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ANALYSIS OF C_2 SWAN BANDS IN ABLATION-DOMINATED ARCS IN CO_2 ATMOSPHERE

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Abstract. A model circuit breaker in a high-pressure chamber filled with CO_2 atmosphere is used to operate a wall-stabilized arc of several kilo-amperes between tungsten-copper electrodes surrounded by polytetrafluoroethylene nozzles. Optical emission spectroscopy (OES) is carried out via quartz plates inserted into the nozzles using a combination of an imaging spectrometer either with a high-speed video camera or with an ICCD camera. Depending on the nozzle geometry and the current, continuum from C_2 Swan bands was detected as absorption as well as emission pattern. After current zero, optical absorption spectroscopy (OAS) using a xenon flashlamp as broadband background radiator was applied. An absorption around 493 nm was detected and attributed to CuF molecules. The study proofs the existence of C_2 in the active phase and the formation of CuF near to current zero.

Keywords: ablation, switching arc, spectroscopy, PTFE, CO_2.

1. Introduction

Self-blast circuit breakers are based on the ablation of material from a nozzle producing a pressure build-up in a heating volume that is used for arc quenching around current zero (CZ). The CZ crossing and the period immediately after current interruption are of high importance for the interruption performance. In these time intervals several physical effects occur, such as flow reversal in the heating channel, transition from an ablation-controlled to an axially blown arc, the extinction of the arc and a continued evaporation of nozzle material after current zero due to the preceding thermal stress. The deeper understanding of the transient behavior and effects on the dielectric recovery are key issues for further development of high voltage switchgear, either based on sulfur hexa-fluoride (SF_6) or alternative gases, e.g. carbon dioxide or mixtures containing carbon dioxide.

The determination of dielectric properties, i.e. the plasma composition, pressure and temperature, as close as possible to current zero is mandatory for an improvement of interruption capability. Therefore, optical access to the arc plasma is needed but not available in commercial circuit breakers. Simplifications have to be allowed to obtain visual access at comparable plasma conditions. Model chambers are applied either with movable pin and tulip electrodes [1], with fixed electrodes ignited by explosion of thin wires [2], or with non-rotationally symmetric nozzles [3]. Recently, we reported on experiments with two pin electrodes of fixed distance placed in a single, long PTFE nozzle without a chamber [4]. The influence of ignition wire and surrounding gas (ambient air) were investigated as well as the PTFE ablation at low current phases, i.e. during the current increase, when the discharge is initiated, and during current decrease, when approaching CZ. Determination of plasma temperature profiles was limited to 0.4 ms before CZ.

In this work, a switching arc of a model circuit breaker similar to [5, 6] with optical access in a CO_2 atmosphere is investigated. The model circuit breaker consists of two nozzles surrounding the electrodes and forming a heating channel. Whereas in [6] the plasma in the heating channel was analyzed during the high-current phase by means of optical emission spectroscopy (OES), the observation position was shifted towards the electrodes by insertion of quartz windows into the nozzle wall in this study. Recently, the temporal evolution of plasma properties during the last millisecond before current zero was investigated for this geometry [7]. It was shown by means of OES that the gas flow changed from a blow-out of the nozzle, due to wall ablation into the heat volume (characterized by atomic F I and ionic C II lines), to a flow-in into the nozzle from the heating volume (characterized by C II and O I lines) at about 2 ms before CZ. While the C II extinguished about 100 µs before CZ, the oxygen triplet at 777 nm could be used for determination of temperature profiles until 10 µs before CZ. Arc constriction from diameters of several mm to less than 0.5 mm and a temperature decrease in the center of the arc from about 20 000 K at 300 µs to about 11 000 K at 10 µs before CZ were measured.

