# Arc Voltage Distribution Measurement in Tube Constricted Ultrahigh-Pressure Nitrogen Arc

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**Abstract.** This work contributes to the fundamental understanding of axial voltage distribution of the arc burning inside polytetrafluoroethylene (PTFE) tube at very high filling pressures of nitrogen. The arc peak current of 85 A at a frequency of 190 Hz with a fixed initial rate of rise of recovery voltage (IRRRV) of approximately 50 V/μs is used throughout the study. Arc burning at three different filling pressures are studied: 1 bar, 20 bar, and 40 bar. To examine the axial voltage distribution in the arc, the arc voltage at three different axial position of the arc is independently measured. For some cases, a 3 cubic centimeter heating volume is attached to the ring electrode, which produces a back flow. For the cases with a heating volume, the pressure rise in the heating volume is also measured. It is observed that the pressure rise in the heating volume increases with the filling pressure. In the presence of the heating volume at a high filling pressure (i.e., 20 bar, 40 bar), the voltage drop increases significantly near the vent due to the relatively cold gas flow.

**Keywords:** Supercritical Fluid, Arc Discharge, Free-burning Arc.

## 1 Introduction

Nitrogen ($N_2$) enters into a supercritical (SC) state when the temperature and pressure exceed the critical point (126 K and 33.5 bar) [1]. High density, high heat conductivity, high diffusivity, the absence of vapor bubbles and self-healing properties are some of the unique features of an SC fluid [2]. For gas circuit breakers, the properties of SC fluid are believed to enhance the current interruption performance [2]. Arc discharges inside SC medium are a relatively new field of research. It has been reported that the free-burning arc voltage increases with filling pressure without any abrupt change during the transition of $N_2$ from gas to SC state [3]. As the filling pressure increases, the energy dissipation in the arc also increases [4]. The arc radius is reported to decrease as a result of the high filling pressure [5]. A successful current interruption must facilitate a quick transition of the arc column from a conducting state to an insulating state near current zero (CZ). To avoid a thermal re-ignition, it is necessary to cool the arc effectively near CZ [6].

The test circuit used in this paper generates an arc peak current of 85 A at a frequency of 190 Hz. This result in a current steepness of 100 A/ms just before CZ. A fixed

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IRRRV of 50 V/µs is applied across the arcing contacts just after CZ. Arc burning at three different filling pressures are investigated: 1bar (atmospheric pressure), 20 bar, and 40 bar. At room temperature and 40 bar filling pressure, nitrogen is in SC state. The conductivity of the switching arc is often not homogeneous axially, leading to some areas of the arc column being more critical in the interruption process [6]. In this paper, a direct measurement of the voltage drop in three axial positions of the arc is independently measured. To study the effect of the gas flow on the axial voltage distribution at different filling pressures, some of the tests are conducted with a heating volume. For the cases with a heating volume, the pressure rise (Δp) in the heating volume is also measured. The voltage distribution across the different sections of the arc are analyzed together with the pressure rise measurements in the heating volume.

## 2 Experiment Setup

The test setup shown in Fig. 1 is used to generate the arc current and the IRRRV. The capacitor, $C$ is charged from a high voltage (HV) source to a charging voltage of 10 kV. Once the capacitor is charged, it is disconnected from the grid by the switch $S_C$. The capacitor, $C$ is discharged by a knife switch $S_D$, the inductor, $L$ and further through the arcing chamber. The opening of the switch $S_C$ and closing of the switch $S_D$ are synchronized by a control circuit to have the same energy in the capacitor, $C$ for all the experiments.

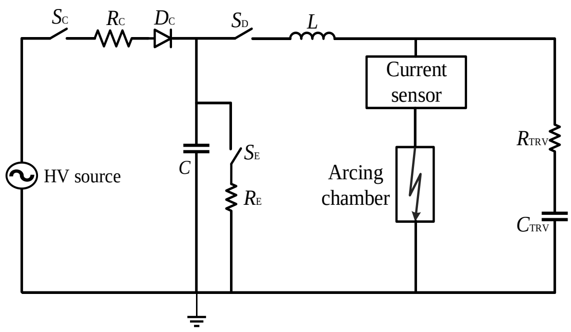


**Fig. 1.** Electrical setup consisting of a resonant circuit to generate the arc current and a TRV shaping part.

A pressure tank of 15.7-liters rated for 500 bar is used as the arcing chamber. The purity of the nitrogen is maintained to at least 99% in all the tests. Arc-resistant copper-tungsten. electrodes (pin and a ring electrode) are kept at a fixed inter-electrode gap of 50 mm, see Fig. 2. A PTFE tube with a vent (2 opposite holes of 3 mm diameter passing through the tube) is firmly mounted on the electrode. A 40 µm diameter copper wire is passed through the PTFE tube and fixed with the electrodes. The arc is initiated by melting of the copper wire. Once the arc is initiated, the current continues to flow

