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CHARACTERIZATION OF THE SWITCHING ARC IN HYDROGEN UNDER DIFFERENT PRESSURE CONDITIONS

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Abstract. The characteristics of filling gas and its resulting arcing behavior is a major factor influencing the current-limiting and switching performance of gas-filled direct current (DC) switches. The use of hydrogen (H_2) or mixtures containing H_2 as dielectric gas has shown increased breaking performance in compact DC switches. However, arcs in such gases, especially in pure H_2 show a complex fluctuating dynamics, especially at higher filling pressures and by simultaneous use of magnetic blown-off. This paper conducts an electrical and optical study of the rapid and unstable arc behavior in H_2 at pressures of 1 and 6 bar using a model switch with arc runners. The results remark the significant impact of filling pressure on the arc voltage and the coupled current limiting performance. Moreover, the arc dynamics become more unstable and faster, and the arc shape becomes strongly distorted. Compared to atmospheric pressure, the rate of increase in arc voltage and arc length are noticeably higher.

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

1. Introduction

With the continuous advancement of the markets for renewable energy, industrial automation, and electric and hybrid vehicles, the demand for direct current (DC) switches is increasing [1]. DC switches are required to provide enhanced switching performance in a smaller device size with reliable arc extinction for DC loads at higher voltage and current magnitudes. The interruption of the current is more challenging in DC than in alternating current (AC), as there is no natural zero crossing, requiring the arc to be extinguished by forcibly reducing the current to zero. In this context, gas-filled DC switches have greater potential for improved arc extinction characteristics. Notably, hydrogen and its mixtures have excellent arc-quenching properties because of their unique physical and thermal properties.

Previous studies have demonstrated that the arc extinction time in DC switches is significantly shorter in H_2 compared to other gases such as air, nitrogen, or helium [2]. Similar results of a much shorter arcing time were demonstrated in H_2-N_2 mixture for low voltage [3]. The performance of the interruption of the DC switches improved with a higher hydrogen content [4]. High-speed imaging and spectroscopic analysis revealed a decrease in arc extinction time with increased pressure and magnetic field [5]. The interaction of the magnetic field in such gases led to elongations and distortions of the arc [6]. In a prototype DC switch with a double-breakpoint bridge, typical arc fluctuations in H_2 were observed under different media conditions. The peak arc voltage can be significantly higher, sometimes reaching two or three times the system voltage, which may result in a very unstable arc with a higher probability of re-strikes [7]. Another study with high-speed imaging [8],[9] revealed erratic arc dynamics in H_2 characterized by frequent elongations and fluctuations in voltage pulses between 2 A and 16 A, where rapid pulses correlate with a fast increase in arc length. For other applications, the dynamics of arc in H_2 are relevant, as [10] showed that increasing the current increases the arc radius effect, the arc dynamics, and fluctuation. The study [11] discussed the instability deformation of the arc in H_2 at higher pressures up to 20 bar in a Kvaerner-type torch.

Existing studies have proven the extinguishing capabilities of the arc in H_2. However, research on arcs in H_2 at increased pressure is still limited. The pressure increase caused higher arc voltages and reduced arcing time, but also leads to more unstable dynamics, distorted arc shape, and unfavorable arc motion [12]. Therefore, further investigations are necessary to understand the behavior of arcs at higher pressures in H_2.

In this study, the behavior of arcs in pure H_2 gas is analyzed using a model switch at pressures of 1 bar and 6 bar. The influence of pressure on voltage-current characteristics and arc dynamics is presented. Erratic fluctuations typically observed in H_2 are thoroughly examined, including comparisons of the rate of voltage increase and the frequency of fluctuations. High-speed imaging is utilized to assess and compare the dynamics and effects of varying pressure levels.

2. Experimental Setup

The model setup was designed to conduct experiments under hydrogen at higher pressures. The experimental setup consisted of a model switch, a discharge chamber, a power supply system, a gas control system, and measurement devices. The inner dimensions of the discharge chamber were 250 x 180 x 180 mm^3. The middle section of the chamber was composed of a transparent acrylic glass (PMMA) wall that allowed optical arc observation. Fig. 1 shows the discharge chamber from outside (a), the configuration of the model switch placed inside the chamber (b), and a diagram of the test circuit (c). Inside the discharge chamber, the model switch was installed. The switching contacts made of pure copper, each with a radius of 5 mm, were in an initially closed position. These contacts were fixed securely to copper arc runners. The design of the arc runner was such that one rail aligned vertically, while the opposite rail was inclined at a 20-degree angle, providing an upward increase in distance between them. Both rails measured approximately 70 mm in length and 4.5 mm in width.