Although the OES of atomic and ionic lines has been established for plasma analysis, there are severe limitations. Usually, these lines have their maximum in the arc center and the temperature profiles are typically limited to minimum values of 8 000 – 10 000 K, due low emission intensities at lower currents and the cold gas flow close to CZ. Thus, spatial temperature profiles do not reach the close vicinity of the wall

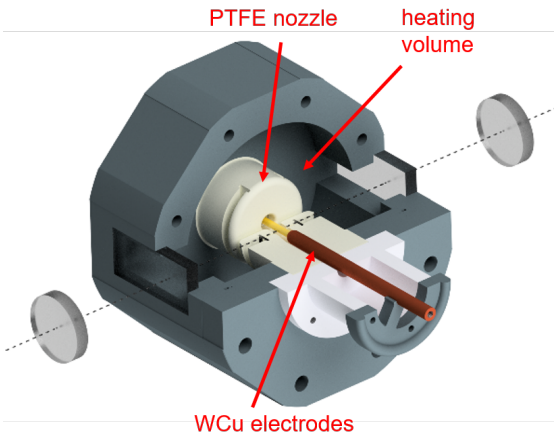

Figure 1. Model circuit breaker geometry. The arc was operated between W-Cu electrodes surrounded by PTFE nozzles. Observation along the arc diameter was provided by vertical slits in the nozzles. Note that windows at both sides of the model chamber and the outer vessel allowed emission and absorption spectroscopy.

region that is of high interest due to importance of the nozzle ablation [8, 9].

However, at reduced temperatures the majority of atoms is in the ground state and could be analyzed by optical absorption spectroscopy (OAS) of resonant lines. Nevertheless, resonant lines of the relevant species are in the UV region (C, F, Cu) that is difficult to investigate under switching-relevant conditions and demands a lot of technical effort. Many other lines are very weak (O I at 630.03 nm). An alternative to the investigation of atomic and ionic lines is the spectroscopic investigation of molecules. Most molecules dissociate above critical temperatures of less than 10 000 K. They may provide insight into the region close to the wall at lower temperature.

2. Experimental Setup

A model circuit breaker in a high-pressure vessel was prepared. A sketch of the setup is shown in Figure 1. Two fixed W-Cu electrodes of 10 mm diameter were placed horizontally with a distance of 40 mm in a metal chamber. Both electrodes were surrounded by nozzles of PTFE doped with <0.5 wt% molybdenum disulfide (MoS_2). The distance between these two nozzles was about 4 mm forming a heating channel in the middle between both electrodes. The inner diameter of the nozzle was about 16 mm at the electrode side end of the nozzle and 12 mm at the nozzle exhaust. The transition from wide to narrow diameter was placed close to the electrode tip. In former experiments, the observation was carried out in the heating channel between the two nozzles [6]. The turbulent gas flow in the direction of observation induces several complication concerning the radial symmetry that is needed for plasma temperature determination. Therefore, a technique recently introduced for a single long PTFE nozzle [4] was adapted: Two vertical

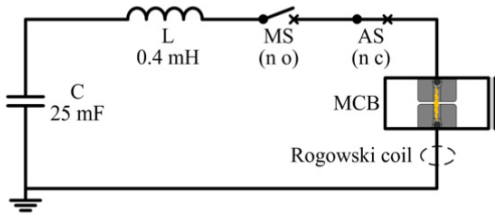

Figure 2. Electric setup for generation of sine-like 50 Hz discharges, initiated and interrupted after one half-wave by the switches MS and AS, respectively.

slits of 2 mm width, allowing access to the full nozzle diameter, were mortised directly into the nozzles. They were positioned about 9 mm away from both, the electrode tip and the nozzle exhaust. To seal the nozzle and to reduce the disturbing influence of the slit, 2 mm-thick quartz plates were applied. In combination with windows of both, model chamber and vessel, a free view through the nozzle has been enabled for observation from opposite directions as well as absorption measurements.

The electrical setup is shown in Figure 2. The LC circuit was discharged via the switch MS. A sine-like current waveform of about 50 Hz frequency and 5 kA peak current was applied for all discharges. After one half-wave the current was switched off by AS. Thin copper wires were used for initiation of the arc discharge. The pressure was measured in the heating chamber by a Kistler sensor of type 603A. A comparison with CFD simulated pressures allowed to estimate the pressure values inside the nozzles.

The spectroscopic setup consisted of an imaging spectrograph with 0.5 m focal length (Roper Acton SpectraPro SP2500i) equipped with either a high-speed video camera (Y4 series of Integrated Design Tools, 10bits monochrome) to record a series of images per shot or an intensified CCD camera (Princeton Instruments PI-MAX) to obtain higher sensitivity. The observation slit of the nozzle was imaged on the entrance slit of the spectrograph by a focusing mirror to observe the cross section of the arc in the direction perpendicular to the arc axis. Deflecting mirrors were used to guide the radiation. Since the sensitivity of non-intensified cameras is limited, the exposure times have to be relatively high.