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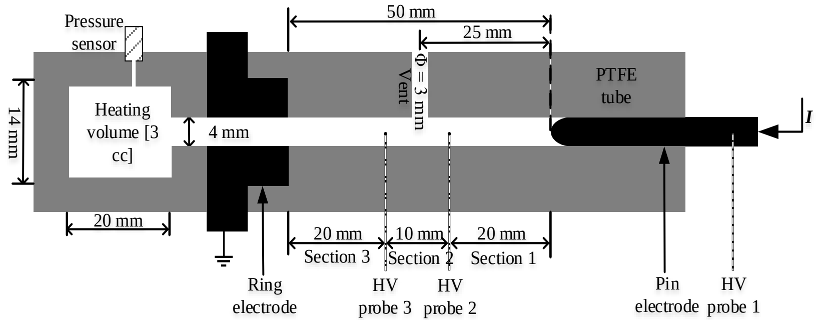


**Fig. 2.** The configuration of the electrode, heating volume and the PTFE tube. The pressure sensor is mounted on one side of the heating volume. The HV probes 2, 3 and the pressure sensor are put inside the pressure tank. For some cases heating volume is removed and for some cases heating volume is attached.

through the arc until CZ, where the current is momentarily interrupted. During this momentary interruption, a controlled voltage stress is applied across the electrodes, depending on the values of $R_{TRV}$ and $C_{TRV}$. In this paper, the $R_{TRV}$ and $C_{TRV}$ are kept constant to 560 Ω and 1.2 µF respectively to generate a fixed IRRRV of 50 V/µs after CZ.

An HV probe 1 is connected across the electrodes from the outside of the pressure tank to measure the total arc voltage. Two other HV electrodes are used to measure the voltage drop at a distance of 20 mm and 30 mm from the pin electrode with respect to ground, as shown in Fig. 2. For this purpose, a thin tungsten wire is inserted into the tube by tiny holes. To avoid the gas flow through the tiny holes, the holes are closed from outside of the tube. These two HV probes are put inside the pressure tank to measure the voltage distribution inside the tube. To measure the arc current, a resistive shunt for the range of ±500 A is used.

Arc burning inside three different gas filling pressures is studied: 1 bar (atmospheric pressure), 20 bar and 40 bar. For the arc voltage distribution tests, total six tests are conducted: one test at each pressure levels, with or without the heating volume. A 3 cc heating volume is mounted behind the ring electrode, as shown in Fig. 2. A piezoelectric pressure sensor is mounted on a side wall of the heating volume to measure the pressure rise in the heating volume. The pressure sensor is recess mounted, and a vinyl electric tape is used to protect it from the thermal blast. Due to the limitation of the available channels in the oscilloscope, three tests with the heating volume is repeated to measure the pressure rise. The same PTFE tube with the vent is used for all the performed tests. The measured signals from HV probe 2, 3 and the pressure sensor inside the pressure tank are sent out via a signal penetrator. All data are transferred via optical fiber link and stored in oscilloscope for further analysis.

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## 3 Experimental Results and discussions

The measured voltages and current for arc burning at 1 bar nitrogen with the heating volume are shown in Fig. 3. In this case, the current was interrupted successfully at the first CZ. The voltage peak around 0.4 ms marks the melting of the copper wire and the initiation of the arc. Before the initiation of the arc, the voltage measured from HV probe 2, and 3 may give an erroneous result as the tungsten wire connected to probes may or may not have touched the copper wire before melting. Near current zero, due to the different frequency response of the voltage probes the measurements from HV probe 2, and 3 are not trusted. The arc voltage distribution analysis in this paper only considers from 1 ms to 50 microseconds before CZ. The voltage drop in section 1 is calculated as the difference in measured voltages of HV probe 1 and 2, section 2 as the difference between HV probe 2 and 3, and section 3 as the measured voltages in HV probe 3.

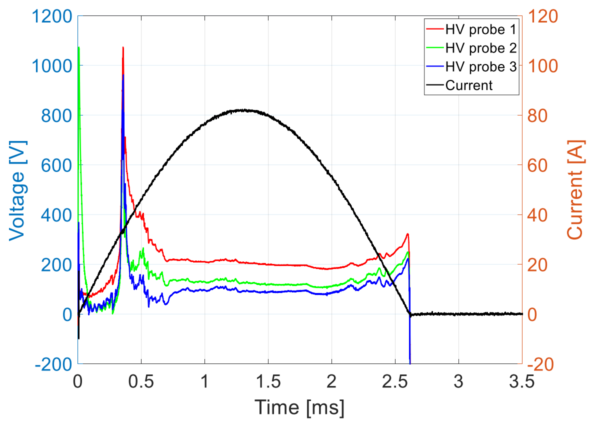


**Fig. 3.** Measured voltages in three probes and measured current for arc burning in PTFE tube with the heating volume at 1 bar nitrogen.