A rectangular DC pulse was produced by series-connected LC elements forming a 10-stage ladder network. The capacitors were initially charged up to a voltage of 1000 V to produce a maximum current amplitude of 150 A. The switching contacts were connected to the output of that current generator, which delivered a pulse of 25 ms duration. The rise and fall times for the pulse were 3 ms and 5 ms, respectively. An electromagnetic relay was placed inside the chamber, which, upon receiving the input signal, opened the switching contacts. A control signal was sent from the control room via fiber optic cable to the microprocessor used as the controller. This signal first triggered the generator and the gas valve, setting the gas inside the chamber to a specified pressure. Once the chamber maintained the set pressure, the controller triggered the current, and 3 ms after the current, the electromagnetic relay was activated to open the contact. Due to spatial constraints within the chamber regarding relay size, the maximum achievable opening speed was 0.23 m/s.

The gas used was pure H_2, at two filling pressures of 1 bar and 6 bar. A permanent magnet generated a magnetic field of 5 mT at the contact switching point, which was necessary to reduce the arc residence time at the contact rivets, minimizing contact erosion, and to support the arc commutation towards the rails as quickly as possible within the pulse time.

The current and voltage waveforms were recorded with a 500 MHz oscilloscope (Yokogawa DLM2054) at a sampling rate of 2.5 megasamples per second. The current was measured using a current transformer (Pearson 1423) built into the generator, with BNC cables connected directly to the oscilloscope. For the voltage measurement, a passive 20 kV probe with 75 MHz bandwidth was used (Tektronix P6015A). To capture arc images, a 12-bit grayscale high-speed camera was employed (Photron NOVA S9), using mirrors to analyze the arc from two orthogonal sides. Results from three repetitions for each pressure setting were presented. The complete experimental conditions are given in Table 1.

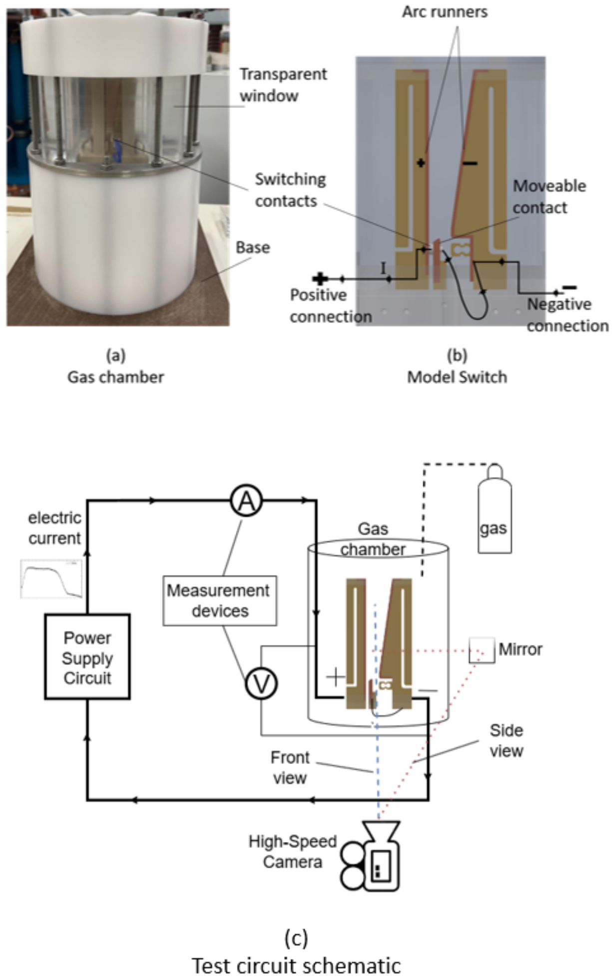


Figure 1. Overview of the experimental setup, (a) the discharge chamber and (b) the model switch with key components. The left side of the arc runner and contact acts as anode, and the right side as cathode, (c) Test circuit diagram.

Parameter	**Conditions**
Gas	H_2
Pressure	1 bar and 6 bar
Contacts materials	Cu
Current	max. 150 A
Avg. contact velocity	0.023 ms^{-1}
Gap distance contacts	0 – 3 mm
Gap distance rails	4 – 20 mm
Frame rate	12 500 fps
Acquisition time	0.2 µs

Table 1. Summary of experimental conditions

3. Results and Discussion

In Fig. 2, typical examples of the arc current and arc voltage are presented for 1 bar (a) and 6 bar (b). As Fig. 2 shows, the effect of the pressure is evident in shortening the arc current duration. At 6 bar, the arc current is driven to zero before the expected pulse length of 25 ms. While for 1 bar H_2, the charging voltage of the generator is able to supply the full pulse duration. In Fig. 3 (a-b), the vertical displacement of the arc roots on the arc runners is presented for the same examples. Fig. 3a shows the position at the cathode, and Fig. 3b shows the position at the anode at both pressures.

