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ELECTRICAL AND OPTICAL INVESTIGATION OF AN ELECTRIC ARC IN HYDROGEN FOR SHORT GAPS

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Abstract. Hydrogen or mixtures containing hydrogen represent attractive gases for low-voltage switching devices because of increased arc quenching behaviour. However, fundamental electrical properties of arcs in hydrogen are still not well known. In this paper, first results of a study of a DC switching arc in pure hydrogen at 1 bar between graphite electrodes are presented for low currents of 8 and 16 A. The arc voltage and current are measured during contact separation. High-speed images of the arc are processed to determine the arc length considering the high arc dynamics with erratic elongations and jumps of the electrode attachment. The arc voltage dependence on the length results in a typical sheath voltage of approximately 23 V and mean electric fields in the arc column of 18.7 $\mathrm{Vmm^{-1}}$ at 8 A and 10.8 $\mathrm{Vmm^{-1}}$ at 16 A.

Keywords: DC arc, Hydrogen, Low-Voltage Switch.

1. Introduction

The need for efficient and compact switching devices for Direct Current (DC) systems has grown alongside the increasing demand for different electric appliances and to protect local DC power grids. Herewith permits the use of hydrogen (H_2) as arc-quenching gas several advantages which may be used in different fields including battery disconnecting units and charging infrastructure for electric and plug-in hybrid vehicles (EVs). In particular, DC relays and contactors have to manage currents from some Amperes to several hundredths of Amperes. Typically, these relays are housed in sealed chambers, which are filled with various gas mixtures. The use of (H_2) as a gas medium in switches has advantages of being compact, lightweight and having better current interruption capabilities.

Recent studies, such as those conducted by Shiba et al. [1], Chao et al. [2], and Bowen et al. [3], found that using a H_2-N_2 mixture with 80:20 ratio in gas-filled contactors results in higher electric field strength and lower arcing time compared to air or pure N_2. Another experimental investigation conducted by Yoshida et al. [4] compared the duration of arcing between H_2, N_2, and He gases. They observed that the duration of arcing in pure H_2 was considerably shorter compared to the other gases and that the ability to extinguish an arc is improved.These studies also revealed that increasing the gas pressure results in a decrease in the arcing time; this could be further reduced by the application of an external magnetic field, as reported by [5]. As suggested by the above mentioned studies that the arc column loses more heat when H_2 is used as gaseous medium, leading to increase in voltage and field strength, which facilitates the current limiting, required to create an artificial current zero-crossing to extinguish the arc. Nevertheless due to its explosive nature and therefore the use of gas-sealed containment, there are limited amount of information regarding the arc, its behaviour and appearance in correlation to its electric and plasma properties. Using MHD simulation, the arc motion and the arc duration in gases were simulated with a focus primarily on the impact of magnetic fields on the extension and lifespan of the arc. [6, 7]. Nevertheless, there remains a lack of comprehensive knowledge regarding the detailed thermal and electrical properties of these arcs in hydrogen

A thorough examination of switching arc characteristics in gas mixtures potentially enhance our understanding of the fundamental mechanisms of DC arcs in such switching devices. The varying length of an electric arc due to its dynamic nature is a significant factor that impacts the characteristics of voltage and current. Some research studies [8, 9] attempted to define the characteristics of DC arcs in H_2, but they do not thoroughly examined the impact of arc length on voltage. In [10], we described the relation between arc length and arc voltage for a switching arc between metal contacts in air and estimated the electric field based on the measured voltage-length data. It was found that different field strengths occur for very short and longer arcs.

In this paper, we extended this work to a fundamental study of arcs in H_2 between graphite electrodes. This paper aims to present initial experimental findings outlining the characterization of the arc in H_2 gas at currents of 8 A and 16 A along with optical investigations using a high-speed camera to examine the arc evolution and its dynamics. Typically, the real length of an electric arc is longer than the gap distance between the contacts. Therefore, we used image processing tools to determine the actual arc length with high-speed images. These results are further used to calculate the electric field strength.

