# Self-blast Current Interruption and Adaption to Medium Voltage Load Current Switching

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***Abstract*— Ablation-assisted current interruption is a candidate for improving interruption capability in medium voltage switchgear. In high voltage switchgear, ablation is utilized to achieve high pressures in self-blast circuit breakers. Self-blast switch technology adapted to medium voltage could represent an attractive alternative to $SF_6$ technology in load current interruption. However, the arc energies involved would be much lower than in fault current interruption, where self-blast technology is traditionally employed, and to achieve sufficient pressure buildup, this must be compensated for. Higher pressure could be achieved by reducing the radius or increasing the length of the nozzle throat, reducing the heating volume size, changing or increasing the amount of ablative material, or restricting the outward gas flow. Interruption experiments in air have been performed on four different model switch designs that are meant to highlight the possibilities and challenges of adapting self-blast technology to medium voltage load current interruption. The results show that typical load currents can be interrupted at 24 kV, but below a certain critical current, in the present case 200 A, interruptions fail. Self-blast technology could prove useful in medium voltage load current interruption in the future, provided a method for interrupting the lowest currents can be found.**

***Index Terms*—Ablation, Auto-expansion, Current Interruption, Load-break Switch, Medium Voltage, Self-blast, Switchgear**

## I. Introduction

THE existing market for medium and high voltage gas-filled switching devices is dominated by $SF_6$ technology, which enables compact, reliable and low-cost switchgear. However, the expected abolishment of $SF_6$, wherever possible, due to its high global warming potential, drives a search for alternative technologies. One possibility is revisiting and improving the technologies that dominated the market before the entry of $SF_6$. Ablation-assisted current interruption, also called wall gassing and hard-gas, is one such technology and could prove useful, particularly in the medium voltage (MV) range.

By studying the past products and published research, it is clear that the presence of certain ablation materials can improve current interruption [1], [2], but a comprehensive understanding of the processes leading to a successful interruption in these MV switches does not exist. On the other hand, extensive research has been carried out for low [2], [3] and high voltage circuit breakers [4], [5], and much of this can be relevant for MV switch designs. However, the studies in [6]-[8] show that geometries that work well at lower voltage ratings, for example, polymer ablation without a well-defined arc-cooling gas flow, cannot necessarily be scaled up to handle higher voltage ratings. The study in [9] emphasizes the contact gap conductance in the post-arc period and the importance of sustained gas flow and thus cooling after the arc is quenched. This becomes increasingly important at higher voltage ratings.

A well-defined arc-cooling gas flow is one of the main features of high voltage gas circuit breaker designs [10]. For interruption of low currents, the gas flow is typically supplied from a compression volume [4], [11]. For interruption of higher currents, a self-blast concept (also called auto-expansion) is employed, where the energy dissipated in the electric arc is utilized to build up very high pressures in a heating volume. When the current approaches its zero crossing, a powerful gas blast from the heating volume interrupts the current. The energies involved in an MV load current interruption are much lower, and the literature about quenching of low current MV arcs is much scarcer, making it an open question whether the designs can be simply scaled down to match the requirements, or whether new challenges and opportunities arise. Because MV load-break switches are rather inexpensive mass products, they must have significant design simplifications compared to the costly high voltage circuit breakers. The cost effectiveness is also the reason why vacuum technology, which dominates in the MV circuit breaker market, is not necessarily the preferred choice for load-break switches. $SF_6$ MV load-break switches can typically have inexpensive knife contacts or simplified puffer designs. Rated currents are up to 1250 A at rated voltages in the range 1-52 kV, with rate of rise of recovery voltage of a few tens of volts per microsecond. More details regarding type testing requirements are given in [12].

In this paper, the possible adaption of self-blast technology to air MV load-break switch design is investigated. The next section lays out the main features of a self-blast switch and discusses the possible adaption to MV load current interruption. This constitutes the basis for the experimental setup described in the following section, focusing on the pressure buildup in the high current phase, the blowing pressure at current zero (CZ), and the effect of blowing pressure and geometry on interruption capability. In the last sections, the results are presented and

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discussed.

