Cu/W Electrode Ablation and Its Influence on Free-Burning Arcs in SF$_6$ Alternatives

Joseph T. Engelbrecht, Pawel Pietrzak, and Christian M. Franck, Senior Member, IEEE

Abstract—A free-burning arc experiment was performed in a gas mixture composed of CO$_2$/O$_2$/C$_5$F$_{10}$O (85%/10%/5%). An optical emission spectroscopy (OES) diagnostic was developed to obtain spatially resolved arc spectra at a high frame rate. Spectral measurements are compared with simulated spectra to estimate arc parameters including temperature and composition. These techniques are used to characterize the arc and its associated electrode jets over a range of conditions, in order to study the influence of ablated Cu/W on arc characteristics. The observed spectra indicate that the ablation of the contact tip primarily occurs through vaporization rather than the expulsion of droplets. The metal vapor content of the arc is investigated as the arc driving current is varied, and a transition threshold for increased ablation at electrode current densities above 50 A·mm$^{-2}$ is determined. The expansion angle of the electrode jet is estimated from the concentration of metal vapor in the arcing region at different axial positions, using a basic conical expansion model. The dependence of the measured voltage on the arc composition is examined, and a positive correlation between Cu content and arc voltage is identified. This trend is attributed to the higher emissivity of the metal vapor, which suppresses the central arc temperature and increases its resistivity.

Index Terms—Arc discharges, gas insulation, sulfur hexafluoride, spectroscopy, switchgear.

I. INTRODUCTION

A COMPARATIVE program to evaluate a number of proposed alternatives to SF$_6$ in gas insulated switchgear (GIS) has been initiated by the High Voltage Laboratory, ETH Zürich, Zürich, Switzerland, [1]. As a part of this study, a test device for investigating unblown (i.e., free-burning) arcs over a large parameter space has been developed. This unblown arc experiment was used to measure the voltage response of arcs in the various alternative gas mixtures under systematic variation of the fill pressure, contact separation, and driving current, which was investigated over a range from 0 to 3 kA. These measurements spanned a range of conditions that are relevant for a number of industrial switching applications, including gas load break switches and induced current switching or bus-transfer current switching in disconnectors.

High-current arcing on metal electrodes can result in substantial ablation of the contact tips, as they experience intense heating due to charged particle bombardment and thermal exchange at the interface with the high-temperature arc root. Temperatures at the contact surfaces can exceed 3000 K, leading to significant ablation that can take the form of metal vapor or droplets that are ejected into the arcing region by so-called electrode jets [2], [3]. When characterizing free-burning arcs in different switching media, it is therefore prudent to develop a measure of the concentration and distribution of the ablated metal species, as these inevitably compose a significant fraction of the arc at kA scale currents [4]. In order to evaluate the electrical characteristics of the arc, it is also critical to study how these parameters may be influenced by the presence of the ablated metal.

In the present work, a method for estimating the metal vapor content of the arc with an optical emission spectroscopy (OES) diagnostic is demonstrated, using an approach similar to [5]. This method is applied to studying the time evolution of the arc and its response to current variation. These measurements are used to estimate the current dependence of the metal concentration of the arc, and a transition threshold for increased vaporization is determined. Measurements performed with varying contact separation are employed to develop a model of how the ablated metal expands from the electrodes. The arc voltage measurements are then examined against these composition measurements to determine the influence of the metal vapor on the arc parameters. The results extend the body of work on electrode ablation in free-burning arcs to novel CO$_2$-based switching gas mixtures and provide a framework for deeper interpretation of the results from the comparative study of SF$_6$ alternatives.

II. METHODS

A. Unblown Arc Experiment

The unblown arc experimental configuration is shown in Fig. 1, together with the OES diagnostic. The arcing chamber is a standard GIS vessel that was used to systematically investigate a variety of switching gases, including SF$_6$ and its alternatives, over a pressure range from 100 to 500 kPa. Arcs were initiated by the pneumatically-driven separation of two pin-type contacts under a quasi-dc current of approximately 300 A, which was sustained for tens of ms until the contacts stabilized at their fully-open position. The current was then ramped up to 3 kA, and allowed to inductively decay over

Digital Object Identifier 10.1109/TPS.2022.3203007
at least 10 ms. Measurements of the arc voltage during the current decay were used to determine the $U$–$I$ characteristic of the arc for a given fill gas, pressure, and contact separation distance [6]. The current pulses were generated by an updated prototype of the flexible pulse current source (FPCS), which uses a power-electronics approach to provide arbitrary current waveforms at a charging voltage of up to 5 kV [7], [8].

The arcing contacts were made from Cu/W (20–80 wt%), and were manufactured with a nominal diameter of 8.4 mm, tapering to a 5.1 mm truncated tip. Severe erosion of the contact surface was observed after sustained arcing, suggesting that the exact contact tip geometry varied over the course of the measurements. The observed erosion was asymmetric and favored the upper half of the contact tip, seemingly due to the self-rising nature of the horizontal free-burning arc.

In order to place upper limits on any influence the ablated electrode material may have on the arc characteristics, conditions producing the highest fractional metal vapor content in the arcing region were of particular interest for spectroscopic investigation. For this reason, and to aid the analysis by reducing pressure broadening of the measured spectral lines, the majority of the measurements presented herein were performed at the lowest investigated fill pressure of 100 kPa, for a gas mixture composed of $\text{CO}_2$/$\text{O}_2$/C$_5$F$_{10}$O (85%/10%/5%). This mixture is typical of the SF$_6$ alternative gas mixtures investigated over the course of this unblown arc experiment, which share a base gas consisting primarily of $\text{CO}_2$ and $\text{O}_2$, with any fluorinated additives not exceeding 10% mixing ratio.

