doi:10.14311/ppt.2019.1.23
Plasma Physics and Technology **6**(1):23–26, 2019

NOZZLE WEAR AND PRESSURE RISE IN HEATING VOLUME OF SELF-BLAST TYPE ULTRA-HIGH PRESSURE NITROGEN ARC

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Abstract. This paper reports on experiments with ultra-high pressure nitrogen arcs in a self-blast type switch design. The effect of filling pressure on nozzle mass loss and pressure-rise in the heating volume is investigated. An arc current peak of 130 A at 190 Hz, and a fixed inter-electrode gap of 50 mm are used. The arc burns inside a polytetrafluoroethylene nozzle with a gas outflow vent in the middle. Three different nitrogen filling pressures were tested: 1, 20 and 40 bar, which also covers the supercritical region. To study the effect of vent size on blow pressure near current zero, three different vent dimensions were investigated. The energy deposited in the arc increases with the filling pressure. It is observed that the pressure-rise in the heating volume is linked to the filling pressure, while the vent size plays a crucial role in the blow pressure near current zero. The nozzle mass loss per unit energy deposited in the arc is found to be independent of the filling pressure.

Keywords: ultrahigh pressure arc, nozzle wear, supercritical fluid, arc discharge.

1. Introduction

The interruption chamber of a medium voltage (MV) gas circuit breaker is generally filled at atmospheric pressure or at a slightly elevated pressure of a few bar. Due to safety reasons, these MV gas circuit breakers are almost never filled with extremely high pressure. For gas circuit breakers, the interruption performance is believed to be related to filling pressure due to the increase of gas flow rate near current zero (CZ) [1]. Switchgears placed at the seabed for subsea power transfer applications have the potential to be filled with extremely high filling pressure. By filling the interrupting chambers of such switchgears at the surrounding pressure, the complexity and cost of the encapsulation can be substantially reduced.

When the pressure and temperature of a gas exceed a critical point, the gas enters into the supercritical (SC) region. High density, high heat conductivity, high diffusivity, absence of vapour bubbles and self-healing properties are some of the unique features of an SC fluid. For gas circuit breakers, the properties of SC fluids are believed to be in favour of improved current interruption performance [2]. For nitrogen (N_2), the critical point is 126 K and 33.5 bar. Nitrogen is chosen in this work due to its environmentally benign nature, good insulation strength and low critical pressure.

There are few publications on gas discharges in ultra-high pressure medium in general, among which almost none of them cover high energy arc discharges typical for power switching applications [2, 3]. Recently, some efforts have been made to investigate arc discharges in SC N_2 at tens of bars filling pressure. The arc voltage is reported to increase with filling pressure, without any abrupt change during the transition from gas to SC state [4]. A higher arc voltage results in an increased energy deposition in the arc channel. Moreover, the arc radius decreases as the filling pressure increases [5].

To investigate the effect of gas flow for very high pressure arc discharges, a self-blast arrangement is adopted in this paper. A self-blast switch design is studied in a fixed electrode arrangement where the arc burns inside a polytetrafluoroethylene (PTFE) nozzle with a gas outflow vent in the middle. During the high current phase, the PTFE nozzle will ablate. Some of the ablated mass escapes through the vent and the rest causes a pressure rise in the heating volume. The compressed gas in the heating volume creates a backflow of relatively cold gas near CZ to cool the arc for current interruption. To study the effect of vent size on blow pressure near CZ, three different vent dimensions are investigated. Experiments are conducted at three different N_2 filling pressures: 1 bar (atmospheric pressure), 20 bar and 40 bar (supercritical region). In this paper, the effect of filling pressure on mass loss of the PTFE nozzle and consecutive pressure rise in the heating volume is reported.

2. Experimental setup

The electrical setup is shown in Figure 1(a). The test circuit consists of the charging and discharging sections of a 7.2 µF high voltage (HV) capacitor bank, C. The capacitor bank is charged through a diode-resistance unit (R_C–D_C) from a HV source. Once the capacitor bank is charged to a predefined voltage, it is disconnected from the grid by switch S_C. Afterwards,

