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Comparative Analysis of Gas Insulation within a Simulated Helical Flux Compression Generator Geometry using Air, SF6, and Novec™ 4710

Nathan Fryar*, K. Schriner*, J. Stephens*, J. Dickens*, A. Young**, and A. Neuber*

***Abstract*—In order to gain a deeper understanding of how well Novec™ 4710 (C_3F_7CN) would work as a substitute for sulfur hexafluoride (SF_6) in helical flux compression generator (HFCG) applications, a comparative analysis was made between the relative dielectric breakdown properties of air, SF_6, and Novec 4710 under the extreme conditions encountered in an HFCG. An experimental apparatus that emulated a helical FCG geometry was developed to allow the measurement of a time-resolved gas resistance using biased wire probes inserted into the device.**

After initiation, the expanding armature causes interplay between the advancing shocked gas region, armature, and the biased wire probes on the microsecond time scale. This leads to eventual dielectric breakdown on a nanosecond time scale. Incorporating piezoelectric pins, shorting pins, and fiber optic time-of-arrival sensors enabled precise tracking of the armature's position and the shock layer's progression, providing a measure of shock layer thickness at critical points. The spatial relationship between the shocked gas region, armature, and wire probes at the moment of breakdown was used to evaluate the relative performance of the different gases. The results demonstrate that Novec™ 4710's performance closely aligns with SF_6, indicating it may be a viable alternative to SF_6 in HFCG applications.

I. INTRODUCTION

Preventing internal electrical breakdown in magnetic flux compression generators (FCGs) is crucial for reliable device performance. Electrical breakdown ahead of the armature-stator contact point is a well-known issue that can lead to significant flux loss, degrading the generator's efficiency [1-3]. Preventing breakdown has typically been accomplished, at least in part, by filling the internal volume of the generator with an insulating gas. Historically, sulfur hexafluoride (SF_6) has seen widespread use as an insulating gas in FCGs due to its proven effectiveness; however, due to its exceptionally high global warming potential, alternatives to SF_6 are currently being evaluated.

Novec™ 4710 (C_3F_7CN), a proposed alternative to SF_6, has shown promise in early studies. Small-scale generators filled with Novec™ 4710 have demonstrated performance comparable to their SF6-filled counterparts [4]. Nevertheless, beyond these initial findings, limited data regarding Novec's behavior under the extreme conditions found in FCGs is available.

Due to the extreme difficulty of accurately modeling gas properties in such harsh environments, this project aims to experimentally measure and compare the dielectric properties of SF_6, C_3F_7CN, and air. Air is used as a baseline, and the properties of Novec and SF_6 are compared to each other to help further answer the question of Novec's suitability to the role.

II. EXPERIMENTAL APPARATUS

An experimental apparatus resembling the geometry of a helical flux compression generator with an expansion ratio of 2 was developed for this study. The device enabled time-resolved measurements of shocked gas resistance in the generator volume along with measurements of the shock layer thickness. It featured a partially annealed 6061 aluminum armature tube measuring 25.4 mm (1") in diameter with a wall thickness of 1.65 mm (0.065") and a polycarbonate outer housing with a 51 mm (2") inner diameter. The test gas was flowed at 1 atm through the generator volume during the test. A cross-sectional diagram of the apparatus is shown in Figure 1. The explosive used, C4, was end-initiated, and the armature expansion angle and velocity were estimated using the Gurney method as 19 degrees and 2.6 mm/µs, respectively, using the following equations [5]:

$$\frac{V}{\sqrt{2E}} = \left[\frac{M}{C} + \frac{1}{2}\right]^{-\frac{1}{2}} \tag{1}$$

$$\frac{M}{C} = [(OD/ID)^2 - 1] * \rho_M/\rho_C \tag{2}$$

$$\theta = 2sin^{-1}\left(\frac{V}{2D}\right) \tag{3}$$

Where,
V = final armature velocity
θ = expansion angle
E = specific energy of the explosive
D = detonation speed of explosive
M = mass of armature
C = mass of explosive

Gas conductivity (as volume resistance) was measured through two wire probes (14 AWG), positioned tangentially to the inner surface of the housing and 90 degrees azimuthally apart to simulate the stator winding of a helical flux compression generator (HFCG). A bias voltage of 2 kV was applied to one probe via a charged pulse forming line (PFL) with an electrical length of 300 ns, while the other probe was terminated through a 50-ohm resistor, see Fig. 2. As the armature expanded, driven by the explosive pressure, it would