B. OES Diagnostic

Emission from the arc was collected with an adjustable focal length camera lens and imaged onto the end of an optical fiber array consisting of seven linearly arranged, 200-$\mu$m-diameter fibers. The output end of the fiber array was coupled to the input slit of the spectrograph. The input end of the array was aligned vertically, to provide spatial resolution across the radial dimension of the horizontal arc. The magnification was set to span a 20 mm imaging region, resulting in a spatial resolution of 3 mm for the seven fibers. Typically only the fiber corresponding to the arc center was analyzed, however, the large de-magnification was necessary to consistently keep the arc center within the field-of-view, due to the highly mobile nature of the free-burning arc.

The spectrograph instrument was adapted from a Czerny-Turner monochromator with a 0.25 m focal length and a 1200 grooves/mm grating. In order to reconfigure the monochromator so that a spectrum with some bandwidth could be recorded, the output slit was removed. A Photon SA-Z high-speed camera (HSC) was mounted at the output with its 1 megapixel CMOS image sensor at the focal plane. Recordings were made at 20 kframes/s, the highest sampling rate that utilizes the full pixel count of the HSC.

A linear intensity correction was applied to the image data to account for variation in camera sensitivity over the measured wavelength range, based on the sensitivity curve given in the datasheet. An absolute intensity calibration was not carried out as part of this work, therefore all measured spectra are presented on an arbitrary intensity scale.

Spectra were obtained over a wavelength range from 772 to 815 nm, with a resolution of 0.2 nm, determined from linewidth measurements of an argon calibration lamp. This region of the spectrum contains strong lines from both of the Cu/W electrode species, in addition to oxygen, a major component of all the gas mixtures investigated. The atomic oxygen triplet at 777 nm in particular proved to be intense enough to be observed through even the most metal-dominated conditions, making it a useful reference line for discerning changes in plasma composition.

C. Spectral Analysis

To obtain useful estimates for the arc temperature and composition from the measured spectra, fits were performed with OPSIAL, an open-source software tool for generating simulated plasma spectra [9]. The use of these simulated spectra allowed for quantitative comparisons over a wider range of conditions and a larger number of measurements than would be feasible with more analytically intensive techniques. Adjustable parameters included temperature, pressure, line-of-sight segment length, and the mixing ratios of the component species. Five species were included in the calculation of the simulated spectra: oxygen, carbon, and fluorine, representing the basic components of the gas mixtures, in addition to copper and tungsten, which make up the contacts. To limit the number of adjustable parameters, the observed emission is treated as originating entirely from a region of fixed thickness that is uniform in temperature and species number density. This approach represents a major simplification, as it treats the metal vapor distribution as being homogeneous along the line of sight, and requires that the temperature and emission volume of the metal vapor match that of the fill gas species.

For sufficient signal-to-noise ratio at lower currents, the fiber corresponding to the arc center needed to be binned for analysis. For consistency and to aid comparisons between measurements, this method was extended to all of the analyzed...
spectra. As the arc is mobile, the central fiber could vary between frames in a given recording. The measured spectra typically exhibited the most intense oxygen emission on a single fiber, with a symmetric decay in line intensity moving away from it, allowing the fiber corresponding to the radial center of the arc to be determined unambiguously. In some cases, this peak in oxygen line intensity did not correspond to the location of the most intense emission from the metal vapor. This could indicate that the arc center did not always overlap with the region of highest metal vapor density. Alternatively, such an intensity distribution could be caused by the occurrence of a normal maximum in the Cu line intensity in an intermediate radial layer of the arc. However, the boundaries of the emitting region for oxygen and the metal vapor species were well matched, allowing both to be described by the same line-of-sight length through the arc plasma.

Fig. 2 shows two contrast-enhanced examples of measured spectra, each typifying different arc conditions, shown together with their best-fit simulated spectra and the resulting fit parameters. The spectrum shown in Fig. 2(a) was taken during the high \((dI/dt)\) rising current phase \((I = 1.9 \text{ kA})\). The resulting fit suggests that the arc is primarily composed of the switching gas components, with minimal contamination from electrode vapor, despite the strength of the two Cu I lines at 793 and 809 nm. The O I triplet at 777 nm has been broadened into a single feature, and strong emission is also observed from the O I doublet at 795 nm. The simulated spectra for such gas-dominated conditions also typically predict an O I multiplet around 799 nm, which was not observed in any measured spectra. The corresponding transition probabilities \(A_{kl}\) of these lines are approximately 1/1000th those of the 777 nm O I lines [10], so it is conceivable that they may not be detected despite the high intensity of the nearby oxygen lines. Good agreement is maintained between the simulated spectrum and the observed lines from both the switching gas and the metal vapor species, preserving reasonable mixing ratios as described in the forthcoming section. We, therefore, conclude that the simulated spectra provide a reasonable estimation of the arc parameters, considering the approximations made in the fitting process, and the absence of the O I multiplet in the measured spectra is not taken as an indication of a serious misdiagnosis of temperature or oxygen content.

The spectrum from Fig. 2(b) was taken at the start of the current decay just after the current peak \((I = 2.8 \text{ kA})\), and is representative of a heavily metal-contaminated arc, as evidenced by the severe broadening and self-reversal of the Cu I lines. The presence of the hot metal vapor increases the absorptivity of the region surrounding the arc, which can substantially increase the optical depth and observed line broadening. The method implemented in OPSIAL assumes that this broadening originates entirely from collisional or Doppler mechanisms. Under these conditions, an abundance of W I lines are also visible, the strongest of which are labeled in the lineout. The remaining low-intensity lines can be attributed primarily to tungsten atoms or copper ions. The only emission lines present in this spectrum that can be conclusively determined to originate from the fill gas species are those from the O I triplet, which has narrowed to the point that the individual line peaks may be resolved.