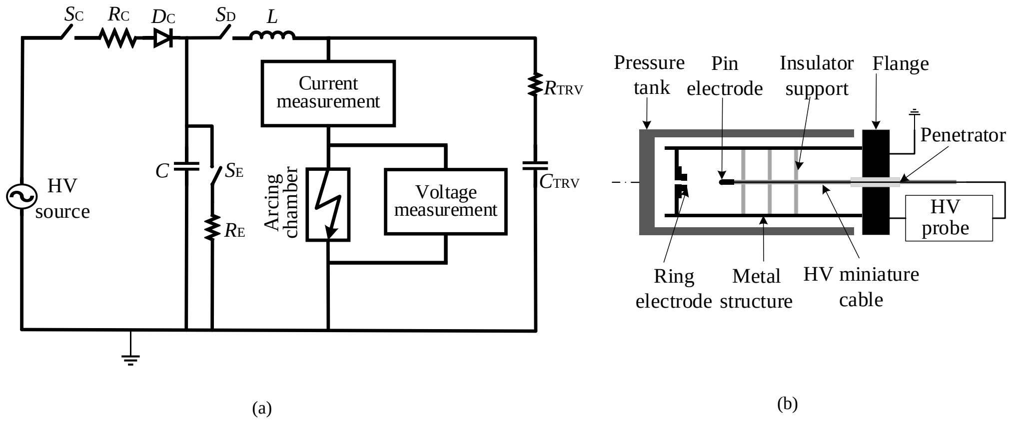

Figure 1. Experiment setup, (a) electrical circuit, (b) interior connection of the pressure tank.

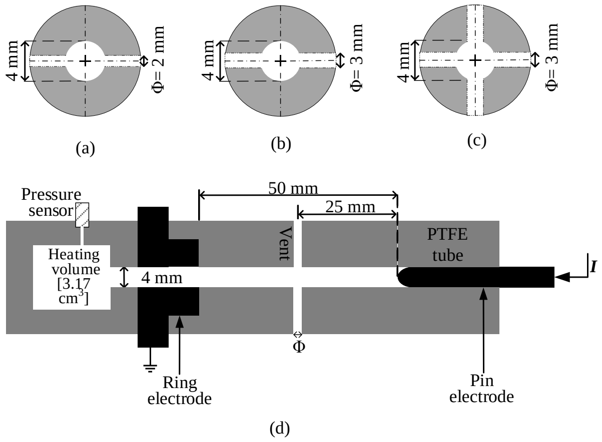

*Figure 2. Cross sectional view of the vent of three designs. (a) design **a**, (b) design **b**, (c) design **c**. Electrode arrangement, nozzle, heating volume, (d) Longitudinal view.*

the switch S_{D} is closed which results in a current flow through the inductor, L and further through a copper ignition wire (40 µm diameter) inside the arcing chamber. The inductance of L, and the charging voltage of C are kept constant to generate a current amplitude of 130 A in the first half cycle at a frequency of 190 Hz for all the experiments conducted. As the arc resistance varies with the filling pressure, the damping of the LC oscillation also changes. Hence, only the first half cycle is considered for all cases. A parallel resistive-capacitive branch (R_{TRV}–C_{TRV}) is placed across the arc to generate a controlled initial rate of rise of recovery voltage (IRRRV) of 43 V/ µs after CZ, see Figure 1(a).

A pressure tank of 15.7 litres rated for 500 bar, is used as arcing chamber. The interior connection of the pressure tank is shown schematically in Figure 1(b). A HV miniature cable is inserted into the pressure tank using a cable penetrator. The arc burns between the pin and the ring electrode. The arc is initiated by melting of a copper ignition wire. To investigate the effect of gas flow on the arc based on self-blast principle, the arc is ignited inside a 4 mm diameter PTFE nozzle with vents in the middle. The electrode arrangement, nozzle and the heating volume are shown schematically in Figure 2(d). A heating volume of 3.17 cm^3 is attached on the ring electrode where the ablated gas is stored during the high current phase and generates a back-flow of the stored gas near CZ. In this paper, three different vent sizes are investigated: 2 opposite holes of $\Phi = 2$ mm (design **a**), 2 opposite holes of $\Phi = 3$ mm (design **b**), and 4 opposite holes $\Phi = 3$ mm (design **c**), see Figure 2(a-c). Three different filling pressures are investigated in this paper: 1 bar, 20 bar and 40 bar, which also covers the supercritical region. For each filling pressure all three designs are tested with a new nozzle.

A HV probe measures the arc voltage across the electrodes while a current shunt is used to measure the arc current. A piezoelectric pressure sensor is mounted on the heating volume to measure the pressure rise, as can be seen in Figure 2(d). The pressure sensor is recess-mounted, and a vinyl electric tape is used to protect it from the thermal blast. All the data are sent to the control room via optical fibre links and stored in a digital oscilloscope with a sampling rate of ten samples per microsecond. For mass loss measurement, weight measurement with an accuracy of 0.1 mg is carried out before and after five tests of all the new nozzles.