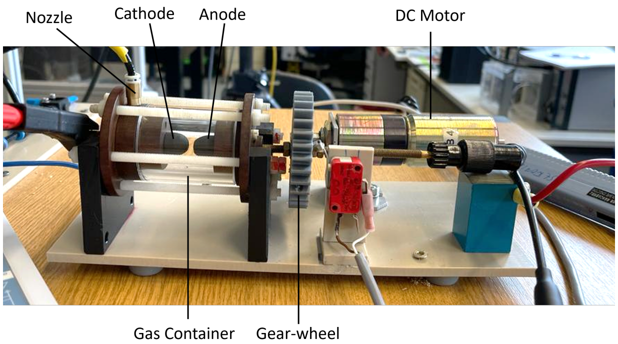

Figure 1. Experimental setup with switching contacts inside a gas chamber operated with a DC motor.

Parameter	Conditions
Gas	H_2
Contacts materials	Graphite
Current	8 A and 16 A
Avg. contact velocity	$0.008\,\mathrm{ms}^{-1}$
Gap distance	0 – 2.8 mm
Camera resolution	640 x 480
Frame rate	500 fps
Acquisition time	1 µs

Table 1. Experimental conditions.

2. Experimental Setup

The switching experiment was performed to investigate the behaviour of an electric arc in a gas medium using a compact experimental setup. The setup consisted of a stationary cathode and a movable anode that are placed in a sealed gas container in a horizontal position. The container is filled with pure hydrogen gas using mass flow controller from MKS Instrument which maintained the pressure at 1 bar. The movable contact is connected to a rotating bolt with a gearwheel driven by a DC motor. Both contacts are made up of graphite material and had a pointed-nose shape with 4 mm width at the connection point. The experimental setup is illustrated in Figure 1.

The signal generator supplied an 800 ms DC pulse as input to a power amplifier which can deliver a maximum voltage and current of 400V and 28A respectively. Depending on the value of the DC pulse, the amplifier supplied a respective constant current across the switching contacts. After the constant current is settled, the DC motor is triggered to initiate a contact separation and an arc is produced between them. The voltage across the contact is measured using a digital oscilloscope (Yokogawa DLM2054) and a differential probe (PBDH0150) and the current waveform is measured with a 100MHz current probe Yokogawa (PCB100). The high-speed camera (Monochrome Y4 from Integrated Design Tools) is used to capture high-speed images at a frame rate of 500 fps and an exposure time of 1 μs . A series of arc images were thus stored for further calculation of the arc length. The complete experimental conditions are given in 1.

3. Image Processing

The high-speed camera is used to capture images of the switching arc which are stored for subsequent analysis of the arc dynamics and computation of arc length. For this purpose, on each 8-bit images, various image processing steps are applied in MATLAB software as previously described in [10]. These image are then transformed into binary images using predefined threshold values to facilitate further processing steps. Figure 2 shows original arc image (a), modified binarized image (b) and final smoothed image (c) which is used to calculate arc length. The appropriate range of threshold values specifically for the calculation of arc length is determined depending on the arc current, which typically changes the overall arc radiation intensity. By performing iterative testing of various threshold values, it was ensured that the binarized images do not result in incorrect arc length estimations due to overexposure or underexposure of the original image.

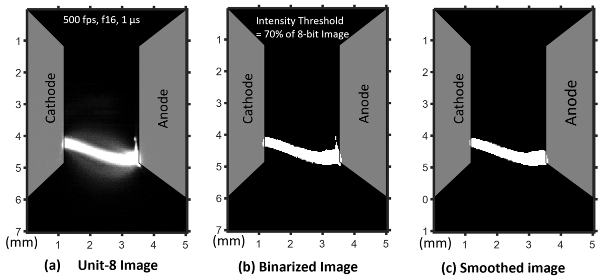

Figure 2. Image Processing a) Original 8 bit image, (b) converted binary image (c) post processed image

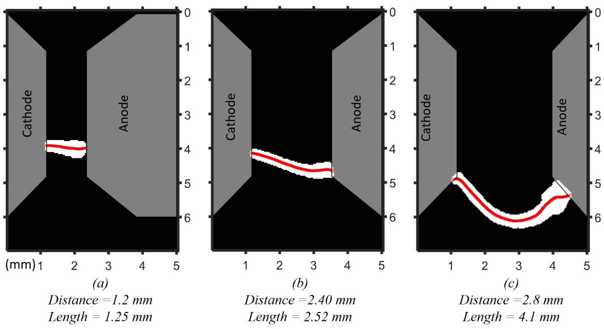

Figure 3. Arc length calculation at different gap distances a) at 1.2 mm, b) at 2.4 mm and (c) at 2.8 mm.