In order to constrain the simulated spectra to solutions consistent with the known experimental conditions, several assumptions were made. First, it was assumed that since
measurements were performed radially through the arc center, the line-of-sight length could be approximated as the observed diameter of the emitting region (i.e., the cylindrical arc). At currents above 1 kA, this diameter could slightly exceed the field-of-view, and in these cases needed to be estimated. This approximation of the line-of-sight length neglects variation in the optical depth, which likely becomes significant as the metal vapor content of the arc increases, based on the observation of self-reversed Cu lines. This lends some uncertainty to both the fit parameter estimates and to determining what radial layer of the arc they are representative of.

For the second assumption, the molar mixing ratios of both the switching gas (O 55%/C 31%/F 14%) and the electrode vapor (Cu 42%/W 58%) components of the mixture were kept nearly stationary, and only their relative contributions were allowed to vary significantly. These specified mixing ratios were determined assuming uniform decomposition and vaporization of the fill gas and the contact material, respectively. In the case of the gas components, this assumption did not significantly affect the resulting fits, as little carbon and fluorine emission was observed within this spectral band, and the oxygen lines almost fully determined the fit parameters, though good agreement was observed when fluorine lines were present. Determination of absolute pressures and mixing ratios cannot be performed with high accuracy using this method without a spectral calibration, however, the self-consistency of the results indicates that useful comparisons can still be made. Generally, this approach resulted in total pressures of the mixture components comparable to the vessel fill pressure, however, during the current-ramping phase, elevated pressures of up to 1 MPa were estimated.

The fitting routine was carried out starting from a reasonable initial guess; typically this was the parameters determined from the previously analyzed frame. In nearly all the analyzed frames, emission lines from both the copper and tungsten components of the electrode vapor were observed. The relative intensity of these lines is quite sensitive not only to mixing ratio but also to temperature. Fixing the ratio of $N_{\text{Cu}}/N_{\text{W}}$, therefore, helped constrain the fit temperature to within 1000 K, as the relative intensities of the Cu and W lines change rapidly with respect to each other as temperature is adjusted in the range around 10 K K. Increasing the simulated temperature much beyond this typically resulted in solutions with inexplicably high tungsten content, while solutions with significantly lower tungsten content corresponded to temperatures too low to produce the strong oxygen line emission that was observed. Previous studies have concluded that the electrode ablation under similar arcing conditions can be attributed primarily to evaporation of the contact material, rather than the ejection of liquid droplets [2], which is to be expected in the absence of a strong gas flow. If a significant fraction of the mass was lost in the form of droplets that never reached vaporization temperatures, the arc composition would disproportionately favor the copper over the tungsten due to its much lower boiling point. Our spectral analysis supports the conclusion that vaporization dominates, as reducing the tungsten fraction of the mixture typically resulted in less satisfactory fits.

D. Uncertainty and Repeatability of Results

In addition to the inherent measurement uncertainties, a number of approximations were applied in the analysis of the results, as detailed in the relevant sections herein. The accuracy of these methods cannot be established in absolute terms, and certainly varied over the wide range of arcing conditions investigated. It is therefore not possible to attach numerical uncertainties to all of the results. However, estimated uncertainties are provided where possible, together with discussion of major approximations in the relevant sections. In the interpretation of the spectroscopic results, we focus on the relationship between precisely determined electrical characteristics and relative changes in arc parameters, (i.e., changes in arc composition and temperature), which can be discriminated with relatively high confidence. This emphasis is intended to reflect the significance of these results over the absolute estimations of arc temperatures and particle number densities, which are subject to additional uncertainty, and only provide representative values along the line-of-sight through the arc.

Furthermore, when interpreting the results it is necessary to consider the statistical nature and high variability of the free-burning arcs investigated, as demonstrated in [6]. For many of the presented results, a selection of measurement data acquired during a single arcing event is used to infer the relationship between electrical measurements and estimated arc parameters for a given set of experimental conditions. This limitation was imposed by the time-consuming nature of the analysis and unfortunately does not allow for statistical variation due to arc fluctuations to be properly sampled. In order to limit the influence of these fluctuations on the results, only measurement instants corresponding to arc voltage minima were used for such comparisons, at which time the arc geometry and parameters should be most directly comparable. A qualitative understanding of the variability that may be introduced by these arc fluctuations can be gained from Fig. 3, as detailed in Section III-A.

III. RESULTS AND DISCUSSION

To seek an understanding of how the ablated Cu & W vapor may influence the free-burning arc characteristics, it was essential to first understand how the metal content of the arc develops in response to the current variation, and how this vapor is distributed across the length of the arc. Our results are thus divided into three sections: in the first, we look in detail at a single arc measurement to study the time-evolution, in the second, we extend these methods to estimate the vapor concentration for different axial positions in the arc, and in the third, we combine these results with the electrical measurements to examine the metal vapor influence on the arc voltage.

A. Time-Evolution of Arc Composition and Temperature

For detailed evaluation of the arc time-evolution, a measurement performed at the axial midpoint of a 45 mm contact gap was selected. Fig. 3 shows current and voltage traces for this arc, with the vertical lines indicating frames that were
Fig. 3. Time-sequence of analyzed spectra from a single free-burning arc measurement in a CO$_2$/O$_2$/C$_5$F$_{10}$O mixture at 100 kPa, with a 45 mm contact gap. All frames are displayed on the same arbitrary intensity scale. Measurement times for the recorded spectra are indicated in the lower plot together with arc current and voltage traces.