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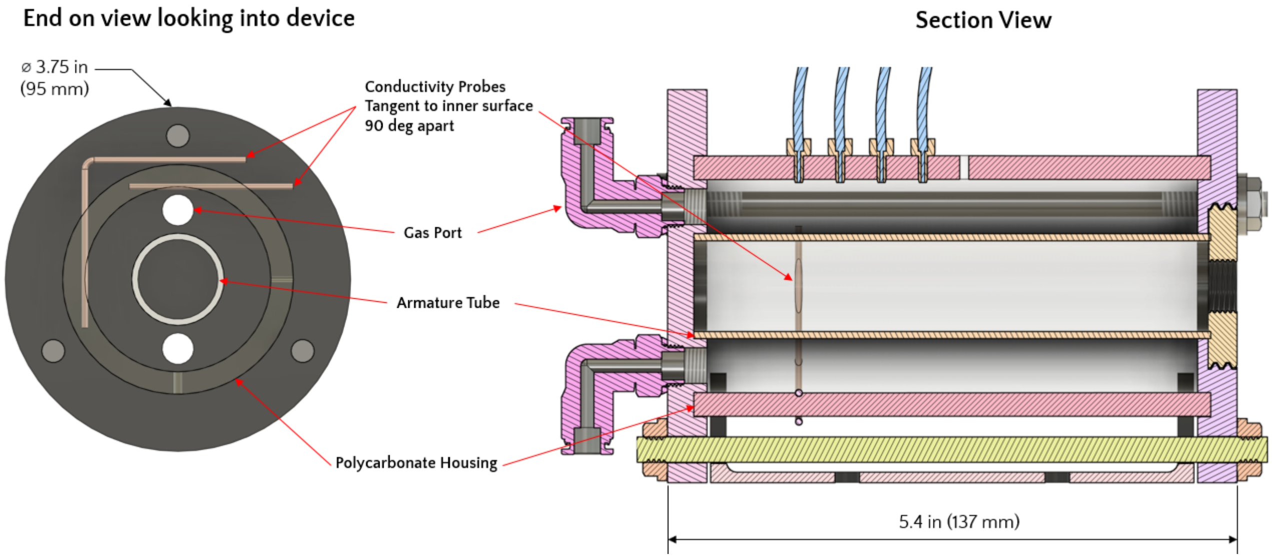

Figure 1: Cross sectional view of experimental apparatus showing the position of the internal components and the diagnostic placement.