For absorption measurements around CZ an intense xenon flashlamp (nearly rectangular pulse with 1 MW electric power input and 1 ms duration) was applied as an external broadband background radiator with a spectrum comparable to a thermal radiator with a temperature of about 14 000 K. A second high-speed video camera (Y6 series of Integrated Design Tools) was applied for the observation of the general behavior of the discharge.

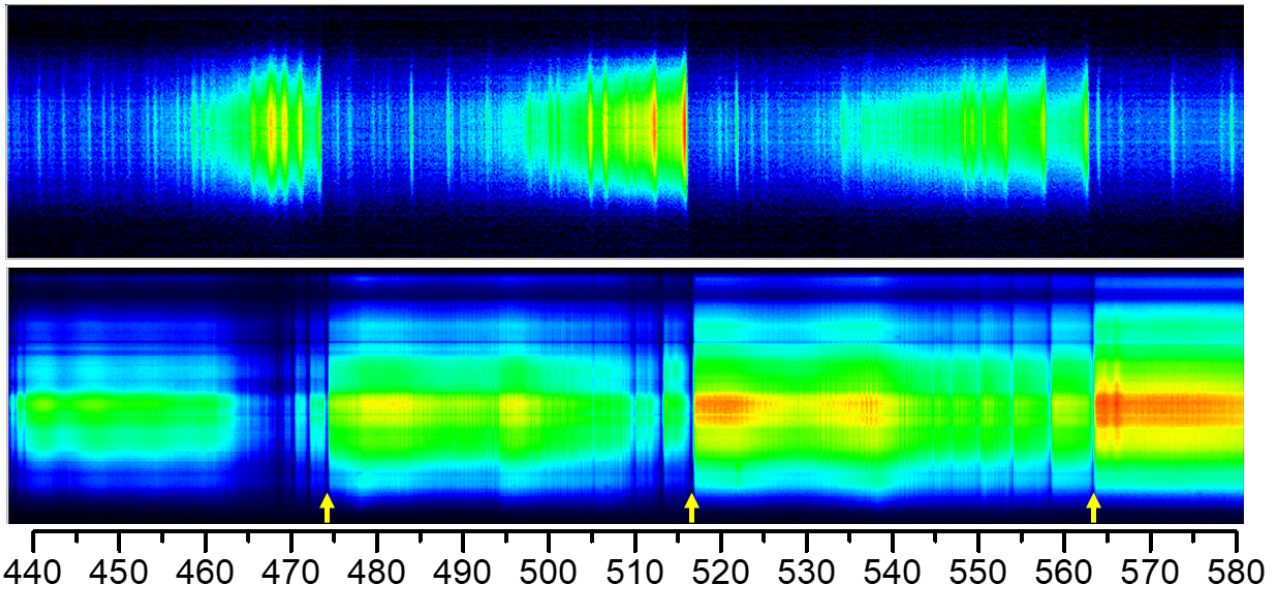

Figure 3. Spectrum during high-current phase of the discharge dominated by molecular radiation of C_2 Swan bands. Depending on plasma conditions (arc current, nozzle geometry) the Swan bands could be observed as emission (top) or absorption pattern (bottom). The band head are labeled by arrows.

3. Results and Discussion

3.1. Optical Emission Spectroscopy

Series of two-dimensional spectra containing spatial as well as spectral information were obtained by the video spectroscopy. The low-current phases after ignition and near CZ are dominated by line emission (Cu, C, O, and F) with highest intensities in the central part of the axis. Those lines could be utilized for an analysis of temperature profiles along most of the arc radius. In cases with significant nozzle ablation, usually fluorine atomic or carbon ionic lines were applied [1, 2, 4, 6]. In the phase of low currents, i.e. without sufficient nozzle ablation, oxygen atomic lines could be applied for the determination of temperature profiles, reaching down to few microseconds before current zero [7]. With increasing current of just 2.5 kA (1.5 ms), also continuum emission was observed as a pattern near to the nozzle wall [10]. It could be attributed to an emission of diatomic carbon molecules, i.e. the Swan band system arising from transitions between the $d^3\ \Pi_g$ and the $a^3\ \Pi_u$ electronic states of the C_2 molecules [10].