Fig. 4. Resulting fit parameters determined from the sequence of spectra in Fig. 3, plotted together with measurements of arc voltage and current.

chosen for spectral analysis from the high-speed recording. These frames provide a representative sample of arc conditions at various current levels during both the current ramping and decay, and also at other electrically interesting times, e.g., during and after the voltage excursion at $t_{11} = 9$ ms. The sequence of images in this figure shows the analyzed fiber from each of these frames. The resulting fit parameters from each spectrum are plotted in Fig. 4. Here the quantities reported include the temperature, the copper partial-pressure $p_{Cu}$, and the relative mixing ratio $N_{Cu}/N_{O}$, representing the most prominent spectral components of the electrode vapor and the switching gas, respectively. Together these estimated parameters provide an indication not only of the arc composition but also the total arc pressure.

Visual inspection of the image sequence in Fig. 3 provides a basic qualitative picture of the time evolution of the arc. The oxygen emission, most visible in the features at 777 and 795 nm, rapidly increases in intensity as the current is ramped, and peaks at $t_3$, which corresponds to the highest $(dI/dt)$. A similar increase is observed during the voltage excursion at
$t_{11} = 9 \text{ ms}$. Increasing emission during the current rise is also evident with the Cu and W emission, both in terms of intensity and the number of lines present, however, the peak emission intensity occurs later, coinciding with the maximum current. During the low current phases at the beginning and end of the pulse, only the two Cu lines at 793 and 809 nm exhibit sufficient intensity for fitting, lending higher uncertainty to the parameters determined during these times.

The spectral fit parameters plotted in Fig. 4 provide more insight into this basic picture. The copper partial-pressure $p_{Cu}$ exhibits a close correlation with the magnitude of the current after a short time delay following the start of the current rise. This delay can be understood as the propagation time for the ablated electrode material to reach the measurement position at the midpoint of the 45 mm contact gap. $p_{Cu}$ ranges from a minimum of 5–40 kPa at peak current. This range is consistent with measurements from [5], who applied similar methods to an ambient air arc 20 mm from the cathode, with an experimental arrangement that separates the anode and cathode jets.

The composition fraction $N_{Cu}/N_{O}$ meanwhile shows a rapid increase in the oxygen fraction and total arc pressure from the start of the current rise just after $t_1$ through $t_2$. Here $p_{Cu}$ remains static, as any current-driven increase to the contact vaporization is not yet observable at the gap midpoint. During this time the emitting region of the arc rapidly expands from less than 10 mm to at least 20 mm in diameter. Adiabatic heating of the gas occupying the expanded arc region to upward of 10 kK likely drives this transient pressure increase.

The composition picture shows a sensitivity to the arc stability: prolonged periods of arc stability correspond to an increase in the relative Cu content of the arc, while the instability growth leading up to the voltage excursion peak at $t_{11} = 9 \text{ ms}$ shows a decreasing trend of $N_{Cu}/N_{O}$. The arc elongation process shifts the arc from its position at the center of the electrode jets and often leads to arc root motion that visibly disrupts the jets themselves. Both effects may contribute to the observed change in composition associated with arc excursions, by allowing a higher fraction of the emission from the arc center to reach the diagnostic, and potentially explaining the elevated arc temperature and pressure observed during this event. The collapse of the voltage following the excursion indicates that the arc has resumed its position near the radial center of the electrode jets. Fits performed just before and after this excursion suggest that the arc quickly recovers its prior state, enabling comparisons of the estimated $p_{Cu}$ for measurements performed under varying stability conditions.

The dependence of the metal vapor content of the arc on the current is shown in Fig. 5. Here a positive correlation between the current and $p_{Cu}$ is evident, but the dependence is relatively weak until a current of 2.4 kA is reached, beyond which it increases significantly. Such a transition may be expected when the diameter of the arc root approaches that of the contact tip, at which point its expansion is limited and the current density increases [2]. Other studies report arc root current densities that range from 50 to 300 A·mm$^{-2}$ [11], [12], [13], [14], depending on the electrode material. A current of 2.4 kA confined to an 8-mm-diameter pin contact represents a current density of $50 \pm 10$ A·mm$^{-2}$, putting the observed transition at the low end of the range observed in the literature, however, we note that the surface area available to the arc root may not match the full pin diameter, due to the tapering and uncertain geometry after erosion, contributing to the reported uncertainty. HSC recordings suggest that the arc root diameter is similar to that of the visible contact surface area during the period around peak current. We, therefore, conclude that the observed increase in ablation above 2.4 kA is caused by an increase in current density that occurs when the arc root cross section approaches this limiting size.

Exceeding this threshold clearly affects the overall contact erosion, which was observed to be substantial in the unblown arc experiment. The contacts exhibited centimeters of erosion after sustained arcing and required frequent replacement. Erosion of Cu/W arcing contacts is a major aging factor affecting the lifetime of gas load break switches. The identification of a $J = 50 \pm 10$ A·mm$^{-2}$ transition threshold for increased ablation may therefore constitute an interesting result that could inform the design criteria of such contacts.

B. Electrode Vapor Distribution

To study the influence of the metal vapor on the arc voltage, arc conditions with varying degrees of metal contamination must be generated. This was done by varying the contact separation distance over a range from 10 to 95 mm, and repeating the spectroscopic measurements at the gap midpoint. For these comparisons, a smaller sample of points were analyzed for each arc, limited to the current range from 2.4 to 3 kA. This limit allowed the influence of the metal vapor to be isolated from the influence of the current variation on the measured arc voltage, and the choice to study currents above 2.4 kA provided high variation in the degree of metal contamination, allowing the measurements to span a wide range of conditions. Within this current range the arc diameter
was nearly static, allowing the line-of-sight length to be held constant during the spectral fitting. For gap distances longer than 45 mm, the arc was highly unstable even at the highest currents. Frames corresponding to local minima in the arc voltage were selected in these cases in order to minimize the influence of arc excursions on the measured parameters.