### 3.1 Without Heating Volume

The voltage distribution across three sections of the arc together with the total arc voltage for the cases without a heating volume at three different filling pressures are presented in Fig. 4. It can be seen that the total arc voltage increases from approximately 200 V for arc burning in 1 bar to approximately 550 V and 750 V at the current peak (at 1.3 ms) for arc burning in 20 bar and 40 bar filling pressures respectively. Due to the fixed pin electrode inside the PTFE tube, the stagnation point is near the pin electrode. As there is no heating volume attached, the ablated PTFE vapor leaves the tube without any backflow. At 1 bar more or less homogenous voltage distribution is observed across three sections (section 2 is half the length of section 1 and 3). Approximately 55% of the total voltage drops are measured across section 2 and section 3 at

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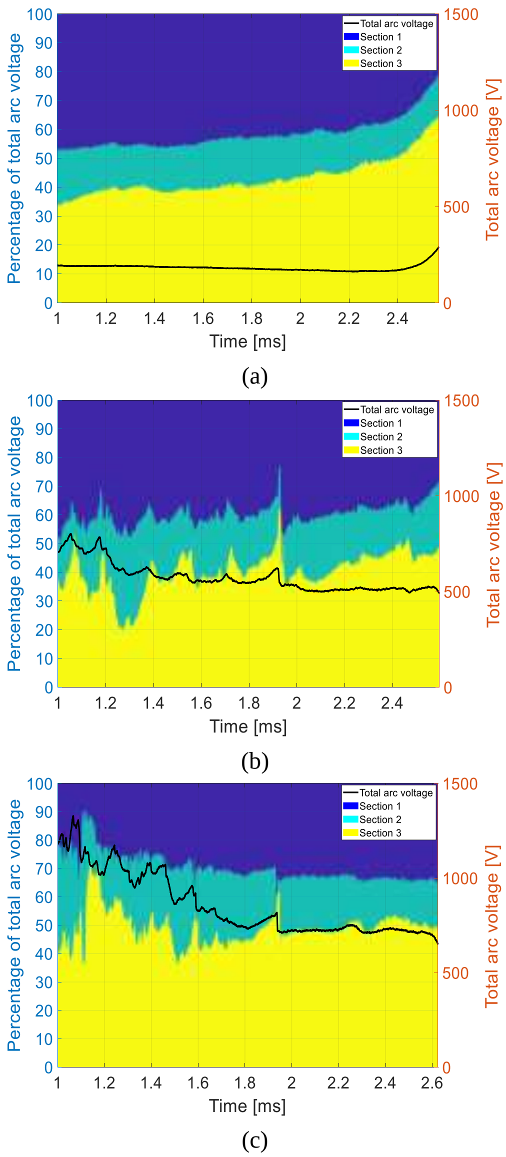


**Fig. 4.** Arc voltage distribution across three sections of the arc for the cases without heating volume. (a) 1 bar. (b) 20 bar. (c) 40 bar.

the current peak for arc burning in 1 bar filling pressure. At 20 and 40 bar filling pressure, the voltage drop across section 2 and 3 corresponds to approximately 60% and 75% respectively during current peak. With the increase of filling pressure, the voltage drop across section 2 increases slightly. At 20 bar and 40 bar filling pressures, the measured voltages show fluctuations compared to atmospheric pressure arc.

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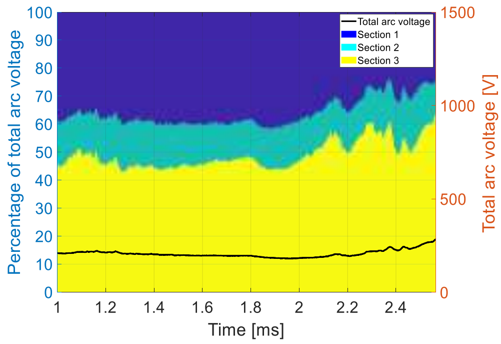
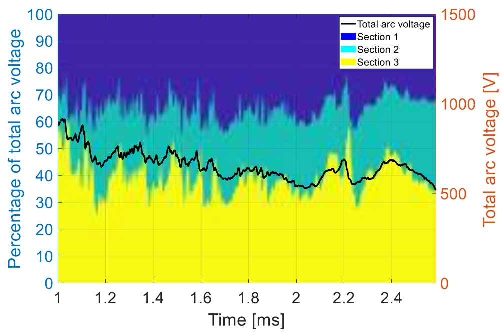
### 3.2 With Heating Volume