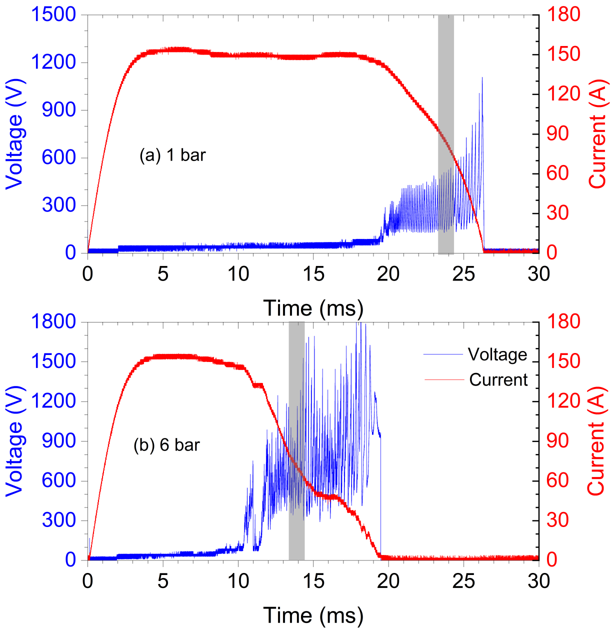


Figure 2. Typical current-voltage characteristics over time at (a) 1 bar and (b) 6 bar pressure during contact separation. Highlighted parts are shown in Fig. 4

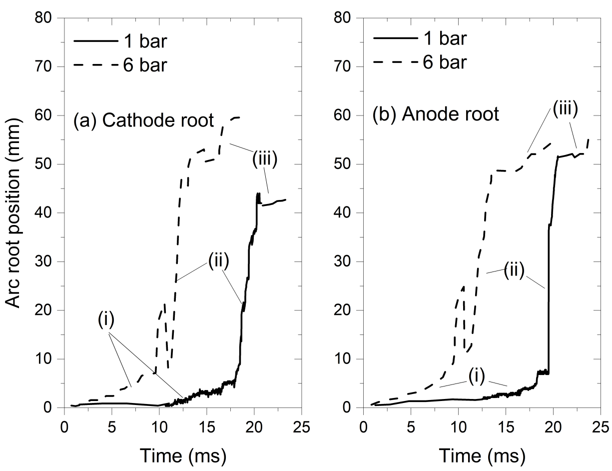


Figure 3. Examples for the typical movements of arc roots on the arc runner (a) position at the cathode (b) position at the anode, for 1 bar and 6 bar pressure.

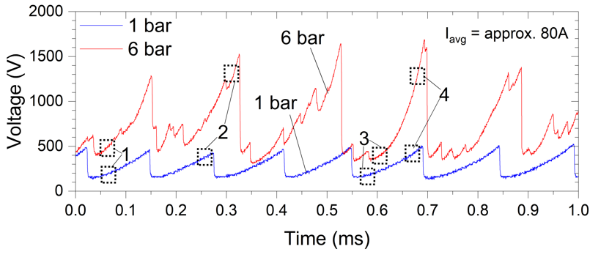
From both figures, the progression of the arc in a typical experiment can be divided into three parts:

(i) First, at the instant of contact separation, i.e. t=2 ms, the arc was ignited following the current reaching the preset value of nearly 150 A. After the ignition, the voltage jumped from some volts (closed contact) to rather low values in the range of some tens of volts. Later, the arc remained between the switching contacts for several milliseconds. Fig. 3 confirms the very short arc length in this region. The arc accelerated and moved towards the arc runners, marking the next phase. This occurred more rapidly at 6 bar, taking approximately 8 ms compared to 17 ms at 1 bar. Several repetitions of the experiments have shown a similar trend; i.e., the transition time at 6 bar was approximately half compared to that at 1 bar pressure. Nonetheless, the exact time varied across repetitions. Since the arc length was relatively small between contacts, the effect of the magnetic field was expected to be less relevant.