Fig. 6(a) shows the maximum $p_{\text{Cu}}$ at the gap midpoint determined from the spectral fits for each gap distance. This maximum typically occurred within 1 to 2 ms of the current peak. It is possible to estimate the expansion of the electrode vapor jet from these measurements by modeling the jet as a cone with an axially varying density distribution, similar to the treatment found in [15]. This treatment, with the assumption of a radially uniform vapor pressure distribution inside the cone, yields the following expression for the expansion angle:

$$\tan \theta = \frac{2(\sqrt{\frac{k}{\pi p_{\text{Cu}}}} - r)}{d}$$  (1)

where $k$ is an experimentally determinable constant representing the force exerted by the heavy Cu particles, $d$ is the contact separation distance, and $r$, the initial radius of the electrode jet, is assumed to equal the contact radius for the high currents investigated. Because measurements of $p_{\text{Cu}}$ are performed at the gap midpoint, this expression is insensitive to asymmetries in the electrode ablation between the anode and the cathode, assuming both jets expand at the same $\theta$. The dashed curve in Fig. 6(a) represents the best fit of this functional form for the pressure dependence on the contact separation distance, yielding a value of $k = 6.95 \text{ Pa} \cdot \text{m}^{-2}$ and an expansion angle $\theta = 11^\circ$. A HSC image of an electrode jet is shown in Fig. 6(b) with the $11^\circ$ cone outline indicated. HSC observations of the jets show reasonable agreement for a range of expansion angles from $8^\circ$ to $17^\circ$, overlapping well with the angle determined from the conical expansion model.

The consistency of the conical model and the small expansion angle determined lends support to the assumption of uniform vaporization of the Cu/W contact material. Models have shown that a narrow range of droplet sizes and initial velocities are required for expelled droplets to subsequently evaporate and contribute significant vapor content to the arc [16]. Under these conditions, the droplets are expected to evaporate within several mm of the electrodes, so it is not clear that the spectroscopic measurements could resolve the influence of this mechanism on the axial metal vapor distribution, or that it would affect the interpretation of uniform vaporization.

The conical expansion model was used to provide a measure of the average Cu content over the length of the arc when comparing measurements performed at the midpoint of different gap settings. For each $p_{\text{Cu}}$ measurement point, a value for the constant $k$ in (1) was determined, holding $\theta$ fixed. This provides a unique curve for the instantaneous vapor pressure distribution, which is integrated over the gap distance to determine an average Cu pressure $\bar{p}_{\text{Cu}}$.

C. Metal Vapor Influence on Arc Parameters

In order to compare voltages measured for the different gap settings, it is useful to define an average electric field $\bar{E}_{\text{arc}}$ that is dependent only on the resistivity of the arc itself. The determination of $\bar{E}_{\text{arc}}$ relies on a correction to the voltage measurement that can be demonstrated with Fig. 7. This plot shows the arc voltage as a function of gap distance and was taken from a single arc measurement during the quasi-dc contact separation phase. The well-documented electrode voltage fall $V_{\text{fall}}$ can be observed from the voltage measured at zero contact separation in this plot. For the specific conditions investigated, a value of $V_{\text{fall}} = 18 \pm 0.5 \text{ V}$ was determined from an average over five measurements, in general agreement with published values for Cu/W electrodes [17]. Also evident in this figure is the highly nonlinear voltage response for contact separations below 6 mm. This nonlinearity originates from electric field enhancement due to the electrode geometry, and the presence of an ion sheath layer and ionization zone at the interface between the arc and the electrode surface [12]. When the arc was stable, a linear voltage response was consistently observed during the contact separation, up to the largest investigated gap distance of 95 mm [6]. By performing a linear fit through the voltage measured for contact separations larger than 6 mm, we can estimate the electrode voltage enhancement to be $V_+ = 48 \text{ V}$, with less than 2% variation in this value.

![Fig. 6(a) shows the maximum $p_{\text{Cu}}$ at the gap midpoint determined from the spectral fits for each gap distance. (b) HSC image of an electrode jet, with $\theta = 11^\circ$ cone overlaid for reference.](image-url)
across this measurement series. Yokomizu et al. [18] observed a similar nonuniform field region extending 6 mm from the electrode tips in their configuration, though they found that the voltage enhancement from this region is significantly lower, approximately 30 V. This discrepancy may be attributed to the substantially smaller contacts and lower driving current used in the present configuration, as both of these parameters have been shown to influence the properties of the sheath region [3].

Extending the measurements of Fig. 7 out to the largest gap distances of 95 mm maintains good agreement between the linear fit and measured voltage minima, with significant deviation only during arc excursions. This is an indication that for the times chosen for analysis, which correspond to the voltage minima, the arc length is approximately equal to the electrode gap distance. The average arc electric field \( E_{arc} \) is thus determined using the voltage correction outlined above and this estimated arc length. Fig. 8 shows \( E_{arc} \) plotted against \( \bar{p}_{Cu} \), and represents the main result of the investigation into the relationship between arc voltage and metal vapor content. Only gap distances of 30 mm and greater are included, as the subtracted electrode voltage enhancement makes up too large a fraction of the measured voltage for meaningful comparison at smaller gap distances. This comparison demonstrates a clear trend toward higher arc voltage with increasing metal vapor content, with the linear fit suggesting a 25% increase in \( E_{arc} \) over the range of conditions investigated. Validation for the arc length estimation and voltage correction method is provided by the consistent overlap and continuity of slope observed between measurements performed at the different gap settings shown in this figure. The projected electric field value of 2 V/mm for an uncontaminated arc is within the range reported in [19] for currents near 3 kA.

