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AGEING OF TECHNICAL AIR AND TECHNICAL AIR WITH 7.5% C5-FLUOROKETONE BY FREE-BURNING ARCS

A. Subhana[a,*], N. S. Støa-Aanensen[b], M. Gammelsæter[b], E. J. Seither[b], F. Mauseth[a]

[a] *Department of Electric Energy, Norwegian University of Science and Technology, Trondheim, 7491, Norway*
[b] *SINTEF Energy Research, Trondheim, 7491, Norway*
[*] arik.subhana@ntnu.no

Abstract. This paper reports on the effect of ageing by free-burning arcs in 7.5% C5-fluoroketone (C5-FK) with 92.5% technical air in comparison to that in technical air (80% N_2, 20% O_2) at 1.3 bar absolute pressure. The gases are aged by applying a series of arcs dissipating an accumulated energy of around 315 kJ. It is found that the arc voltages in technical air and technical air with C5-FK are in the same range and do not vary significantly as a function of ageing or current amplitude (∼40-900 A). Contact erosion in both mediums is found to be similar if the discharge procedure is same. However, erosion increases significantly if ageing is performed in a short contact gap that needs more arcing operations to achieve similar level of arcing energy accumulation. Furthermore, gas decomposition by-products are analysed using gas chromatography coupled with mass-spectrometry.

Keywords: free-burning arc, environmentally friendly insulation gas, ageing, arc contact erosion.

1. Introduction

Sulfur hexafluoride (SF_6) has been the preferred current-interrupting medium in gas insulated switchgears (GIS) for decades, due to its excellent arc quenching ability, high breakdown strength, good thermal conductivity, and great dielectric recovery characteristics. However, SF_6 has a major drawback: it is the most potent greenhouse gas known, with a global warming potential (GWP) 24,300 times higher than that of CO_2 over a 100-year time horizon [1].

Several gases have been investigated as alternatives to SF_6. Among these, C5-fluoroketone ($C_5F_{10}O$, CAS: 756-12-7, also commonly known as C5-FK) is found to be promising in MV applications. Since C5-FK has a relatively high boiling point (26.9 °C), it is used in gas mixtures, typically with technical air (80% N_2, 20% O_2). Gas mixtures of 7.5% C5-FK and 92.5% technical air are already commercially available in MV GIS at 1.3 bar absolute pressure [2].

The insulation gas in a GIS will be subjected to electrical discharges, like arcing during load break switching. The high temperature in the arcing channel decomposes and ionizes the gas. Unlike SF_6, the by-products generated from C5-FK mixture due to arcing may not recombine. Electrical discharges may permanently change the chemical composition as well as the dielectric properties of the insulation gas, resulting in gas degradation and ageing. Investigating the effect of such ageing is crucial for ensuring a sustainable and resilient power grid in future.

While some studies have been conducted to estimate the fundamental electrical properties of the gas mixture in virgin state, e.g., [3, 4], less has been reported on the effect of ageing due to arcs in 7.5% C5-FK with 92.5% technical air (one example is [5]). By-products generated from electrical arcing may vary with the amount of energy dissipated in the discharge channel, which further depends on the arc voltage and the current flowing through the system. While the current is in general determined by the external circuitry, the arc voltage varies depending on the intrinsic properties of the switch, such as, arcing medium, gas pressure, contact gap, forced cooling (if any), materials and shapes of the contacts and their surroundings [6].

This paper investigates arc voltage characteristics, arc contact erosion and gas degradation in 7.5% C5-FK with 92.5% technical air mixture in comparison to that in technical air at 1.3 bar absolute pressure as a function of ageing by free-burning arcs. The findings from a total of five test series are reported which can contribute to the knowledge-base of arc, gas decomposition and contact wear in SF_6-alternatives.