The typical range of threshold values for 8 A and 16 A current of H_2 arc is between 60 and 80% of the maximum intensity values for the 8 bit images. The elimination of smaller spots outside the arc region and the filling of any gaps within the arc radiation area are performed to refine the binarized image. Furthermore, the edges of the arc radiation intensities are smoothed by implementing morphological operation of opening on arc images. Figure 3 shows the midpoint estimation and arc length calculation for three different arc positions. The process of calculating the arc length involves finding the middle point of each vertical column of pixels in the arc image and joining these points to obtain the overall length of the arc. To improve the accuracy of the calculation, a regression analysis is applied with a 3-pixel window which involves fitting a line to the midpoints of the arc image. In each experiment, a total of 350 images are captured at a frame rate of 500 fps. The arc length values obtained from these images are then synchronized with the voltage data that is measured across the contact with an oscilloscope.

4. Results and Discussion

The plasma characteristics of switching arc in H_2 gas are evaluated at DC constant currents of 8 A and 16 A. In Figure 4a, a typical example of the arc voltage measurements at 8 A current is presented for 600 ms.

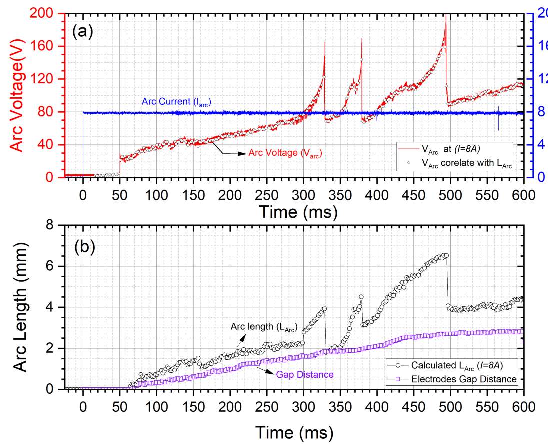

Figure 4. Voltage waveform at 8 A during contact switching process (b) Measured arc length for 8A

As the average speed of switching is 0.008 ms^{-1}, the contacts required 350 ms to open completely up to a maximum of 2.8 mm distance and afterwards stay constant for the rest of the time. The current starts flowing through the contacts at 0 ms and remains constant at a value of 8 A for 700 ms before it is turned off. Once the current is settled, the switching of contacts is triggered at 50 ms. When the contacts separate, an initial voltage drop of approximately 23 V is observed. This initial voltage is significantly higher when compared to the initial voltage of arc between metal contacts under ambient condition, as previously shown in [10]. Figure 4b shows the corresponding arc length measurement for 8 A along with contact distance. The voltage increases with the motion of contacts from the start for 250 ms, along with an increase of the arc length up to about 2 mm and the voltage to about 80 V. Following this, there is a noticeable increase in voltage from approximately 80 V to 160 V within only 30 ms, with simultaneous elongation of the arc length to approximately 4 mm. At 330 ms the arc attachment at the contacts abruptly changes their position in this example, causing the arc length to jump back to about 2 mm, and the voltage to drop back down to 80 V. This process of elongation and shortening of the arc is repeated three times in this example, with the maximum length of the arc extending up to 6.5 mm at 495 ms and the voltage rising to a maximum of approximately 200 V at this time. As previously stated, the power amplifier has a maximum output voltage of 400 V. This ensures that there will be no interruption even at a peak arc voltage of 200 V.

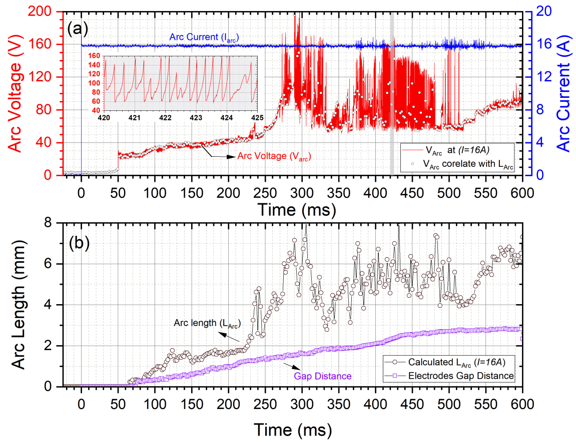

Figure 5. Voltage waveform at 16 A during contact switching process, (b) measured arc length for 16A