## II. Self-Blast Switch Design and Adaption to MV Load-Current Interruption

### A. Heating Volume

The heating volume is a closed volume that stores energy dissipated in the electric arc during the high current phase in the form of compressed gas, which can create gas flow that extinguishes the arc at its CZ. The heating volume is connected to the arcing chamber so that hot gases from the arc can flow to the heating volume. The pressure in the heating volume rises because of the added gas, but more importantly, the energy transferred by this hot gas causes the gas in the heating volume to expand thermally. The resulting pressure is responsible for the gas flow. The gas temperature is important for the dielectric recovery of the contact gap. According to [4], the choice of heating volume size for a high voltage circuit breaker is mainly dependent on the rated short-circuit current, maximum allowable temperature, and the mechanical integrity of the design. A typical heating volume is 1-2.5 liters with the relevant energies of 50-200 kJ. In MV load current interruption, the energy is only a small fraction of that, so the volume must be much smaller to obtain sufficient pressure buildup. However, the volume must be large enough to sustain the required gas flow up to and after the time of CZ.

The mixing of hot and cold gas in the heating volume is important. The most decisive parameter for ideal mixing is the ratio of the radial and axial dimensions of the annular volume, and the best mixing is achieved when this ratio is one [4]. This is probably the case at lower currents and voltages as well.

### B. Blow Pressure

The CZ blow pressure is dependent on the pressure buildup in the heating volume during the high-current phase and the pressure decrease in the period from peak pressure to CZ.

In a steady-state ablation-dominated arc, as illustrated in Fig. 1, the flow is maintained by the ablated mass from the inner wall of the nozzle and intensified by the heat dissipated in the arc. If the current is low, the flow velocity will be subsonic. The pressure profile in the axial direction of the nozzle is then continuous and increasing from the ambient pressure to the maximum pressure at the stagnation point, that is, where the gas velocity is zero, typically inside the tube or in the heating volume. If the current is increased, the heat and ablated mass added to the arc increase, and to conform to the conservation of mass and energy, the flow velocity out of the nozzle increases.

At some point, the flow becomes sonic and the flow is choked. This occurs at a critical pressure ratio between stagnation pressure, $p_0$, and sonic pressure for a choked flow, $p^*$, which varies with gas composition and temperature and is typically $p_0/p^* \approx 2$. If the current is increased further, the velocity cannot increase above sonic speed. Therefore, the pressure at the exit and through the whole nozzle will increase to the level necessary to obtain conservation of mass and energy. Thus, both stagnation pressure and sonic pressure are increased. Downstream from the nozzle throat, flow can, depending on nozzle geometry, be either subsonic, supersonic, or a combination of the two, including the formation of shock waves [13].

This choked flow regime is central in high voltage circuit breaker designs because it creates the desired high pressures of several megapascals in the heating volume. The process of pressure buildup and flow reversal in a uniform cylinder such as in Fig. 1, with a heating volume in one end and exhaust in the other, has previously been described through four modes A-D [10]. They are aimed to explain the operation of a high voltage self-blast circuit breaker but are equally relevant for describing the processes in a self-blast switch at more modest ratings. In mode A, the flow is symmetric and sonic in both directions. At some point, as the pressure in the heating volume, $p_1$, rises, the flow toward the heating volume becomes subsonic, and the flow becomes asymmetric; the stagnation point moves toward the heating volume. This is mode B. When the heating volume pressure reaches the stagnation pressure, typically because the current has reached its maximum and is declining, there is no flow in or out of the heating volume. This transition mode is mode C. Mode D sets in as the current is further reduced and gas flow is reversed, flowing from the heating volume through the tube alongside the arc, cooling it as it approaches CZ.

Somewhat simplified, the process can be described by two variables: the pressure in the heating volume, $p_1$, and the tube length multiplied by the current density squared, $l \cdot (I/\pi R^2)^2$, where $l$ is the distance from the stagnation point to the nozzle throat exit, $I$ is the current and $R$ is the tube radius. The ambient pressure, at the opposite end of the tube, is assumed constant. The stagnation pressure in modes A-C can then be described as $p_0 = K_p \cdot l(I/\pi R^2)^2$, where $K_p$ is a material dependent constant, and the flow at the tube opening is assumed sonic [10].

The MV load-break switch deals with small currents, compared to the circuit breaker and as a result, the stagnation pressure is lower. This can be partly compensated for by reducing the tube radius, $R$, or increasing its length, $l$. On the other hand, because the interruption requirements are less demanding, it may not be necessary to reach the same stagnation and blow pressures to achieve satisfactory performance.