2. Experimental description

Figure 1 shows a schematic diagram of the experimental setup. For a more detailed description, see [6]. The ageing is performed by discharging a capacitor bank to a pair of copper-tungsten (20% weight Cu / 80% weight W) contacts which are pulled apart to create an arc. The arcing contacts are housed in a cylindrical stainless steel 130 L pressure vessel. At first, the contacts are kept in closed position by pushing a spring inward with a step motor, which are then held by an electromagnet, as depicted in Figure 2. The arc is created by de-energising the electromagnet which releases the spring. When fully opened, the contact gap length is around 20 mm. The test vessel has one more electrode pair and a vertical bushing to conduct

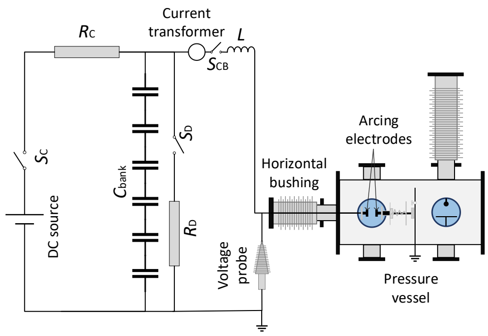

Figure 1. Schematic diagram of experimental setup

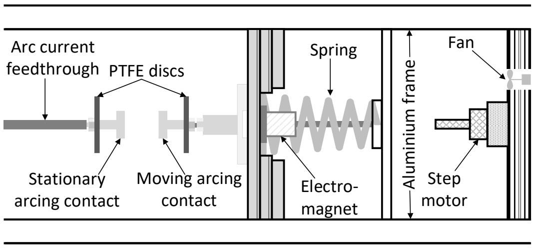

Figure 2. Schematic diagram of the arcing setup

dielectric withstand tests of the insulation gas mixture while it undergoes ageing by arc. This paper, however, does not focus on the dielectric performance of the studied gas mixture and the corresponding parts of the test setup may be ignored hereafter.

The circuit for creating the arc is depicted at the left side of Figure 1. An HVDC power source charges a 6-stage capacitor bank, C_{bank} with a total capacitance of 167 µF. C_{bank} is charged to 20 kV to achieve a first peak current of approximately 1000 A. To initiate the arc between the ageing contacts in the pressure vessel, a synchronized closing signal of S_{CB} and opening signal of the ageing contacts are given by the control system. C_{bank} then discharges through the inductor L and the arc burning between the arcing contacts. The inductor L in the test setup has an inductance of around 34.7 mH, which results in a current frequency around 60 Hz.

To estimate the energy dissipation within the arc channel, the arc current, I, is measured with a current transformer, and the voltage drop, V, across the pressure vessel is measured using a voltage probe. The discharge energy is then found from the time integral of the voltage and current product. Straight inductance, the resistance of the connections across the vessel and electrode voltage drop were not compensated while calculating the arc energy. However, voltage measurements before contact separation are found to be minimal.

A typical MV LBS is rated for 100 load current interruptions and a few making operations during high inrush currents. The total accumulated energy dissipation in a 630 A MV LBS (3 phases, 1.3 bar filling pressure and 100 – 150 liters) has been estimated to be

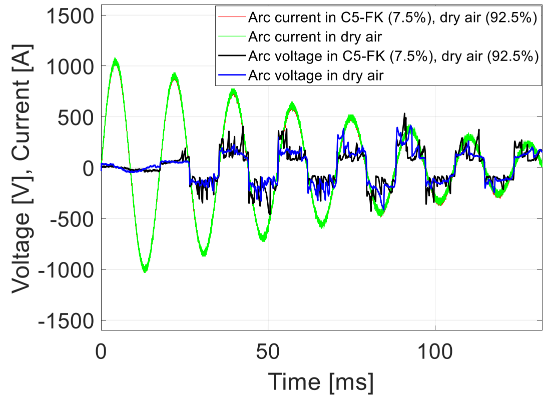

Figure 3. Arc voltage and current waveshapes before ageing, from test series 3 and 4.

around 280 kJ [6]. The accumulated energy dissipation in the test series varied between 143 – 315 kJ.