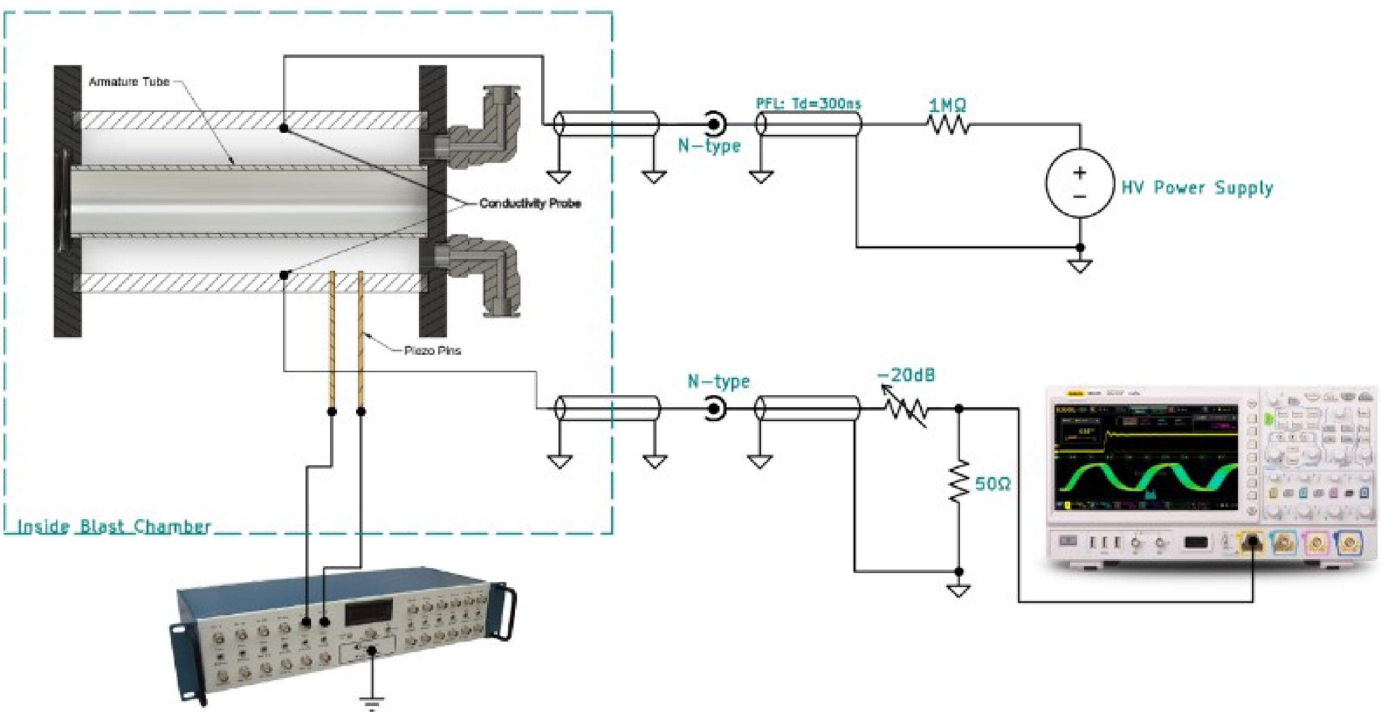

Figure 2: Schematic diagram of test apparatus. A high voltage power supply charges a 300 ns long PFL that is used to bias one of the inserted wire probes. After sufficient armature expansion, breakdown is triggered from the charged probe, through the fill gas and armature tube, to the uncharged 50 Ω terminated probe. The voltage across the 50 Ω termination is monitored to calculate gas resistance. Pressure measurements are recorded on electrically isolated equipment to prevent current flowing down alternative ground paths.

eventually reach the vicinity of the wire probes, where breakdown would be initiated either due to the conductive shocked gas layer or due to the increasing electric field resulting from the armature approaching the probes. While the armature approached the stator, the bias voltage remained constant as the PFLs pulse duration was much longer than the breakdown event. The voltage across the 50 Ω termination was monitored throughout the experiment using a high-quality 7 GHz attenuator, and the impedance of the gas was then derived using the following equation:

$$R = \left(\frac{0.5 * V_{charge}}{V_{measure}} - 2\right) * 50\Omega, \quad (4)$$

where V_{charge} is the initial charge voltage of the PFL and $V_{measure}$ the measured voltage across 50 Ω termination. The apparatus had an estimated rise time limit of approximately 2 nanoseconds, constrained by the stray inductance of the wire probes.

In addition to conductivity probes, several other diagnostics were used to track armature position, measure detonation velocity, and record a pressure-time history, including piezoelectric pressure transducers, fiber optic time of arrival sensors, and ionization pins. Based on the results from these sensors, the armature position and the thickness of the shock layer could be estimated along with the relative position of the armature at the time of breakdown. The piezoelectric transducers used were lead zirconate titanate (PZT-5A) 1.6 mm in diameter and 0.5 mm thick. The tips of the transducers were coated in a thin heat-reflecting copper coating, which prevented biasing due to the intense light emitted from the shocked gas layer. To prevent breakdown between the conductivity probes and the piezo pins during the experiment, the pin mixer and recording oscilloscope were electrically floated, and relative timing between the instruments was established via an optical pulse.

III. Simulation

Two-dimensional hydrodynamic simulations of the test apparatus geometry, including the diagnostic pins were conducted using Lawrence Livermore's ALE3D simulation code to aid data analysis and enhance the understanding of experimental results. For air, high-confidence results were obtained assuming gamma gas law with a gamma value of 1.4 and the Jones-Wilkins-Lee (JWL) equation of state for the C4 [6]. The same methodology was applied to SF_6 with a gamma value of 1.0984. However, the simulations involving SF_6 should only be considered very approximate due to the absence of an accurate equation of state for the gas and the fact that it remains uncertain if the gamma gas law is appropriate for use with SF_6. Novec was not simulated.