Another way to increase the stagnation pressure is to change the material, and thereby the constant $K_p$. However, changing the material also changes the gas composition and can affect the

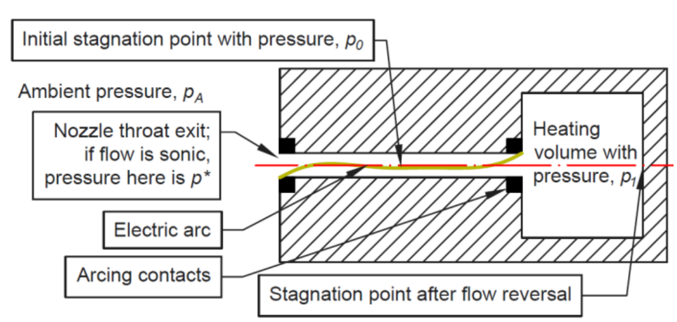


Fig. 1 An arcing chamber connected to a heating volume (schematical). The drawing is axisymmetric along the horizontal center axis and the electrodes are ring contacts.

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post-arc conductance and dielectric recovery of the interruption medium [9]. The nozzle erosion is also a factor to consider in a practical switch design. These two factors make polytetrafluoroethylene (PTFE) a natural choice of material, as it is also the dominating nozzle material for high voltage circuit breakers.

### *C. Nozzle and Contact Geometries*

In high voltage circuit breakers, the flows around the instance of current interruption are typically sonic or supersonic, and the nozzle shape and exhaust area are designed to take advantage of this in the interruption and post-arc phases. For example, turbulence in the layer between arc and gas flow is an important cooling mechanism in high-velocity $SF_6$ [11] but has proven much less important in other gasses [14]. It is also shown that the formation of shock waves affects the dielectric breakdown strength [15]. However, these factors are probably less important in the less demanding MV load current interruption, where the flow is not necessarily sonic or supersonic around current interruption.

## III. Experimental Setup

### *A. Model Switch*

The experiments are designed to resemble real load current switching duties, but to improve reproducibility, the arc is ignited with a copper explosion wire with a diameter of 80 μm. In a practical switch, there would be moving contacts and, ideally, the current should be interrupted as soon as possible after contact separation, that is, at the first CZ crossing. The self-blast switch requires some time and energy dissipation to be able to interrupt the current. It is, therefore, desirable to have a geometry that allows for the pressure in the heating volume to build up as soon as possible after contact separation.

Fig. 2 presents a model switch that is meant to address the main aspects of self-blast current interruption. It is based on the discussion in Section II and designed for studying pressure buildup and interruption performance. Four variations of this switch are used. In switch 1—shown in Fig. 2—the heating volume is annularly shaped with a volume of 10 cm$^3$ placed 31 mm from the ring contact. The heating volume is connected to the arcing volume by four 2-mm diameter channels. The heating volume in switch 2 is identical but is placed 6 mm from the ring contact, causing the pressure in the heating volume to start building up just after contact separation. The maximum pressure is expected to be lower than in switch 1 because the heating volume is closer to the exhaust. In switches 3 and 4, the heating volumes of 1 and 2, respectively, are replaced by a single 3-mm diameter channel from the arcing volume to the pressure sensor. Thus, switches 3 and 4 are virtually without a heating volume. An overview is given in Table 1.

TABLE 1
OVERVIEW OF THE FOUR TESTED SWITCH DESIGNS

| Switch | Heating volume | Distance, d | Description |
|---|---|---|---|
| 1 | 10 cm$^3$ | 31 mm | Annular heating volume with four channels to the arc zone at distance d from the nozzle throat exit |
| 2 | 10 cm$^3$ | 6 mm | |
| 3 | ~0.25 cm$^3$ | 31 mm | A single channel connects the pressure sensor to the arc zone. |
| 4 | ~0.25 cm$^3$ | 6 mm | |

Contact distance is 35 mm and nozzle inner diameter is 6 mm

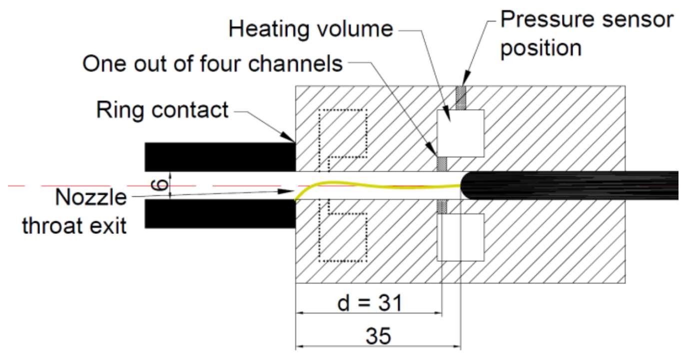


Fig. 2 Sketch of model switch 1, showing the volumes and pressure sensor position. The switch is axisymmetric around the center axis. The connecting channels (grey) are not axisymmetric. Details are given in Table 1. The heating volume position of switch 2 is indicated by dotted lines. Dimensions are in millimeters.