3. Results and discussion

3.1. Test series overview

This paper reports the findings from a total of five test series, as listed in Table 1. In series 1, the ageing was stopped after 16 arc discharges due to commutation of the arc to the back side of the PTFE plates. The accumulated arcing energy was 143 kJ. Table 1 also presents the amount of ageing in terms of the accumulated charge transfer during the arc discharges and it is 907 As in case of series 1.

In the second series, some issues with the arcing setup led to a change in the procedure. Instead of pulling the contacts apart, the contacts were placed at a fixed distance of approximately 3 mm, and the arc was initiated by an electrical breakdown in the air + C5-FK contact gap (the capacitor bank was charged to 20 kV). Due to this short and fixed gap, the arc voltage (and thus arcing energy) was limited per discharge operation. To achieve 313 kJ, 114 discharge operations were required. The amount of charge transfer was 8446 As in total.

Test series 3, 4, and 5 were carried out according to the planned procedure, with moving arcing contacts and without any arc commutation to other parts of the setup, and a total arcing energy of 313 – 315 kJ and total charge of 2391 – 2602 As.

Series 2 and 4 were carried out with 7.5% C5-FK and 92.5% technical air, whereas series 1, 3, and 5 were carried out with 100% technical air.

3.2. Arc voltage

Figure 3 depicts the waveshapes of the arc voltage and current through the arc channel for both technical air and a mixture of 7.5% C5-FK with 92.5% technical air, before any ageing, from test series 3 and 4. Figure 4 shows the respective waveshapes after >300 kJ of arcing energy accumulation. As can be seen, the arc

Test series	**1**	**2**	**3**	**4**	**5**
Gas	Air	C5-FK + air	Air	C5-FK + air	Air
Ageing, accumulated [kJ]	143	313	315	314	313
Ageing, accumulated [As]	907	8446	2391	2602	2514
Ageing operations	16	114	46	48	52
Ageing per operation [kJ]	9.4	2.75	6.85	6.54	6.02
Ageing per operation [As]	56.69	74.09	51.98	54.21	48.35
Surface scan?	no	yes (after)	yes (after)	yes	yes
Chemical analysis?	yes	yes	yes	yes	no
Contacts weighted?	yes	yes	yes (after)	yes	yes

Table 1. Test series overview

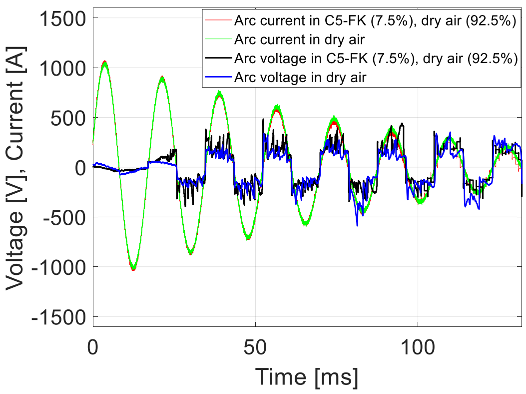

Figure 4. Arc voltage and current waveshapes after ageing by >300 kJ, from test series 3 and 4.

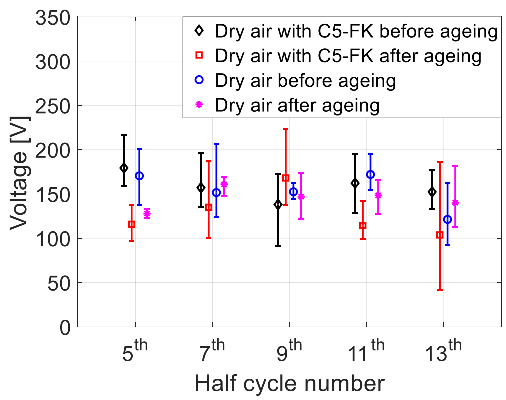

Figure 5. Mean arc voltages at different half cycles.

voltage values and waveshapes are similar, irrespective of mediums and ageing, and the voltage rapidly increased from around 20 V to approximately 170 V as the contacts were pulled apart (from 0 to 20 mm). The minimal voltage of ∼20 V corresponds to the electrode voltage drop reported previously for CuW arcing contacts [7, 8].