3. Results and discussions

A typical measurement of the arc voltage, arc current, and pressure rise in the heating volume for design **a** at 40 bar filling pressure is shown in Figure 3. The ignition wire melts at approximately 0.2 ms marked by a voltage peak. The pressure in the heating volume starts building from approximately 0.5 ms. The pressure rises to a maximum of 13.5 bar at approximately 0.8 ms. Afterwards, the back-flow of stored gas from heating volume starts and flows out completely at approximately 2.9 ms. The CZ occurs approximately

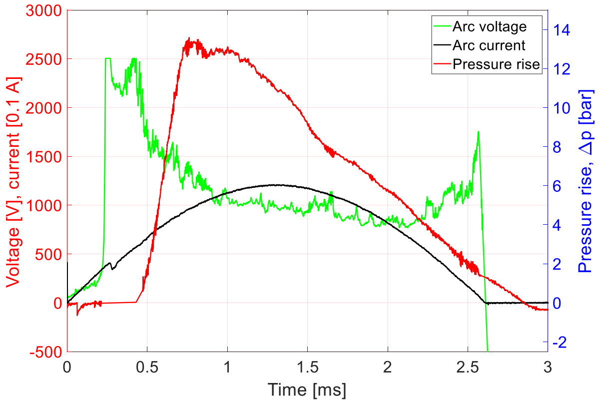

Figure 3. Arc voltage, current and pressure rise in heating volume for design **a** *at a filling pressure of 40 bar.*

at 2.61 ms where the current is interrupted by the self-blast test switch. The over-pressure in the heating volume at CZ in this case is approximately 1.64 bar. The back-flow of stored gas in heating volume near CZ cools the arc, which can be seen by the extinction peak of the arc voltage.

3.1. Pressure rise in heating volume

The measured over-pressures in the heating volume for three designs at three different filling pressures are plotted in Figure 4. The measured pressure-rise in the heating volume is different for different vent dimensions. As the hole size in the vent is increased, more ablated PTFE vapour leaves the arcing zone through the vent instead of contributing to the pressure build up in heating volume. As a result, design **a** shows higher pressure rise in comparison with design **b** and **c** for any specific filling pressure.

The vent dimension also plays a crucial role in the outflow of the stored gas. The heated N_2 and PTFE vapour flows out more slowly in design **a** compared to other designs. In contrast to design **a**, the stored gas leaves completely in design **b** at approximately 1.75 ms. As a result the over-pressure at CZ is low for design **b**. For design **c** however, a negative pressure rise in the heating volume is observed at 20 bar and 40 bar filling pressure, indicating a gas intake through the hole.

The filling pressure also has a significant effect on the pressure-rise in the heating volume. For all designs, the highest pressure rise is observed for 40 bar filling pressure, followed by 20 bar and 1 bar. The rate of change of over-pressure in the heating volume around CZ determines the gas flow rate, hence, the effective cooling of the arc. The measured over-pressures at CZ for all the cases tested are presented in Table 1.

3.2. Mass loss of PTFE nozzle

Five tests were conducted for each filling pressure and for each design. Among them, the only design that resulted in successful current interruption in the first two CZ was design **a**. The current interruption in design **b** and **c** happened after first, second or several half cycles. Consequently, only design **a** is considered for mass loss analysis.

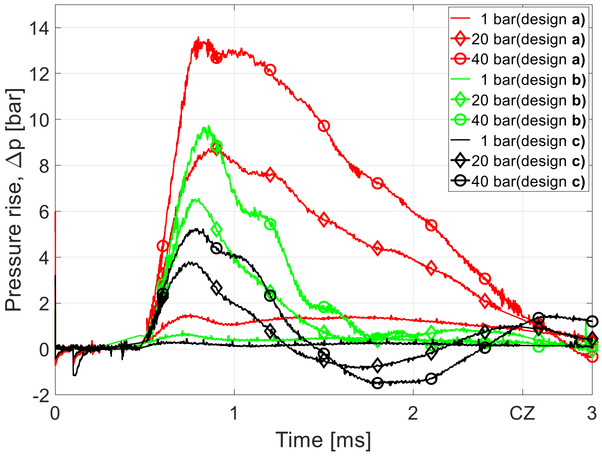

Figure 4. Pressure rise in the heating volume as a function of filling pressure for different designs.