In a cylindrical nozzle design, the choice of inner nozzle diameter is limited by the diameter of the pin contact, which, in turn, should have a minimum diameter to limit contact erosion. Consequently, the nozzle diameter is set as a trade-off between required pressure buildup and contact erosion. A 6-mm nozzle diameter is used in the current setup.

Where not stated otherwise, every nozzle has been used only once to rule out the effect of nozzle wear. The contacts are made of copper-tungsten and nozzles of white PTFE.

### *B. Electrical Circuit*

According to IEC 62271-103 [12], a MV load-break switch must pass two mainly active load current test duties with identical supply circuits, at 100% and 5% of the rated current. The load shall consist of parallel reactors and resistors, as shown in Fig. 3a, which results in a less severe transient recovery voltage (TRV) than serially connected circuit elements.

In the present study, the low current range is of interest. Because of practical limitations, the alternative circuit shown in Fig. 3b—with the load elements in series—was employed, where the initial TRV is controlled by the total power factor and the damping circuit. By simulating the current and voltage in a circuit according to the standard and adjusting the impedance values of the alternative circuit, the initial phase of the interruption up to a certain point could be imitated, as shown in Fig. 4. After that point, the alternative circuit creates a higher voltage than the circuit derived from the standard.

The circuit is supplied from the 11.4 kV utility grid through an 11.4/24 kV laboratory transformer. Thus, all tests are performed at 24 kV and 50 Hz. The experiments are conducted in atmospheric air.

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The voltage across the contact gap was measured with a parallel resistive-capacitive voltage divider with the bandwidth of 4 MHz, and the main current was measured with a coaxial resistive shunt. Accurate current measurement around CZ was provided by a post-arc current sensor based on [16]. Model “DMP 320” pressure transducer from “BD sensors” with a range 0-16 bar and accuracy of 0.1 % was used for measuring the heating chamber pressure. The sampling rate of the data acquisition system was 4 MS/s.

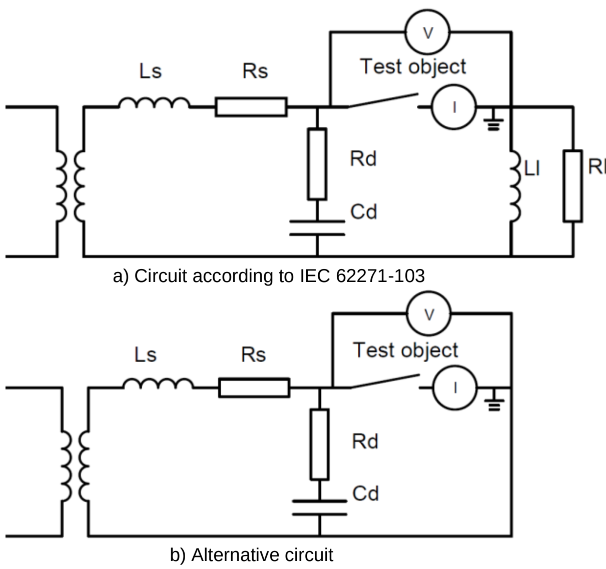


Fig. 3 Circuit diagrams according to the standard (a) and the alternative circuit (b) that, after adjusting the impedances, produce the same current and voltage up to a certain point. Voltage and current measurement sensors are indicated. Supply elements are denoted with *s*, load elements with *l*, and damping elements with *d*.

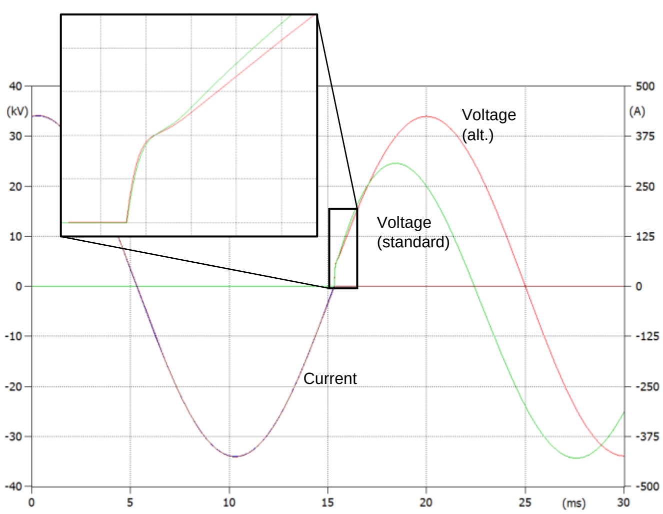


Fig. 4 Simulation results showing the current and voltage waveforms derived from the standard IEC 62271-103 (green) and with the alternative test circuit (red). The transient recovery voltage (TRV) is nearly identical up to 22 kV. After that, the TRV of the alternative circuit continues up to the peak of the source voltage, giving a more onerous duty.

