficient of H_α spectral line and method III on OES using the ratio of black-body radiance at different wavelengths. At a current amplitude of 5 kA plasma temperature was determined to be about 18 500 K using method I and II. Caused by the uncertainty no clear temperature can be determined at 11 kA. Alternative methods applied to even higher currents are under investigation to obtain temperatures from Planck like spectra. However, especially at a current amplitude of 5 kA it is shown that combined measurements of pressure, electrical conductivity and temperature can be used in order to verify plasma parameters with theoretical data for electrical conductivity depending on pressure and temperature. This may offer an option to proof theoretical plasma transport data by experiments in the presented model spark gap. For this purpose the composition of plasma should be known precisely, which makes further experiments with non-gaseous chamber walls advantageous.

References

[1] B. Schottel and et al. Investigations on the influence of surge current on plasma in a model spark gap. In *Proc. International Conference on Lightning protection*, Shanghai, China, 2014.

[2] S. Ait-Amar. Arc extinguishing method of spd type1. In *Proc. International Conference on Lightning protection*, Uppsala, Sweden, 2008.

[3] T. Runge and et al. Experimental investigation on plasma pressure in an narrow gap for short time currents. In *Proc. International Conference on Electrica Contacts*, Edinburgh, Great Britain, 2016.

[4] T. Runge, T. H. Kopp, and M. Kurrat. Experimental investigations on electrical plasma conductivity in a model spark gap for surge currents. *submitted to Plasma Physics and Technology*, 2017.

[5] T. Runge and et al. Measurement of plasma pressure in a narrow gap for different surge currents. In *Proc. International Conference on Gas Discharges and their Applications*, Nagoya, Japan, 2016.

[6] A. D'Angola, G. Colonna, C. Gorse, and M. Capitelli. Thermodynamic and transport properties in equilibrium air plasmas in a wide pressure and temperature range. *Eur. Phys. J. D*, 46(1):129–150, 2008. doi:10.1140/epjd/e2007-00305-4.

[7] Q. Ma, M. Z. Rong, A. B. Murphy, Y. Wu, and T. J. Xu. Simulation Study of the Influence of Wall Ablation on Arc Behavior in a Low-Voltage Circuit Breaker. *IEEE Trans. Plasma Sci.*, 37(1):261–269, 2009. doi:10.1109/TPS.2008.2007733.

[8] P. André, L. Brunet, W. Bussiere, J. Caillard, J. M. Lombard, and J. P. Picard. Transport coefficients of plasmas consisting of insulator vapours - Application to PE, POM, PMMA PA66 and PC. *Eur. Phys. J.-Appl. Phys.*, 25(3):169–182, 2004. doi:10.1051/epjap:2004007.

[9] R. L. Kurucz and B. Bell. Atomic Line Data. Kurucz CD-ROM No. 23. [online], Smithsonian Astrophyical Observatory, 1995. URL: http://www.cfa.harvard.edu/amp/ampdata/kurucz23/sekur.html.