The Swan bands were found to occur under quite different conditions. The most pronounced emission spectra were obtained in the experiments with a single long PTFE nozzle [4]. In the example shown in the upper part of Figure 3, the complete spectrum at all radial positions (vertical axis) is dominated by the Swan bands (observed at currents above 10 kA). With the current setup in the model circuit breaker, however, the C_2 continuum was visible in emission only close to the nozzle wall. More typically, it appeared as an absorption pattern at moderate currents >4 kA, as shown in the lower part of Figure 3, taken 6.1 ms after ignition at (4.7 kA), i.e. shortly after the current maximum. Here, the hot plasma in the core served as an internal background radiator and the absorption close to the wall becomes visible. The band heads at 473.7 nm, 516.5 nm, and 563.6 nm are indicated by arrows (another one is at 438.2 nm). The spectra also contain several C II lines from carbon ions, e.g. at 564.06 nm, 564.81 nm, and 566.26 nm, mainly emitting in the center of the arc with higher temperatures. For the above described arcs with strong flow of ablated material towards the electrodes, no copper lines were visible. The F I lines were not in the chosen wavelength range.

The Swan bands have been widely investigated by laser-induced optical breakdown spectroscopy (LIBS) of graphite targets [11, 12]. For laser irradiation it was reported that the dominant mechanism for the production of C_2 molecules at low power is the collision of electrons with larger molecules like C_3, C_4 followed by photodefragmentation whereby one of the emitted products is an exited C_2 molecule. At higher laser irradiance, the Swan band emission is mainly caused by excitation resulting from electron-ion and ion-ion recombination [11]. The shape of continuum is influenced by pressure and temperature in the range of 5 000 – 8 000 K. Thus, an estimation of the vibrational temperature could be obtained by comparison of measured and simulated spectra [13, 14].

3.2. Optical Absorption Spectroscopy around Current Zero

Around current zero, neither emission nor absorption of Swan bands was observed, although weak O I line radiation was observed in the last 10 µs. As described above, most of the ablated wall material is blown

towards the electrodes by the reversed gas flow from the heating channel. However, the spectral absorption was carried out systematically using a xenon flashlamp as an external wide-band background radiator (Figure) 4). Scanning through the wavelength ranges from about 400 nm to 800 nm, no hint on Swan bands or any absorbing lines could be detected around current zero, even with the application of the intensified camera with higher sensitivity and dynamic range. The only feature that was found was a multi-peak structure with a pronounced maximum around 493 nm and a weaker above 500 nm. An example for an absorption spectrum with increased spectral resolution (using a grating with 1800 instead of 150 lines per mm and an exposure time of 98 µs) is shown in the upper part of Figure 4 recorded 0.5 ms after current zero. The edges of the nozzle are indicated by a sharp transition from the bright stripe caused by illumination with the xenon lamp and the dark areas. The horizontal stripes are due to deposition on the quartz glass sealing the slits, e.g. by particles, and do not change from one video frame to the next. The occurrence of this structure was very reproducible and faded out within several hundreds of microseconds after current zero. Line absorption (Cu, O, C, F, H, or Xe) could be easily excluded. The only known absorber in that wavelength was the molecule of CuF.

Since no absorption spectra were available for CuF, a comparison was carried out with emission spectra of photofragments in a gas phase photochemical fragmentation process excited by 308 nm-laser radiation [15]. In the lower part of Figure 4 the emission spectrum from Cheon et al. [15] was added as an overlay (black curves) to the calculated absorption spectrum (red curve) for comparison. Taking into account the different experimental conditions and methods, a compelling agreement was found.

The occurrence of a considerable amount of CuF molecules was not expected for several reasons, especially regarding that no other molecules were observed around CZ. A possible explanation is as follows: Around CZ it is expected that convective fluxes are significantly reduced due to equalization of pressures. This allows diffusive expansion of copper from the hot electrode along the nozzle towards the slit position. At the same time there is still some release of fluorine from the PTFE nozzle wall. The chemical reaction of the fluorine and copper atoms forming CuF molecules could happen at the hot electrode surface followed by evaporation of molecules or in the gas phase with copper atoms evaporated from the electrode.

4. Summary and Conclusion

A wall-stabilized arc of several kilo-amperes between tungsten-copper electrodes surrounded by polytetrafluoroethylene nozzles was operated in a model circuit breaker in CO_2 atmosphere. Optical emission spectroscopy as well as absorption spectroscopy were carried out via quartz plates inserted into the nozzles.