## IV. Results and Discussion

### A. *Pressure development in switch 1-4*

The energies involved in load current interruption are much lower than in fault current interruption, so a main motivation for the present work is to investigate how the pressure builds up in a heating volume at these relatively low currents. An example of obtained current and voltage waveforms and the resulting pressure is given in Fig. 5. The first pressure peak is a result of the ignition wire explosion and is not of interest here. The different flow modes, as described in Section II.B, are indicated in the figure. Mode A and mode B cannot be separated as there is no way to find out when the flow into the heating volume goes from sonic to subsonic regime based on the available measurements.

Switch designs 1 and 2 were tested at nine different currents from 50 to 450 A, and switches 3 and 4 were tested at 200 A and 400 A. Also, reproducibility of the tests and the effect of nozzle wear were tested by performing nine consecutive tests on one sample of switch 1 and four tests on one sample for switch 2, all at 240 A.

The pressure development in the different switches at 200 A and 400 A is shown in Fig. 6. The pressure peak occurs 3-5 ms before CZ. After that, the pressure drops as the current is

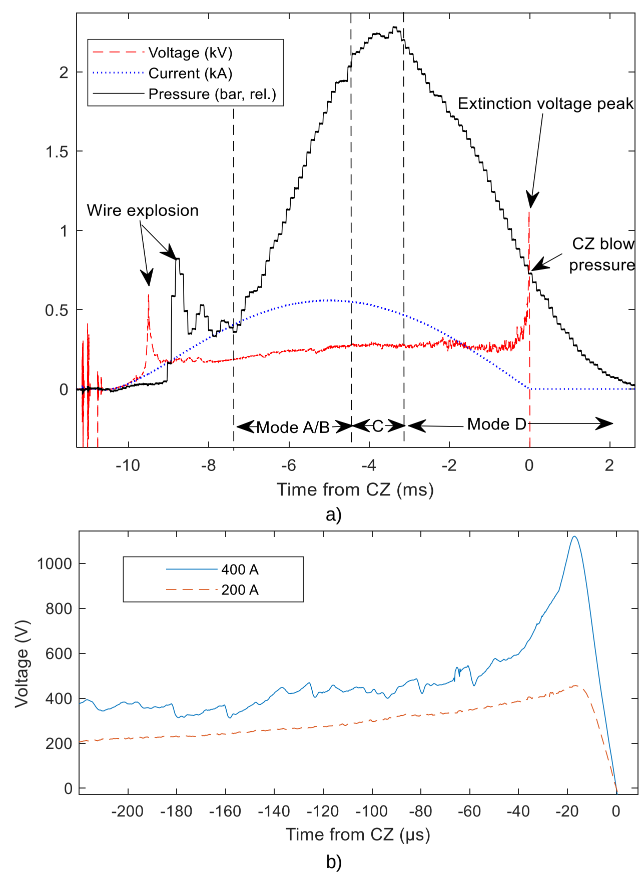


Fig. 5 a) Results from experiments with the heating volume at 31 mm from the nozzle throat exit (switch 1). The different flow modes, as described in Section II.B, are indicated. b) High resolution view of the extinction voltage peak at 400 A and 200 A.