In Figure 5a and Figure 5b, the arc voltage waveforms and arc length measurements are shown for an example at the current of 16 A respectively. Similar to the 8 A case, the initial voltage observed is also approximately 23 V. Additionally, the arc voltage and arc length increase linearly over the first 200 ms and up to about 2 mm. However, after 200 ms the arc elongates and shortens much faster with higher frequency than in the 8 A case. As a result, the voltage also changes at a much faster rate, which is clearly visible in Figure 5a. The zoomed-in graph in Figure 5a shows that the voltage increases from 60 V to approximately 160 V in just 0.3 ms, and this behaviour is repeated 3 to 4 times within one millisecond.This phenomenon can be attributed to the fact that the arc attachment with the contacts changes rapidly its position after expansion, which leads to higher fluctuations in the arc length.

Because of the limited frame rate of the camera, the arc length could be determined only for selected time instants, and the fast change of the arc length could not be monitored. However, thanks to the small acquisition time of 1 µs, each arc length value could be related to the corresponding measured voltage value. Several experiments have been performed for both current values showing each a similar general behaviour of the arc, however with an individual erratic arc elongation. Figure 6 shows the voltage over length plot acquired after synchronising the arc length with the corresponding voltage measurements for both 8 A and 16 A. For each of the current values, the voltage and length data from three typical experiments are included.

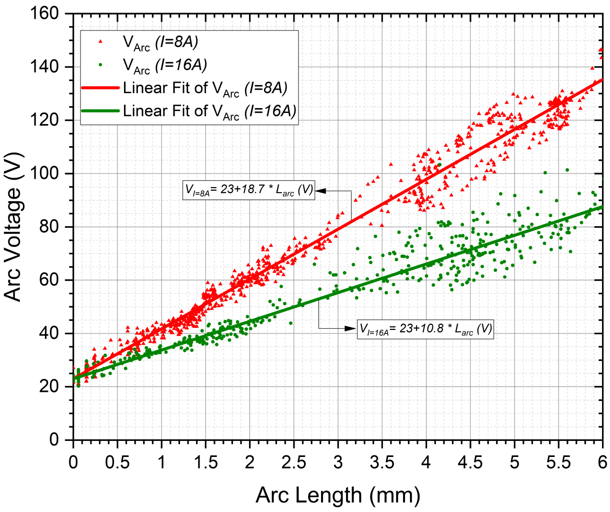

Figure 6. Voltage over the arc length plot for 8 A and 16 A for each three experiments along with the linear regression analysis

As is evident from the figure, at the same arc length, the arc voltage at 8 A is higher than 16 A, and the voltage difference increases with the length. The voltage increases almost linearly with the arc length for both current values, and the spread of data can be attributed to inaccuracies in the arc lenght determination during fast elongation of the arc in three dimensions, which could not be covered by the optical analysis with one camera. Hence we applied linear regression on both data. The y-intercept is fixed at 23 V which was observed as a sheath voltage in Figure 4 and Figure 5. From the linear regresion analysis, a mean electric field of 18.7 $\mathrm{Vmm^{-1}}$ is obtained for 8 A current, which is almost double of the electric field of at the current of 16 A i.e 10.7 $\mathrm{Vmm^{-1}}$. The results are given in Table 2 together with the standard errors (SE) and goodness of model (R^2).

Current	Slope	SE	R2
8 A	18.7 $\mathrm{Vmm^{-1}}$	0.3%	0.99
16 A	10.8 $\mathrm{Vmm^{-1}}$	0.7%	0.98

Table 2. Electric field values for 8A and 16A current.

5. Conclusions

Arcs between movable graphite electrodes in pure hydrogen at 1 bar have been studied at low currents, and the arc length has been determined from processing of high-speed images during and after contact separation. DC currents of 8 A and 16 A have been considered in first experiments. The voltage at 16 A arc current shows stronger fluctuations with a much higher frequency in contrast to the arc at 8 A. The voltage fluctuations correlate sufficiently with the captured arc length. The arc voltage over length graphs show for both currents an almost linear dependence. A sheath voltage of about 23 V have been extracted from the voltage jump during first contact separation. Mean electric fields in the arc column of 18.7 V/mm for 8 A and of 10.8 V/mm for 16 A have been deduced from a linear regression analysis.
An extension of the study to a larger current range and other molecular gases is planned as next steps.

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