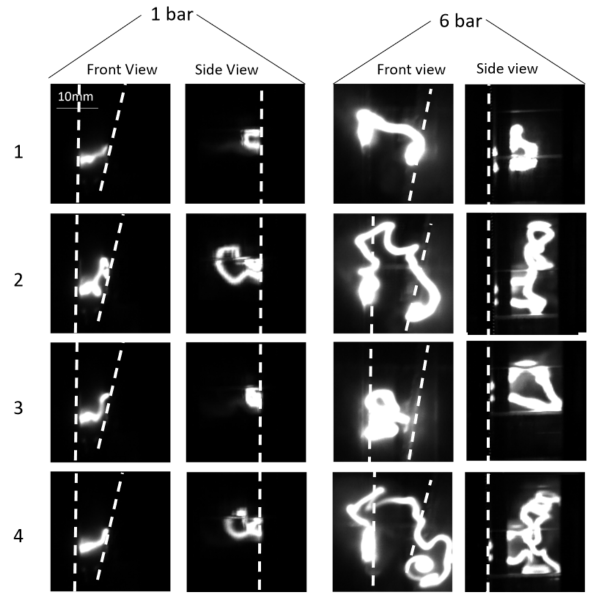
(ii) In the second phase, the arc moved from the switching contacts to the arc runner. It traveled along the arc runners with a stronger bend due to the magnetic field. Since the distance between the two arc runners increases vertically, the minimum available gap for the arc also increases. The minimum voltage of the fluctuations depended on the position of the arc root. During this phase, the arc movement was faster at 6 bar compared to 1 bar pressure, and generally, the arc root was therefore able to cover a longer distance. In addition, the arc root behavior showed faster and more discrete jumps in this region. Clear indications for the impact of the moving arc roots on the arc voltage have not been found as the roots are at a fixed position most of the time.

(iii) In the third phase, the arc roots were stabilized at a fixed position or moved very slowly. While maintaining the arc root position, the arc voltage increases to a certain level due to arc elongations in both the internal and external magnetic field. The slower voltage increase is followed by a sudden decrease due to a short circuiting of the elongated arc and the jump to a short current path as shown in Fig.4a. In this region, the current cannot maintain a constant value but rather decreases as the average voltage increases. Our primary focus was to determine the characteristics of these voltage fluctuations. From the stationary position of arc roots or their minimal movement in this region, the influence of their movements on arc voltage is expected to be small.

Fig.4 illustrates voltage fluctuations at intervals 1 ms for both 1 bar and 6 bar pressures, occurring approximately for a current average of 80 A. Fig.4 also includes high-speed images of an arc. The front and side views are orthogonal views of the arc at the same time instant, captured using a mirror. There, images No. 1 and No. 3 show the arc at relatively lower voltages, while images No. 2 and No. 4 show the arc at higher voltages for both pressures. At 6 bar, the voltage peaks are three times higher than at 1 bar, reaching 1500 V compared to peaks of 500 V



(a)
Zoomed in view of voltage fluctuations



(b)
Front and side view arc images at times mentioned in part (a)

Figure 4. (a) Fluctuations of arc voltages at I_{avg} = 80 A for 1 and 6 bar. (b) Front and Side-view arc images at both pressures; the arc shifts left at 1 bar and right at 6 bar. Dotted lines are electrode positions

at 1 bar. The base voltage of the peak primarily depends on the vertical position of the arc root at the time of the fluctuations, which was slightly higher for 6 bar. In particular, at 1 bar, the fluctuations exhibit a smoother increase, whereas, at 6 bar, they present abrupt spikes even within each fluctuation. Comparison of the figures at 1 bar and 6 bar suggests a compact, smooth, and stable arc at 1 bar, in contrast to the highly volatile, turbulent, and complex arc formation observed at 6 bar. High-speed imaging also suggested that voltage changes are related to variations in arc length. However, even without directly considering the length of the arc in this study, the results illustrate that increased pressure not only influenced electrical characteristics but also the commutation and dynamics of the arc. A detailed analysis of the reasons for the higher arc dynamics at higher pressure would require measurements of the physical plasma properties, which is planned for future work. One reason for the stronger arc elongation can be higher breakdown strength at higher pressure, which hinders the establishment of new current paths to short-circuiting an elongated arc.

Fig. 5 presents the average current-voltage characteristics between 50 A and 150 A. These were obtained through three repetitions of experiments for both pressures, each with a maximum current pulse of 150 A, similar to examples shown in Fig. 2. The data was processed by grouping current values into bins of 10 A, and calculating the averaged voltages for each bin. These averaged voltages of each bin are then plotted as a function of the averaged current as shown in Fig. 5. Apart from some statistical distribution, it is quite obvious that higher voltages, due to the elongation of the arc column, reduce the current. This is a result of the properties of hydrogen combined with the higher pressure and the interaction of magnetic fields, which lead to an overall strong reduction of the plasma conductivity. Therefore, at 6 bar, the average voltage is more than twice that observed at 1 bar pressure.