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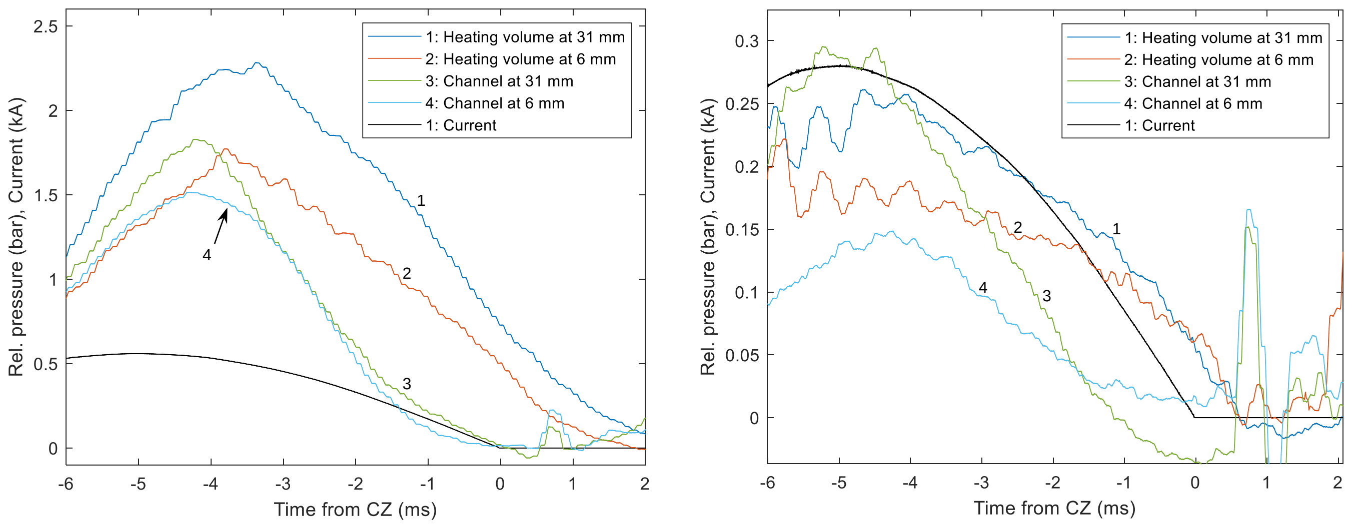


Fig. 6 Pressure evolution in the experiments at 400 A to the left and 200 A to the right. The black line shows the current waveform for the test with switch 1. Colored lines show the pressure in the heating volume in the four different switches. The pressure rise after CZ in switches 2-4 is due to re-ignitions. A possible explanation for the negative relative pressure values (under-pressure around CZ) is the contraction of the arc core as the current and temperature decrease.

approaching the zero crossing and the gas starts flowing from the heating volume through the tube and out the exhaust. A successful current interruption depends on the gas flow around and after CZ, driven by the blow pressure at CZ, which, in turn, is a result of the peak pressure and the pressure drop up to the time of CZ. The role of the heating volume is clearly illustrated by the results from the switches 3 and 4 without heating volumes. Here, the pressure peak is comparable to those with a heating chamber, but the pressure drops much faster and reaches ambient pressure, or lower, at CZ, thus not providing any gas flow.

The peak pressure is, as expected, higher when the channel is placed 31 mm away from the outlet. At 200 A, the peak pressure in switch 3 is 0.3 bar, and in switch 4, it is only half of that. However, at higher currents, the relative difference decreases; at 400 A, the peak pressures are 1.8 and 1.5 bar, respectively. This could be explained by a transition into a choked flow, in which there is a pressure drop at the nozzle throat exit, which becomes increasingly dominant compared to the pressure gradient inside the nozzle as current is increased.

### B. *Interruption performance in switch 1 and 2*

The main purpose of this study is to investigate the interruption performance of switch 1 and 2 at different current levels, as presented in Fig. 7. Filled symbols in the figure indicate successful interruptions at the related CZ blow pressure. Interestingly, switch 2 (shown in red and circles), with heating chamber at 6 mm, fails at all currents, whereas switch 1 (shown in blue and triangles), with the heating volume at 31 mm, interrupts successfully at all currents from 200 A and above, even though the CZ blow pressures are almost identical in switch 1 and 2.

This highlights the differences between geometries where, in switch 1, the gas flow interacts with the arc over a stretch of 31mm; in switch 2, the interaction is limited to only 6 mm. Assuming that only the section of the contact gap with gas flow is cooled and the rest of the contact gap is still conductive, the