Figure 5 shows the mean arc voltages at different current half cycles for both mediums, before and after ageing by >300 kJ. Here, the arc voltages are averaged over the respective half cycles. Furthermore, three shots of arcing were considered in each case and the corresponding mean, maximum and minimum values are presented by the error bars in Figure 5. The arc voltages in technical air and technical air with C5-FK were in the same range and did not vary significantly with ageing or change in current amplitude (∼40 − 900 A) over different half cycles. Similar findings have been reported in [9], where it is suggested that addition of C5-FK to technical air does not significantly alter the arc voltage. Moreover, the same observation was made for free-burning arcs in CO_2 and C5-FK mixed with CO_2 in [10].

In series 2, where arc had been initiated between stationary contacts, the arc voltage remained stable at around 40 V throughout the time. Due to the lower arc voltage, the current decayed more slowly in this case, resulting in much higher charge transfer in series 2 (8446 As), compared to series 3–5 (2391 − 2602 As) which had similar arcing energy accumulation (313 − 315 kJ).

3.3. Arcing contact erosion

To investigate arcing contact erosion in both mediums, the contacts were weighed, and the surface profiles were scanned with a Contour GT-K 3D optical profiler before and after ageing. Table 2 summarizes the surface profile measurements and contact mass. As expected, the surface roughness increased and mass got decreased after ageing for all test series. Comparing series 3, 4, and 5, no significant differences between contact erosion in air and air with C5-FK can be seen. In series 1, as mentioned before, ageing was stopped earlier as the arcs were jumping to the back side of the PTFE plates. Therefore, erosion and weight loss of the contacts after this series was much lower.

The arcing contacts in series 2 encountered significantly higher contact erosion and weight loss; around 2.9% compared to less than 1.4% for the other series. Furthermore, mean surface roughness (S_a) of the contacts after conducting series 2 was found to be several times higher than that in other series, as can be seen from Table 2. The reason could be that short arcs have the main voltage drop across the anode and cathode, and hence a larger part of the arcing energy is dissipated close to the contacts. Moreover, due to the need for more arcing operations in series 2, the

Test series	**1**	**2**	**3**	**4**	**5**
Surface roughness					
S_a [µm], before, centre				1.71, 2.78	1.28, 1.172
S_a [µm], before, edge				3.49, 3.42	1.75, 1.60
S_a [µm], after, centre		28.01, 34.51	3.68, 5.22	2.41, 2.66	2.73, 1.297
S_a [µm], after, worn area		290.20, 208,24	37.41, 32.53	14.80, 5.14	10.79, 15.56
Arcing contact weight					
Before ageing [g]	22.268, 23.533	21.878, 22.950		31.616, 33.420	30.047, 31.810
After ageing [g]	22.237, 23.502	21.235, 22.280	33.643, 35.186	31.396, 33.155	29.774, 31.549
Weight reduction [%]	0.14, 0.13	2.9, 2.9		0.7, 0.8	0.9, 0.8
Weight reduction [mg/kJ]	0.22, 0.22	2.05, 2.14		0.70, 0.84	0.87, 0.83
Weight red. [mg/As]	0.0342, 0.0342	0.0761, 0.0793		0.0846, 0.1018	0.1086, 0.1038

Table 2. 3D profilometer and weight measurements of arcing contacts before and after ageing for both arcing contacts. S_a: mean surface roughness.