Filling pressure [bar]	**1**	**20**	**40**
Design **a**	0.81	1.31	1.64
Design **b**	0.27	0.53	0.28
Design **c**	0.15	0.96	1.07

Table 1. Over-pressure in the heating volume at CZ [bar].

As the filling pressure increases, the energy deposition in the arc increases too as a result of the increased arcing voltage. From the measured arc voltage and arc current, the energy deposited in each test is calculated until the current is interrupted. At 1 bar, a total nozzle mass loss of 9.2 mg was measured after five tests, while the total energy deposition of five tests was approximately 313 J. For 20 bar and 40 bar, the mass losses measured after 5 tests were 31.1 mg (851 J) and 42.3 mg (1186 J), respectively. Afterwards, the mass loss per unit energy deposited in the arc at different filling pressure is calculated, which is shown in Table 2. It can be seen that although the overall mass loss in PTFE nozzle increases with the filling pressure, the mass loss per unit energy deposition is not strongly dependent on the gas pressure.

3.3. Current interruption performance

The number of successful interruptions after first half cycle among the five tests conducted for each case are plotted in Figure 5. For design **a** at 1 bar pressure, the current was interrupted 4 times among the 5 tests conducted. The number of successful interruption increased to 5 out of 5 for both 20 bar and 40 bar filling pressure using design **a**. For design **b**, however, the interruption performance deteriorated for all filling pressures. Interruption performance is observed to

Filling pressure [bar]	**1**	**20**	**40**
Total energy deposited [J]	313	851	1186
Mass loss [mg]	9.2	31.1	42.3
Mass loss/energy [mg/kJ]	29.4	36.5	35.7

Table 2. Nozzle mass loss as a function of filling pressure.

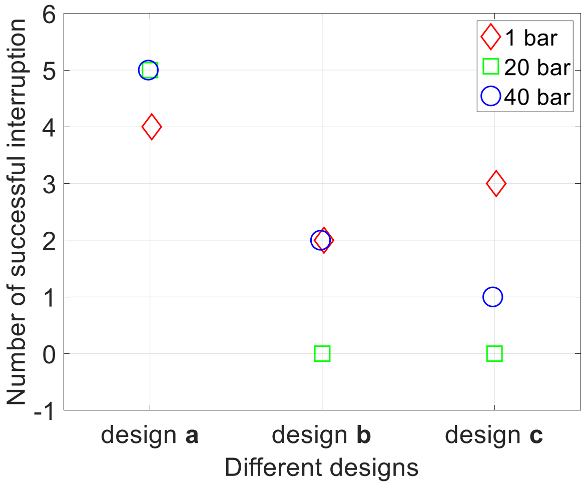

Figure 5. Number of successful interruption among the five tests conducted at different filling pressures for three designs.

deteriorate as the filling pressure increases for design **c**.

For a successful current interruption, effective cooling of the arc is necessary. The arc resistance build-up just before CZ is a key parameter for a successful current interruption [6]. As the gas filling pressure is increased, the arc radius decreases, while the temperature of the arc column increases. Without the sufficient flow at a higher filling pressure (i.e., 20 bar, 40 bar), the arc resistance fails to build up before CZ resulting in a poor interruption performance. The rate of change of overpressure near CZ is high in design **a** for all the filling pressures tested in comparison to other designs, see Figure 4. The gas flow due to high rate of change of over-pressure near CZ results in an improved cooling of the arc and hence, better interruption performance for design **a**. The filling pressure also affects the flow field near CZ [7]. Without sufficient cooling of the arc, the high filling pressure can deteriorate the interruption performance, in this case design **b**, and **c**. This paper underpins the importance of gas flow near CZ for ultra-high pressure N_2 arc for current interruption application.

4. Conclusions

The mass loss of PTFE nozzle, pressure rise in the heating volume and interruption performance for arc burning at different filling pressure of nitrogen are reported in this paper. To study the effect of vent size on blow pressure near current zero, three different vent dimensions are studied. Based on the experimental results following conclusions have been drawn.

1. The pressure rise in the heating volume increases with the filling pressure. The outlet vent dimension plays a decisive role in both the pressure rise in the heating volume and the back-flow near CZ. With proper designing the interruption performance can be improved for ultra-high pressure nitrogen arcs.
2. Total nozzle mass loss is found to increase with the filling pressure. A high filling pressure also constitutes for a high energy deposition in the arc as a result of high arcing voltage. Nevertheless, the mass loss per unit energy deposition in the arc is found to be less dependent on filling pressures.

Acknowledgements

This work is supported by the Research Council of Norway, project number 280539.

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