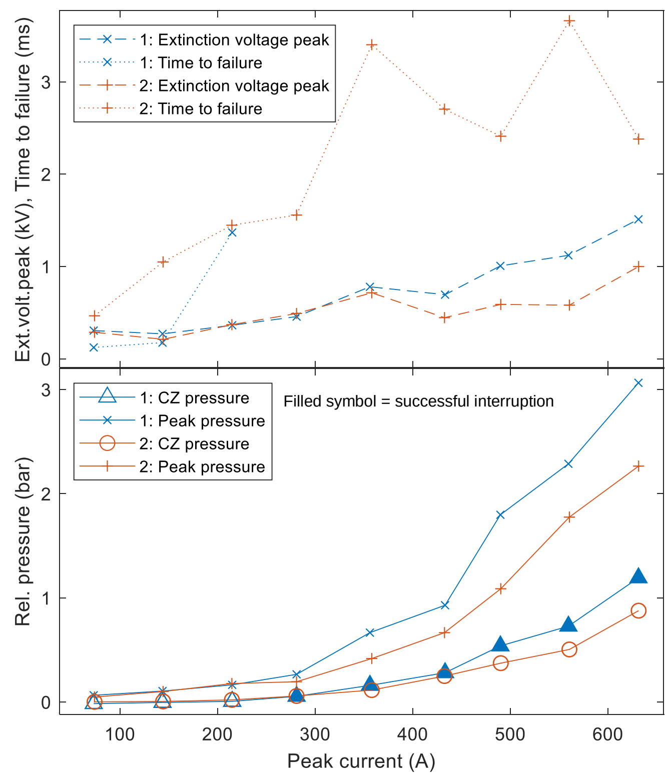


Fig. 7 Results for switch 1 and 2 at currents from 50 to 450 A. Only the first CZ is considered. CZ pressure and peak pressure are shown in the lower figure. Successful interruptions are indicated by filled symbols at the related CZ pressure. Extinction voltage peak and time from CZ to failure are shown in the upper figure.

average electric field at the first voltage peak after a successful interruption in switch 1 is 1.1 kV/mm. In switch 2, the failure occurs at 3.0 kV/mm at 200 A and 5.3 kV/mm at 400 A. Considering the time to fail and reignition voltage—several milliseconds from CZ to failure and reignition voltage of up to 32 kV—it is clear that the initial (thermal) phase of the interruption process is successful in both geometries, but the high TRV peak leads to failures in switch 2. Similarity in the

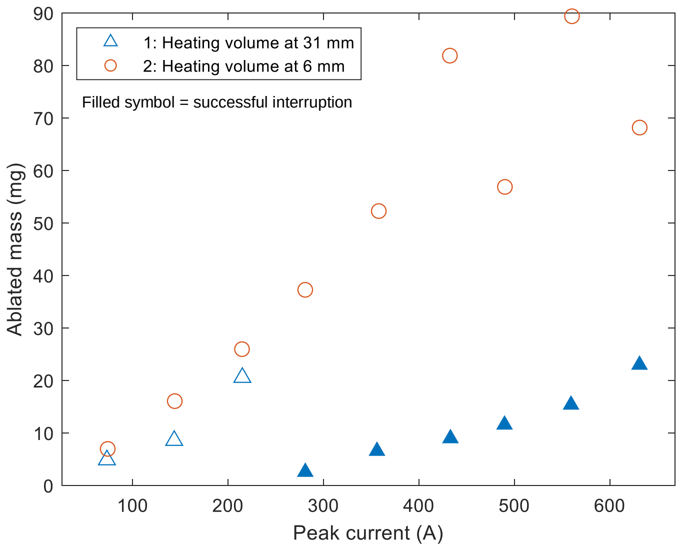


Fig. 8 Ablated mass from the nozzle at different current amplitudes. The ablation is significantly lower in the case of successful interruptions (filled symbols) with arcing time of about 10 ms. In failed interruptions (open symbols), the total arcing time is up to 50 ms, but varying because of varying reignition voltage.

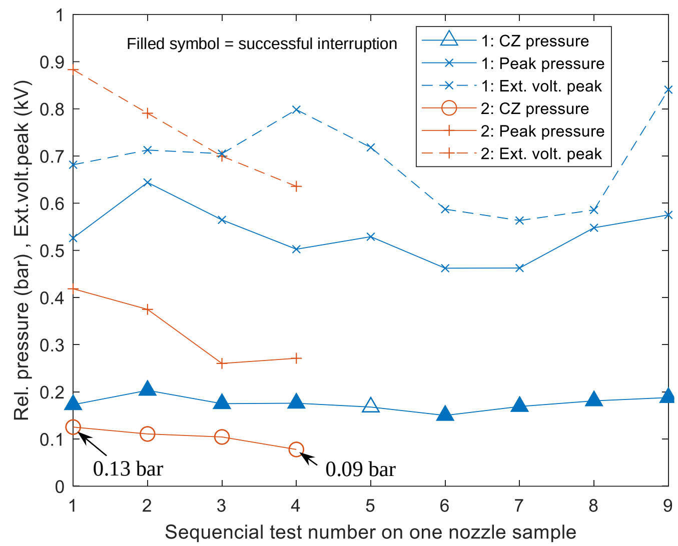


Fig. 9 Consecutive tests on one nozzle sample at a current of 240 A rms, showing the evolution in CZ blow pressure, peak pressure and extinction voltage peak in switch 1 and 2. Filled symbols indicate successful interruptions. The fifth test on switch 1 (in blue) resulted in a reignition after the first CZ, and successful interruption on the second CZ.

initial phase of the interruption can also be seen in the extinction voltage peak, especially for the lower currents and pressures. This indicates that the initial interruption occurs where the gas from the heating volume first interacts with the arc, as this feature is identical in both switches.