1	**2**	**3**	**4**
CO_2	C_2F_6	CO_2	C_2F_6
	CF_4	CF_4	CF_4
	C_3F_6		C_3F_8
	C_3F_8		C_3H_6O
	C_4F_{10}		C_4F_{10}
	C_6F_{14}		
	powder	(powder)	(powder)

Table 3. By-products formed due to ageing by arcing in series 1–4. An off-white powder was formed in series 2. Small traces of powder were also seen in series 3–5.

contacts carried a higher number of high-current half-cycles than in the other series (more than three times higher ampere-seconds than the other series).

In series 2, the weight of one contact decreased by around 2.14 mg/kJ, while that of the other contact decreased by around 2.05 mg/kJ. In contrast, the weight loss of the arcing contacts in series 1, 4, and 5 did not exceed 0.87 mg/kJ. Table 2 also presents the weight reduction of the arcing contacts in terms of mg/As, since the arcing energy does not fully correspond to the erosion of the arcing contacts (but also to heating of the gas volume, changing the gas composition etc.). Considering mg/As, it can be seen that weight reduction of the contacts in series 2, 4 and 5 is more similar, or in fact slightly lower for series 2.

3.4. Gas analysis

Gas samples were extracted from the pressure vessel before, during, and after the ageing process by opening a valve to 0.15 l vacuumed steel bottles. The by-products were then detected through gas chromatography coupled with mass-spectrometry (GC-MS) analysis using an Agilent 7890/5977 GC/MS system with Agilent GS-Gaspro 30 m, 0.32 mm GC columns. Table 3 lists the by-products detected due to ageing of both technical air and mixture of technical air with C5-FK (not quantified). Several byproducts, e.g., C_2F_6, CF_4, C_3F_6, C_3F_8, C_4F_{10}, C_6F_{14}, and C_3H_6O are detected in the aged mixture of technical air and C5-FK. This is in agreement with [11], where CF_4, C_2F_6, C_3F_6, C_3F_8, C_4F_{10} and CF_2O had been detected after successive breakdown tests in a mixture of 13.6% C5-FK with air.

In test series 3 with air, tetrafluoromethane (CF_4) was detected in the fully aged air sample, which is suspected to come from ablation of PTFE plates in the vicinity of the arcing contacts. PTFE degrades due to high temperature of arc and the polymer chains may break. CF_4 can then be expected as one of the pyrolysis products [12]. Another reason could be small residues from the test series with C5-FK, although CF_4 was not detected in the gas samples taken during the ageing process (only in the fully aged sample).

Solid by-products (off-white powder) were found after ageing in series 2 (and small amounts in series 3–5), which is yet to be analyzed. More findings concerning the gas analysis (including quantitative details) will be published later, together with the dielectric performance.

4. Conclusion

This paper investigates arc voltage characteristics, arcing contact erosion and gas by-product formation during ageing by electric arcs in technical air and technical air with 7.5% C5-FK. The main findings are:

- Arc voltages do not differ much due to addition of 7.5% C5-FK to technical air, nor as a function of ageing or current amplitude (∼ 40-900 A).
- As expected, the arc voltage depends on contact separation and is less dependent on arc current. The voltage was around 20 V at the beginning of contact separation and grew to approximately 170 V at fully open position (∼ 20 mm).

- □ Several by-products (e.g., tetrafluoromethane, hexafluoroethane, hexafluoropropylene, perfluoropropane, perfluorohexane, and acetone) are formed due to arcing in the C5-FK mixture, whereas no significant change is observed in case of technical air, except detection of CF_4, which is suspected to come from PTFE ablation.
- □ Given the same discharge procedure, the contact erosion in technical air and technical air with C5-FK is similar and equal to around $0.70 - 0.87$ mg/kJ, or $0.0846 - 0.1086$ mg/As. Contact erosion increased significantly when ageing operations were performed in a short contact gap with more arcing operations (series 2). Moreover, more solid by-products were formed in this air and C5-FK series compared to that with longer contact separation and higher arc energy dissipation per operation (similar accumulated arcing energy).

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