IV. Experiment

During the preliminary testing phase, several shots were conducted using atmospheric air as the fill gas to verify the functionality of the apparatus and establish a performance baseline. Results of these tests show a large "precursor" event in the pressure data (*dp/dt*) prior to armature impact (indicated by the large amplitude pulse in the pressure/piezo data in Fig. 3) that wasn't seen in either Novec or SF_6. This observed precursor region corresponded to the shocked layer of gas that traveled ahead of the armature. At the point of probe contact (2mm from the polycarbonate housing), the shock thickness was measured to be approximately 1 mm, corresponding to recorded precursor durations of 300-450 ns at a pressure of 20-50 bar. These observations were corroborated by and were in strong agreement with ALE3D simulations, see Fig. 4. Measurements indicate this shocked gas region was highly conductive as gas resistance began collapsing almost immediately upon the shock front reaching the wire probes. The bulk resistance decreased at a linear rate from the upper limit of our measurement range (30 kΩ) to less than one ohm at the time of armature impact. As a result, air tends to perform poorly in FCG applications, partly due to the thick conducting layer of shocked gas that proceeds armature stator contact.

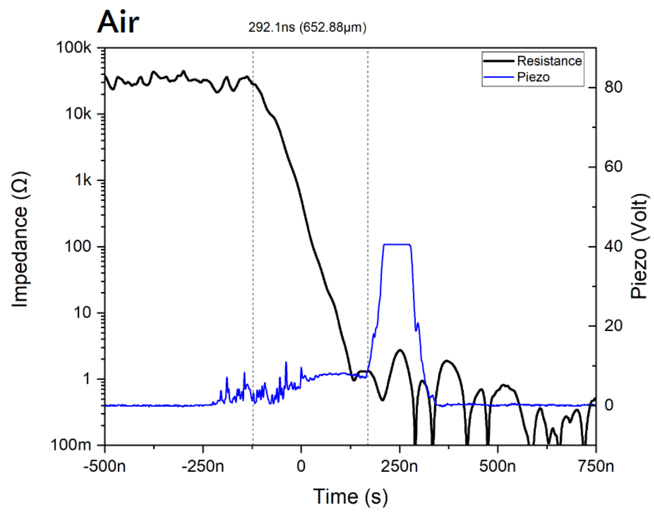

Figure 1: Measurement of gas resistance and pressure history for air. Impedance begins collapsing at a linear rate as soon as the shocked region reaches the probes, indicating the region is highly conductive. Note that the upper limit of the apparatus resolution was ~30 kΩ.

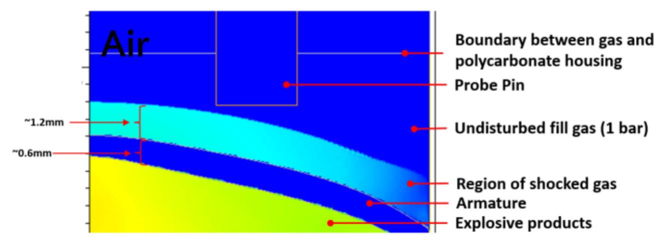

Figure 2: ALE3D simulation results with air (γ = 1.4) as the fill gas.

SF_6 and Novec^{TM} exhibited very different behavior to air. The defined precursor wave observed in the air shots was almost completely hidden or not present in the pressure data. This is believed to be a result of the extreme gas density found in the shocked region approaching densities similar to the aluminum armature tube. This made the distinction between the shocked gas and the armature itself difficult. Results from the ALE3D suggested a significantly thinner shocked region for SF_6, a characteristic likely shared with Novec due to similar initial conditions and gas density. The model predicted a shock layer thickness of ~300μm for SF_6, roughly 4x thinner than predicted values for air. Despite the absence of a defined precursor wave, a subtle change in slope recorded in the pressure data was observed in both Novec and SF_6 and has been highlighted by the dotted red line in Figs. 5 and 6. This occurred in both gases around 30-40 ns after contact with the piezo probe hinting at a much thinner shocked region than predicted by the model. If the assumption that this small slope change marks the transition between the shocked gas region and armature tube holds, it would indicate the the shock layer thickness is closer to 60-85μm in both gases.

Measurements of time-resolved gas resistance also showed strong similarities between Novec and SF_6. Contrary to the results obtained in air, no measurable drop in resistance was detected in either gas prior to or even during the time the shocked layer was in contact with the probes.