The demonstration of a positive correlation between \( E_{arc} \) and \( \bar{p}_{Cu} \) in metal-contaminated arcs is an interesting result, as the effect of metal contaminants on free-burning arc voltage has not been conclusively determined, and is subject to potentially competing effects. A number of experiments using ignition wires rather than moving contacts for the arc initiation have been performed in both unblown and blown conditions, and may hint at the influence of the metal vapor on the arc voltage [20], [21], [22]. Although the metal vapor was not studied explicitly, these experiments each exhibit an elevated arc voltage that endures for up to several ms following the wire explosion; too long of a timescale for the effect to be explained by transient arc processes. Huo et al. compared modeling and experimental results from a mobile free-burning arc in a Jacob’s ladder configuration. Their results showed that a reduction in the Cu concentration during the arc elongation coincided with an arc voltage plateau that was observed in both the model and the experiment [23]. Such a plateau could indicate that the expected voltage increase due to the arc elongation was offset by the reduced Cu concentration of the arc, leading to a reduction in \( E_{arc} \). Zhang et al. performed a computational investigation into the influence of metal vapor contamination on arc parameters under blown conditions for currents up to 2.5 kA. They found an increase in the arc voltage of 6% when electrode vaporization was included in their simulation, due to a higher emissivity that suppressed the arc temperature, lowering the electrical conductivity [24].

The effect of metal vapor on arc parameters has been investigated more thoroughly in the context of welding arcs. Here the basic processes and dependencies are well understood, and can also inform the interpretation of the results for free-burning arcs. For temperatures below 15 kK, Cu contamination can increase the electrical conductivity of the arc due to higher ionization, while at higher temperatures the effect is reversed [23], [25]. Estimated arc temperatures are consistently below the 15 kK threshold that would lead to a reduction in the electrical conductivity, as demonstrated by Fig. 4. Although these estimates provide representative values along the line-of-sight, and may not accurately reflect the highest temperatures achieved in the arc, they are in line with temperatures determined for arcs under similar high metal contamination conditions [5], [26]. The arc temperature in the present study is therefore almost certainly too low for the
observed voltage correlation to be caused by a reduction to the electrical conductivity at temperatures above 15 kK.

A number of welding arc studies have demonstrated an increase to radiative emission from arcs with metal vapor contaminants such as Cu, Fe, or Si; this effect limits the temperature and current density achieved at the arc center [25], [26], [27]. For low temperatures and metal vapor concentrations, the aforementioned electrical conductivity increase can lead to a slight reduction in the arc voltage, while at concentrations above 5% mass fraction, this is overridden by the temperature-limiting effect, which drives the conductivity down and the arc voltage up with increasing arc metal content [25], [28]. The present investigation focused on high current density conditions with \( \bar{\rho}_{Cu} \geq 20 \text{kPa} \), putting it firmly in the latter regime of metal-dominated, temperature-suppressed arcs, where a positive correlation between the arc voltage and metal vapor might be expected. The temperature and current density limitation imposed by high metal concentrations may also contribute to the somewhat low arc current density determined in Section III-A.

D. General Discussion

The results of this investigation have particular significance for the comparative study of arcs in SF\(_6\) alternatives, the primary motivation for this work [1]. During this study, similar arc voltages, electrode voltage effects, and contact erosion rates were observed for all of the CO\(_2\)-based mixtures investigated. This suggests that the conclusions drawn about the electrode vaporization and its influence on the arc voltage may be extended when interpreting the results from these gases. For the most metal-dominated conditions investigated, i.e., 100 kPa fill pressure, 20 mm gap distance, and currents above 2.4 kA, \( E_{\text{arc}} \) may be significantly higher due to the metal vapor presence. However, the influence on the total measured voltage will be less than the 25% figure cited, as the electrode voltage enhancement makes up a large fraction of the measured voltage for small gap distances. For longer gap distances, the voltage influence becomes less significant due to the decreased \( \bar{\rho}_{Cu} \), and at higher fill pressures the relative concentration of the Cu with respect to the switching gas is lower, weakening the effect further. For arcs under blown conditions which actively exclude the metal vapor from the arcing region, such as those found in gas circuit-breakers, any metal vapor influence on the arc voltage is expected to be minimal. Still, for free-burning arcs under certain conditions, the metal vapor has been shown to have a clear and measurable influence on the arc voltage, which should be considered in future interpretation of the broader comparative study results. For best comparison of arc characteristics between the various gases in this configuration, focus should be laid on the largest gap distances and highest fill pressures, where differences in the intrinsic arc properties are least likely to be disguised or outweighed by the influence of the metal vapor.

The results may also be of further interest for disconnectors and load break switch applications, where a number of CO\(_2\)-based mixtures, including the C\(_5\)-perfluoroketone mixture investigated, are under consideration to replace SF\(_6\) [29]. The relative characteristics of arcs in these mixtures has been the topic of recent investigations, particularly for gas load break switches [30], [31]. Here, arcs in SF\(_6\) have been studied thoroughly, and demonstrated the ability to interrupt currents even in the absence of a gas flow, due to their intrinsic mobility and cooling [32]. With the newfound understanding of the time evolution of the arc composition and the axial distribution of the metal vapor, consideration could also be paid to how this vapor affects the stability of the arc in the CO\(_2\)-based mixtures. Further investigation of the electric field in the nonlinear region near the contact tips is also of interest, to determine if the parameters \( V_{\text{fall}} \) and \( V_{+} \) are sensitive to changes in current, gas species and fill pressure. Validation of our spectra simulation method by comparison with more rigorous techniques is also planned for subsequent measurements with this diagnostic.