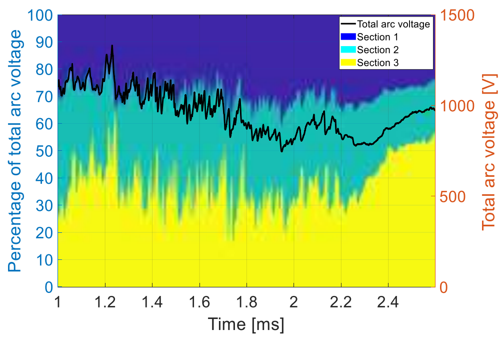
The voltage distribution across three sections of the arc together with the measured arc voltage for the cases with a heating volume attached to the ring electrode at three different filling pressures are presented in Fig. 5. At atmospheric pressure in Fig. 5 (a), the voltage drop across section 2 and 3 increases to approximately 60% compared to 55%




(a)




(b)




(c)

**Fig. 5.** Arc voltage distribution across three sections of the arc for the cases with heating volume. (a) 1 bar. (b) 20 bar. (c) 40 bar.

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in Fig. 4 (a). At 20 and 40 bar filling pressures, the voltage drop across section 2 and 3 are approximately 65% and 75% respectively. However, the voltage distribution across section 2 at 20 bar filling pressure are comparable and at 40 bar are higher than the drop in section 1 and 3 although section 2 is half the length of section 1 and 3. The total arc voltages are also observed to increase with the attachment of heating volume at all three filling pressures compared to without any heating volume. The total arc voltage at 20 and 40 bar with a heating volume show more fluctuations compared to without a heating volume.

### 3.3 Pressure Rise in Heating Volume

The pressure rise in the heating volume for arc burning at three different filling pressures is plotted in Fig. 6. The pressure rise in the heating volume increases to 5 bar and 8 bar when burning at 20 and 40 bar filling pressures respectively compared to an increase of 1 bar at atmospheric pressure arc. The increase in pressure rise is in line with the energy dissipation in the arc at different filling pressures respectively. Fig. 6 shows that at 20 and 40 bar filling pressure the pressure rise goes to a negative value at approximately 1.5 ms, which is probably due to cold gas intake through the vent to the heating volume.

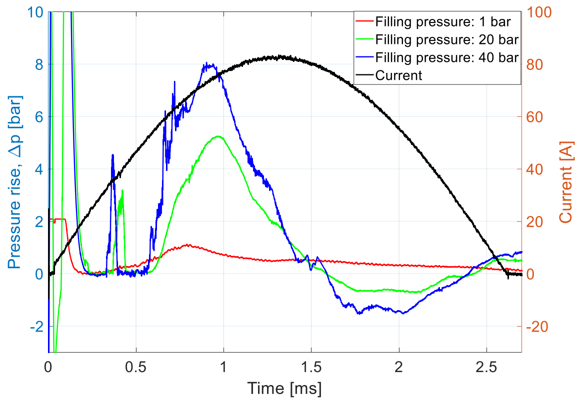


**Fig. 6.** Pressure rise in the heating volume for three different filling pressures.

The increased gas flow due to the presence of the heating volume at 20 and 40 bar filling pressures can be responsible for the relatively high voltage drop near the vent. It is observed that at a high filling pressure, the arc voltage shows unsteady nature by fluctuations in the measured arc voltage. Erratic gas flow can cause turbulence near the arc boundary which can explain the fluctuations in the arc voltage [7].

## 4 CONCLUSIONS

The arc voltage distribution for arc burning inside 4 mm diameter PTFE tube between a fixed inter-electrode gap of 50 mm at three different filling pressures (1 bar, 20 bar,

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and 40 bar) of nitrogen are reported in this paper. For that purpose, a direct measurement of voltage drop at three axial positions of the arc is independently conducted. For some of the cases, a heating volume is attached to the ring electrodes. For the cases with a heating volume, the pressure rise in the heating volume is also measured.

It has been observed that without a heating volume as the ablated gas axially leaves the PTFE tube, the axial voltage distribution in the arc is more or less homogenous. At a high filling pressure, the pressure rise in the heating volume increases due to increased energy dissipation at high filling pressures. The presence of heating volume forces gas flow outwards or inwards through the vent, depending on the pressure on the heating volume. This flow of relatively cool gas near the vent causes significantly high voltage drop near the vent at a high gas filling pressure.

## Acknowledgement

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