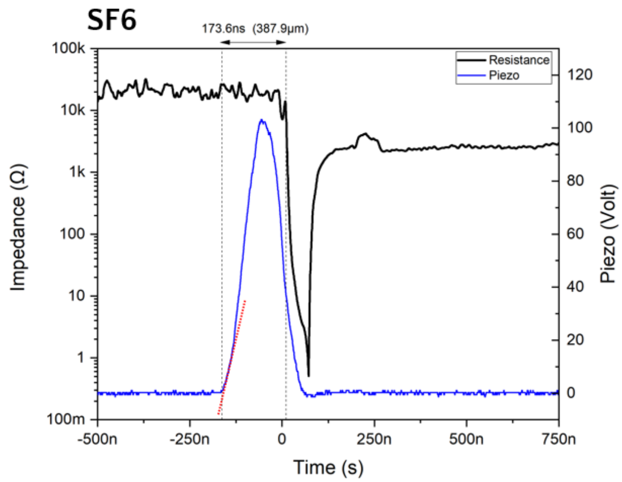

Figure 3: Time-resolved gas impedance and pressure history for SF_6. The dotted red line highlights the subtle slope change in the pressure history ~30ns after initial detection.

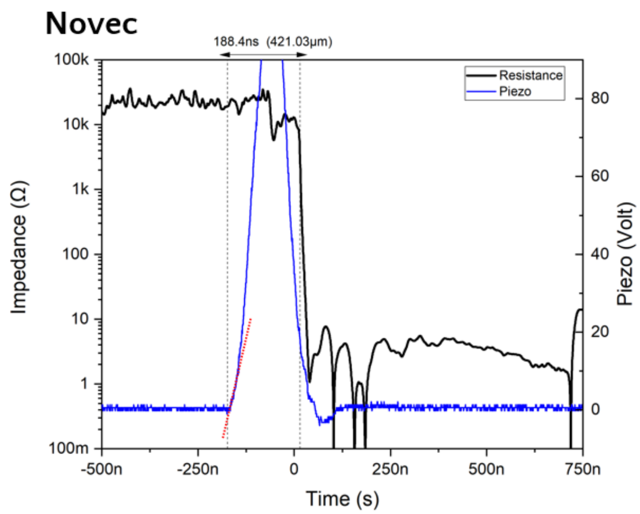

Figure 4: Time-resolved gas impedance and pressure history for Novec™. The dotted red line highlights the subtle slope change in the pressure history ~30 ns after initial detection.

Additionally, even after the armature fully expanded and made contact with the probes, there was a significant delay of ~190 ns for Novec and ~175 ns for SF_6 before the impedance rapidly collapsed. For SF_6, these behaviors are consistent with previous studies that found no measurable drop in impedance of shocked SF_6 and, in similar FCG studies, delayed breakdown even after armature impact with the stator [7, 8]. It has been theorized that the delayed breakdown results from a layer of highly compressed gas at or above liquid density being trapped between the armature and probe.

V. CONCLUSION

Internal breakdown inside FCGs can present considerable issues for device operation if not appropriately addressed. SF_6 is often times used as a fill gas in this application to suppress breakdown and has repeatedly shown from experimental data to work well in FCGs. Despite this, environmental concerns drive the search for alternate gases. Novec™ 4710, on paper, has similar desirable properties to SF_6 but with a much lower global warming potential. As a result, it has been proposed as a possible alternative to SF_6 and has shown promise in previous experiments with similar operating conditions. Prior to the presented investigation, it still remained unclear, however, just how similar to SF_6 the alternate gas behaves under the extreme conditions present in an FCG. To address this question, an FCG-like apparatus was developed that allowed for the time-resolved measurement of gas resistance, armature position, and shock layer thickness. The obtained results revealed a high degree of similarity between the two gases, showing that both Novec 4710 and SF_6 produced thin, nonconductive shocked layers, and a significant electrical contact delay, even after the armature made contact with the stator. These similarities and the previously reported success with Novec-filled FCGs indicate with high confidence that generators filled with Novec should perform similarly to their SF_6-filled counterpart, at least for generators operating at atmospheric fill pressure. Future work may evaluate if this trend holds true for devices pressurized above 1 atmosphere.

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