To continue the interruption process and to withstand the applied TRV stresses, the gas flow must interact with a larger section of the arc; this is the main difference between the two switches.

### C. *Ablation rate and nozzle degradation*

The total mass ablated from the nozzle is of interest for lifetime evaluation and is presented in Fig. 8. It is much higher in the case of failed interruptions than otherwise because the arcing time is up to 50 ms before it is cleared by the laboratory circuit breaker. However, this is not relevant, as a real switch would not be permitted an arcing time of more than some 15 ms. The ablated mass varies quite a lot also for successful interruptions, from 2.6 mg at 200 A to 23 mg at 450 A. The average ablation rate is 16.5 mg/kJ for switch 1 and 24.9 mg/kJ for switch 2. For reference, 17 mg/kJ is the rate given for gray PTFE in [17].

The effect of nozzle erosion is shown in Fig. 9, where consecutive tests are performed on a single nozzle sample of switches 1 and 2 at 240 A. The tests on switch 2, with only failed interruptions, show a steady decrease in peak pressure, CZ blow pressure, and extinction voltage peak through the test series. The tests on switch 1, however, show a remarkably steady performance throughout the test series. The total arc energy per test (not shown in figures) with switch 2 is about 2 kJ, and with switch 1 it is typically about 0.4 kJ, except in the fifth test. Here, the first CZ resulted in a reignition and the current was interrupted in the second CZ. The total arc energy was 0.66 kJ.

### D. *Implications for switch development*

The fixed contact setup presented here has served to investigate the pressure development in the heating volume and the corresponding interruption performance without the reproducibility problems that arise from using a moving contact, such as uncontrolled variation in friction, time of separation, contact speed, and gas leakage between pin contact and nozzle. However, a practical switch design must incorporate moving contacts and, ideally, in such a way that the heating volume pressure starts to build up as soon as possible after arc ignition, much like in switch 2. However, there is the dilemma that in order to attain good interruption performance, the gas flow path around CZ should include as much as possible of the contact gap length. That favors switch 1. In a practical switch design, these two features must be combined, and at the same time, measures must be taken to ensure sufficient pressure buildup also at low currents.

Such measures could be restricting the outlet area, increasing the mass ablation rate, or changing the material, all of which are likely to also have disadvantages. Restriction of the outlet area was the method applied in the present setup, simply by letting the pin block the nozzle in one direction. Further pressure buildup could be achieved by also restricting the flow in the other direction, but then the gas flow around CZ would also be restricted, leading to a poorer interruption performance.

The second method, increasing ablation rate, could be achieved by exposing more ablative material to the arc. This method possibly requires more moving parts, which could add too much complexity for the relevant product range. The last measure, changing the material, would be an easy way to increase the pressure. However, that changes the gas composition, and could lead to problems in the post-arc recovery process [9]. This illustrates that designing an MV self-blast switch is not an easy task, with the wide range of concerns that must be taken into account.

Moreover, several practical issues have not been treated in depth here. The nozzle erosion could become a problem over time because the nozzle geometry slowly changes and loses its intended function. The short circuit making requirements for this class of switches is another critical issue, and one of the reasons why the pin should have a large diameter. Six millimeters, like the one in this study, may not be sufficient.

## V. Conclusion

- The model self-blast switch 1 in this study demonstrates the capability to interrupt typical load current duties up to 24 kV voltage rating. The model switch is not able to interrupt currents below a certain critical current; the lowest interruptible current is 200 A.
- A main dilemma is that the outlet area needs to be limited to get sufficient pressure buildup, whereas certain flow path cross-sectional area is necessary to establish the flow required for good interruption performance.
- When adding moving contacts, it is desirable to place the heating chamber so that the pressure can start to build up as soon as possible after arc ignition, like in switch 2. However, for interruption performance, the gas flow path should include as much as possible of the contact gap length, which favors switch 1.
- The nozzle erosion is a concern in ablation-assisted switching, but consecutive tests on one nozzle have shown that the performance of an appropriately designed switch does not degrade significantly after several successful interruptions.
- For a practical switch design, these factors must be taken into account, and a solution for the interruption of low and very low currents must be introduced.

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