IV. Conclusion

A free-burning arc in a CO\(_2\)-based gas mixture was experimentally investigated and spectroscopically diagnosed. A method for estimating the arc temperature and composition was demonstrated and used to characterize the arc over a broad range of conditions. The metal vapor content of the arc was studied, and the findings suggested uniform vaporization of the Cu & W components of the contact material. Investigation of the arc metal vapor content as function of current level indicated a direct relationship between the current and the Cu content of the arc. A transition threshold of 2.4 kA was identified, beyond which the metal vapor content of the arc exhibited a stronger current dependence. It was concluded that this threshold represents the point at which the arc root current density increases after it fills the available contact surface area, corresponding to a current density of \( J = 50 \text{ A} \cdot \text{mm}^{-2} \). This result may prove relevant to application in the design criteria for arcing contacts in a number of switching applications.

The electrode gap distance was systematically adjusted to produce arcs with varying levels of metal vapor contamination. A simple conical model for the vapor distribution was applied to estimate the electrode jet expansion angle to be \( \theta = 11^\circ \). The arc voltage was then analyzed as a function of the contact separation in order to determine a value for the electrode voltage \( V_{\text{fall}} = 18 \text{ V} \), and for the total voltage enhancement due to the nonlinear region near the electrode surface, \( V_{+} = 48 \text{ V} \). The latter value was used to determine an average electric field due to arc conductivity \( E_{\text{arc}} \). This parameter was shown to increase in proportion to the copper content of the arc, quantified by \( \bar{\rho}_{Cu} \), the average Cu partial pressure determined using the expansion model. The observed trend toward increasing voltage with arc metal vapor content seemingly results from a reduction in the arc temperature and electrical conductivity, due to increased radiative emission from the metal vapor.

Acknowledgment

The authors would like to thank Martin Seeger, Pascal Devaud, Laura Engelbrecht, Henning Janssen, Mahir Muratovic, and Philipp Simka for their valuable contributions to this research.
REFERENCES

[1] C. Franck, J. Engelbrecht, M. Muratovic, P. Pietrzak, and P. Simka, “Comparative test program framework for non-SF6 switching gases,” *BH Electr. Eng.*, vol. 15, pp. 23–30, 2021.

[2] J. Tepper, M. Seeger, T. Votteler, V. Behrens, and T. Honig, “Investigation on erosion of Cu/W contacts in high-voltage circuit breakers,” *IEEE Trans. Compom. Packag. Technol.*, vol. 29, no. 3, pp. 658–665, Sep. 2006.

[3] L. Dabringhausen, D. Nandelstädt, J. Luhmann, and J. Mentel, “Determination of HID electrode falls in a model lamp I: Pyrometric measurements,” *J. Phys. D: Appl. Phys.*, vol. 35, no. 14, pp. 1621–1630, Jul. 2002.

[4] K. Etemadi, G. Y. Zhao, and J. Mostaghimi, “Impact of cathode evaporation on a free-burning arc,” *J. Phys. D: Appl. Phys.*, vol. 22, no. 11, pp. 1692–1696, Nov. 1989.

[5] S. Franke, R. Methling, D. Uhrlandt, R. Bianchetti, R. Gati, and M. Schweinne, “Temperature determination in copper-dominated free-burning arcs,” *J. Phys. D: Appl. Phys.*, vol. 47, no. 1, Jan. 2014, Art. no. 015202.

[6] P. Pietrzak et al. (Jun. 2022). Voltage-Current Characteristic of Free Burning Arcs in SF6 Alternative Gas Mixtures. [Online]. Available: https://www.techrxiv.org/articles/preprint/Voltage-Current_Characteristic_of_Free_Burning_Arcs_in_SF6_Alternative_Gas_Mixtures/20190854

[7] M. Walter and C. Franck, “Flexible pulsed DC-source for investigations of HVDC circuit breaker arc resistance,” in *Proc. 15th Int. Conf. Gas Discharges Their Appl. (GID)*, Greifswald, Germany, 2010, pp. 170–174.

[8] A. Ritter, L. S. J. Bort, and C. M. Franck, “Five years of pulsed current testing for HVDC switchgear,” in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHEV)*, Sep. 2016, pp. 1–4.

[9] X. Tan, “A software package for rigorously calculating optical plasma spectra and automatically retrieving plasma properties,” *J. Adv. At. Spectrometry*, vol. 33, no. 11, pp. 1867–1874, 2018.

[10] A. Kramida, Y. Ralchenko, and J. Reader, “NIST atomic spectra database (version 5.9),” Nat. Inst. Standards Technol., Gaithersburg, MD, USA, Tech. Rep., Nov. 2021. [Online]. Available: https://physics.nist.gov/PhysRefData/ASD/HTML/nisthtml

[11] J. D. Cobine and E. E. Burger, “Analysis of electrode phenomena in the high-current arc,” *J. Appl. Phys.*, vol. 26, no. 7, pp. 895–900, 1955.

[12] X. Zhou, J. Heberlein, and E. Pfender, “Theoretical study of factors influencing arc erosion of cathode,” in *Proc. Annu. Holm Conf. Electr. Contacts*, no. 1, Oct. 1992, pp. 71–78.

[13] X. Zhou and J. Heberlein, “An experimental investigation of factors affecting arc-cathode erosion,” *J. Phys. D: Appl. Phys.*, vol. 31, no. 19, pp. 2577–2590, Oct. 1998.

[14] M. S. Benilov and A. Marotta, “A model of the cathode region of atmospheric pressure arcs,” *J. Phys. D: Appl. Phys.*, vol. 28, no. 9, pp. 1869–1882, Sep. 1995.

[15] Z. Kohacinski, “Plasma contamination with electrode metal vapor jets,” *Plasma Chem. Plasma Process.*, vol. 6, no. 3, pp. 299–310, Sep. 1986.