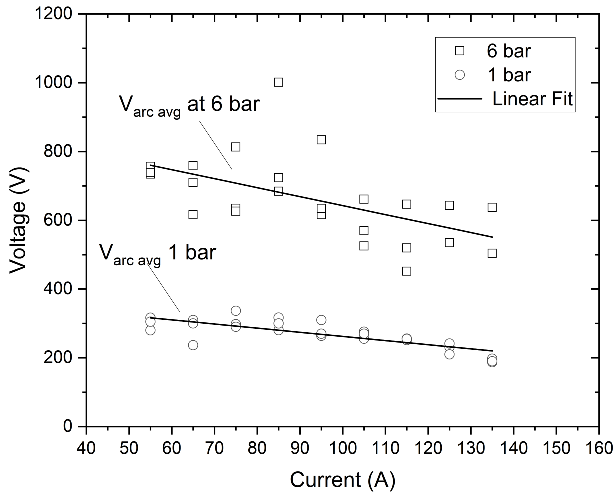
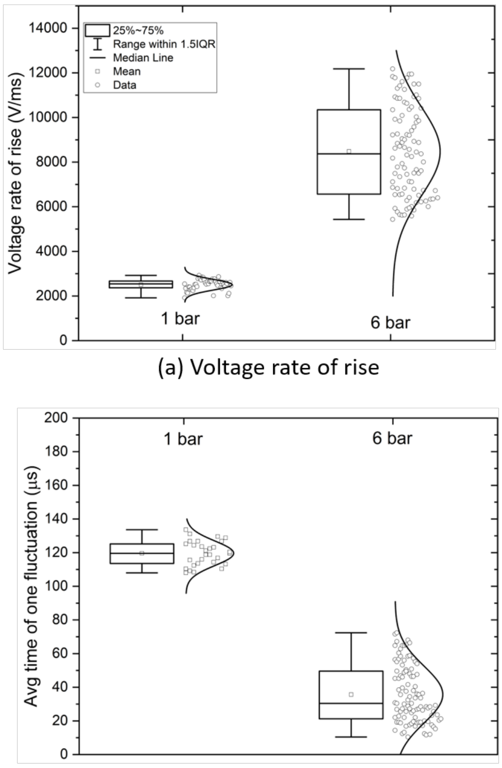


Figure 5. Averaged voltage as a function of current at 1 bar and 6 bar.

Fig. 6 shows the analytical analysis of the voltage fluctuations at two 1 bar and 6 bar. Fig. 6a shows the voltage rate of rise from the minimum value to the peak value of an individual fluctuation. The results were acquired from the three repetitions under similar conditions. They were obtained from only the third phase of the switching process (see Fig. 1) as mentioned earlier. It clearly shows that the voltage increases much faster at 6 bar pressure, nearly 3–4 times faster compared to 1 bar. However, the spread of results is much wider at the higher pressure, indicating that the shape at the individual fluctuation might be different.

In Fig. 6b the duration of the voltage fluctuations are given. The durations are much longer for 1 bar and cover a lower range of times, whereas the fluctuation durations for 6 bar change considerably. Comparing the figures, we conclude that the typical fluctuation at 6 bar increases with an average rate of 9000 V/ms and has an average duration of 40 μs, whereas the 1 bar



(a) Voltage rate of rise

(b) Avg. fluctuation time

Figure 6. Analytical analysis of arc voltage fluctuations from three repetitions for each pressure in H_2 (a) Voltage rate of rise and, (b) time of individual voltage fluctuation.

fluctuation curve increases with around 2200 V/ms has an average duration of 120μs.

4. Conclusions

The study compared arc behavior in hydrogen at 1 bar and 6 bar using a model switch. At higher pressure, the arc exhibited considerably higher voltage and stronger and irregular fluctuations, in contrast to the smoother fluctuations observed at 1 bar pressure. The arc roots commutation occurred more quickly from contact to the arc runner at 6 bar, although in both cases, the current amplitude and applied external magnetic field were kept constant. Also, the rate of the voltage increase was significantly faster at 6 bar, averaging about 9000 V/ms compared to 2200 V/ms at 1 bar pressure. As a next step, an extension of the study plans to include a wider range of currents and pressures, as well as the consideration of actual arc length. Additionally, spectroscopic analysis of the arc is planned to reveal the differences in the plasma properties at different pressures. The latter are expected to be the main reason for the different arc dynamics and voltages.

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