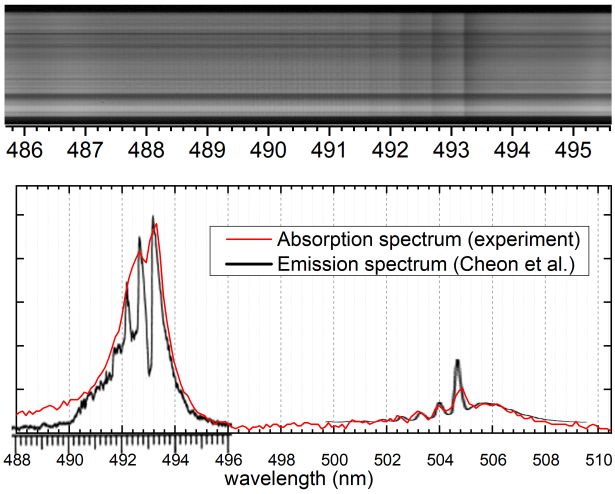

Figure 4. Absorption spectrum around current zero and comparison with emission spectra of CuF molecules from [15].

The results of spectroscopic analysis can be summarized as follows:
Line as well as continuum emission was observed. At the beginning of the discharge, i.e. when the current is rather low and no significant ablation of the PTFE nozzle takes place, only emission from ignition wire (Cu I) followed by the filling gas (C II, O I from CO_2) and the electrodes (Cu I from W-Cu) can be observed.
By increasing current with time, the wall ablation changes the behavior of the arc. The filling gas is blown out due to the pressure increase resulting from the ablated and dissociated PTFE wall material. Thus, line emission of fluorine atoms F I accompanies that of the carbon ions C II whereas O I and Cu I can not be observed any more. This state remains most of the discharge time, i.e. just down close to current zero.
Nonetheless, in cases with strong wall ablation and pressure build-up, e.g. with long and narrow PTFE nozzles and rather high arc currents, Swan bands from C_2 molecules can be observed. Here, for the spectra three forms of appearance can be distinguished:

1. The Swan bands are observed mainly close to the nozzle wall in emission [10].

2. With stronger ablation of wall material, the Swan bands are observed as absorption pattern all over the nozzle cross section (lower part of Figure 3). The occurrence of rather intense C II lines at 564.1, 564.8, and 566.2 nm hints at relatively high temperatures at least in the center of the arc.

3. With even higher impact of the C_2 molecules, the Swan bands appear as pure emission pattern (upper part of Figure 3). Here, the C II ionic lines are less prominent (or not observed any more) hinting on lower arc temperatures than in the case above.

With decreasing current and wall ablation, the pressure inside the nozzle decreases, too. When it falls

below the pressure inside the heating volume, the direction of the gas flow turns back, now flooding the nozzle with cold gas from the heating volume that is dominated by CO_2. Consequently, the spectra of C_2 and ablated wall material vanishes, and species from CO_2 appear (again, as in the starting phase). While the origin of C II lines remains uncertain, the flow reversal can be easily followed by the relation of line emission of F I to O I. Temperature profiles of the arc can be deduced down to few µs before current zero from the O I line emission.

Around current zero, optical absorption spectroscopy using a xenon flashlamp as an external broadband background radiator was carried out in addition to the OES. In the wavelength range under investigation (400-800 nm), only one absorption pattern around 500 nm was found, clearly belonging neither to any Swan band nor to lines of the expected elements C, O, F, and Cu. The absorption with a stronger maximum around 493 nm and a weaker around 506 nm could be attributed to CuF molecules by comparison with known CuF emission spectra. The occurrence of CuF absorption at the observation slit position around CZ is a little surprising since after the reversal of gas flow the nozzle is filled mainly by CO_2 and the electrodes as possible source of copper is some mm away from the observation slit in the nozzle. However, there must be a chemical reaction of fluorine atoms with copper from the electrodes either at the electrode surface that is hot and followed by evaporation of molecules, or directly in the gas phase with copper atoms evaporated from the electrode.

The study proofs the existence of C_2 in the active phase and the formation of CuF close to current zero. As a next steps, the absorption experiments should be repeated without Cu-containing electrodes. Furthermore, a quantification of the continuum analysis would be very interesting since it might reveal the less-known field of processes near to the nozzle wall as well as after current zero.

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