[16] T. Niesien, A. Kaddani, and S. Zahrani, “Modelling evaporating metal droplets in ablation controlled electric arcs,” *J. Phys. D: Appl. Phys.*, vol. 34, no. 13, pp. 2022–2031, Jul. 2001.

[17] Y. Yokomizu, T. Matsumura, R. Henni, and Y. Kito, “Electrode-fall voltages of SF6 and air arcs between electrodes of Fe, W, Cu-W, Cu and Ti in the current range from 10 A to 20 kA,” *Eur. Trans. Electr. Power*, vol. 8, no. 2, pp. 111–115, Sep. 2007.

[18] Y. Yokomizu, T. Matsumura, R. Henni, and Y. Kito, “Total voltage drops in electrode fall regions of SF6, argon and air arcs in current range from 10 to 20 000 A,” *J. Phys. D: Appl. Phys.*, vol. 29, no. 5, pp. 1260–1267, May 1996.

[19] J. J. Lowke and H. C. Ludwig, “A simple model for high-current arcs stabilized by forced convection,” *J. Phys. D: Appl. Phys.*, vol. 46, no. 8, pp. 3352–3360, Aug. 1975.

[20] T. Schultz, B. Hammerich, L. Bort, and C. M. Franck, “Improving interruption performance of mechanical circuit breakers by controlling pre-current-zero wave shape,” *High Voltage*, vol. 4, no. 2, pp. 122–129, Jun. 2019. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/hve.2018.5103

[21] F. Abid, K. Niayesh, and N. S. Støa-Aanensen, “Ultrahigh-pressure nitrogen arcs burning inside cylindrical tubes,” *IEEE Trans. Plasma Sci.*, vol. 47, no. 1, pp. 754–761, Jan. 2019.

[22] N. T. Basse, C. Kissing, and R. Bini, “Measured 3D turbulent mixing in a small-scale circuit breaker model,” *J. Phys. D: Appl. Phys.*, vol. 44, no. 24, pp. 6381–6391, 2011.

[23] J. Huo et al., “Development of an arc root model for studying the electrode vaporization and its influence on arc dynamics,” *AIP Adv.*, vol. 10, no. 8, Aug. 2020, Art. no. 085324.

[24] J. L. Zhang, J. D. Yan, and M. T. C. Fang, “Electrode vaporization and its effects on thermal arc behavior,” *IEEE Trans. Plasma Sci.*, vol. 32, no. 3, pp. 1352–1361, Jun. 2004.

[25] A. B. Murphy, “The effects of metal vapour in arc welding,” *J. Phys. D: Appl. Phys.*, vol. 43, no. 43, Nov. 2010, Art. no. 434001.

[26] M. Schnick, U. Füssel, M. Hertel, A. Spille-Kohoff, and A. B. Murphy, “Metal vapour causes a central minimum in arc temperature in gas-metal arc welding through increased radiative emission,” *J. Phys. D: Appl. Phys.*, vol. 45, no. 2, Jan. 2012. Art. no. 022001.

[27] J. J. Lowke, M. Tanaka, and A. B. Murphy, “Metal vapour in MIG arcs can cause (1) minima in central arc temperatures and (2) increased arc voltages,” *Welding World*, vol. 54, nos. 9–10, pp. 292–297, 2010.

[28] L. Gu, A. Arntberg, and J. Bakken, “DC arc behaviour in mixtures of argon and metal (Si) vapour from a liquid metal anode,” *J. High Temp. Chem. Process*, vol. 1, pp. 350–357, 1992.

[29] M. Seeger et al., “Recent development of alternative gases to SF6 for switching applications,” Cigre’s ELECTRA, Apr. 2017, pp. 26–29, no. 291.

[30] N. Ranjan, J. Carstensen, and S. Scheel, “ Interruption of weakly cooled arcs in air and airplus,” in *Proc. 22nd Symp. Switching Arcing*, Sep. 2017, pp. 194–197.

[31] M. Bendig and M. Schaak, “Design rules for environmentally friendly medium voltage load break switches,” *IEEE Trans. Power Del.*, vol. 36, no. 5, pp. 2668–2675, Oct. 2021.

[32] T. E. Browne and A. P. Strom, “ Interruption of capacitance charged currents in sulfur hexafluoride [includes discussion],” *Trans. Amer. Inst. Electr. Eng. III, Power App. Syst.*, vol. 75, no. 3, pp. 1357–1362, Jan. 1956.

Joseph T. Engelbrecht received the B.A. degree in physics from the Ithaca College in 2013 and the M.S. degree in applied physics from Cornell University, Ithaca, NY, USA, in 2016. In 2016, he joined the U.S. Naval Research Laboratory, Washington, DC, USA, where his research was focused on pulsed-power-driven plasmas and X-ray sources. Since 2020, he has been with the High Voltage Laboratory, ETH Zürich, Zürich, Switzerland, studying switching arcs in SF6 alternative gases. His current research interests include arc dynamics during current interruption, optical plasma diagnostics, and arc modeling.

Pawel Pietrzak received the M.Sc. degree in electrical engineering from the AGH University of Science and Technology, Krakow, Poland, in 2015. He is currently a Scientific Assistant with the High Voltage Laboratory, ETH Zürich, Zürich, Switzerland, researching SF6 alternatives for switching application.

Christian M. Franck (Senior Member, IEEE) received the Diploma degree in physics from the University of Kiel, Kiel, Germany, in 1999, and the Ph.D. degree in physics from the University of Greifswald, Greifswald, Germany, in 2003. From 2003 to 2009, he was with ABB Swiss Corporate Research Center, Baden, Dättwil, Switzerland, as the Scientist and the Group Leader of gas native gases. His current research interests include main research interests switching arcs.