Dielectric Withstand of a Mixture of Fluoroketone C5F10O and Air When Cooling Below Its Dew Point

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***Abstract*— We investigate the temperature dependence of the dielectric withstand of a specific gas mixture consisting of a C5-fluoroketone (C5-FK) and air below its dew point. Both lightning impulse (LI) and ac dielectric withstand are investigated. Using standard testing techniques, it is found that the ac withstand stays constant until the dew point of the mixture and then decreases following the predicted withstand for the concentration of fluoroketone at the given temperature. On the contrary, when measuring the LI withstand using a common dielectric testing approach, one does not find a decrease but instead, in certain cases, an increase of the dielectric performance. We attribute this behavior to the charging droplets of the condensate fluoroketone after each dielectric breakdown event. Flipping the polarization of the LI after every breakdown event reestablishes the behavior seen with the ac stress application. Overall, these results confirm that the dielectric behavior of this alternative insulation gas for electrical devices is well understood and that the dielectric withstand at −40 °C of a mixture specified for medium-voltage applications down to −25 °C still shows 80% of the dielectric withstand measured at the dew point.**

***Index Terms*— Dew point, dielectric withstand, gaseous insulation, sulfur hexafluoride (SF6) alternative.**

I. INTRODUCTION

THE global CO_2-equivalent emissions have to decrease if mankind wants to attain the Paris Agreement goal to limit global warming to 1.5 °C compared to preindustrial levels [1]. Sulfur hexafluoride (SF_6) has a global warming potential over 100 years (GWP-100) that is 23 500 times higher than the one of CO_2. Nowadays, this gas is mostly used in gas-insulated switchgear products used for electricity transmission and distribution. Although at medium-voltage levels these switchgears are sealed for life and their SF_6 content is retrieved at end of life [2], [3], small leakages during operation lead to a total amount of SF_6 lost constituting about 0.5% of total greenhouse gases (GHG) [4]. The need to replace SF_6 by alternative gases with lower GWP is therefore urgent.

In the last decades, a few gases have been proposed for use in switchgears as alternatives to SF_6 [5], [6]. One approach used in the electrotechnical industry is to replace SF_6 by known, naturally occurring gases like air or mixtures of CO_2, N_2 and O_2, and increase the gas pressure to compensate their lower intrinsic dielectric and interruption performance. Another way to increase the performance of naturally occurring gases without having to increase the gas pressure is to consider admixtures of a high performance, often fluorinated additive to a naturally occurring carrier gas.

The two fluorinated additives that are being presently used in recently launched gas-insulated switchgear products are the 1,1,1,3,4,4,4-heptafluoro-3-(trifluoromethyl)-2-butanone, C5-fluoroketone (C5-FK) and 2,3,3,3-tetrafluoro-2-(trifluoromethyl)-propanenitrile, and C4-fluoronitrile (C4-FN) [6]. These fluids have a very high dielectric performance but a high boiling point that is above the typical minimum operating temperature of the switchgears, so they are used in a gas mixture with a background gas that is usually synthetic air. The amount of additive in the mixture is typically limited by the vapor pressure of this fluid at the minimum operating temperature of the equipment, ensuring that the performance of the gas mixture remains constant over the whole range of allowed operating temperature of the equipment. However, during transportation, temperatures below the dew point of the mixture can be reached resulting in partial condensation and thus potential reduction of the withstand voltage. Furthermore, if the device is de-energized for some time, no resistive heating occurs, and the temperature might drop below the dew point of the gas mixture. In both cases, the device might be turned on without preheating leading to the question how the gas would behave under such conditions.

The new molecules and the background gas mix well, and it has been proven that the stratification during mixing is negligible [7]. The good mixing of the mixture was confirmed in the present experiment even after cooling and heating cycles.

The thermodynamic properties of these alternative gases have been investigated theoretically and experimentally [7], [8], [9]. The vapor pressure curves of the fluorinated additives are well known, and therefore, the precise mixing ratio to be used to maximize performance while avoiding condensation at the minimum operating temperature can be calculated easily. Their room-temperature dielectric properties have also been investigated in detail, for many different compositions and pressures, both in breakdown and swarm experiments [5], [10],

Manuscript received 29 April 2022; revised 19 August 2022; accepted 13 September 2022. Date of publication 16 September 2022; date of current version 26 January 2023. *(Corresponding author: Gabriel Lantz.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TDEI.2022.3207447.

Digital Object Identifier 10.1109/TDEI.2022.3207447

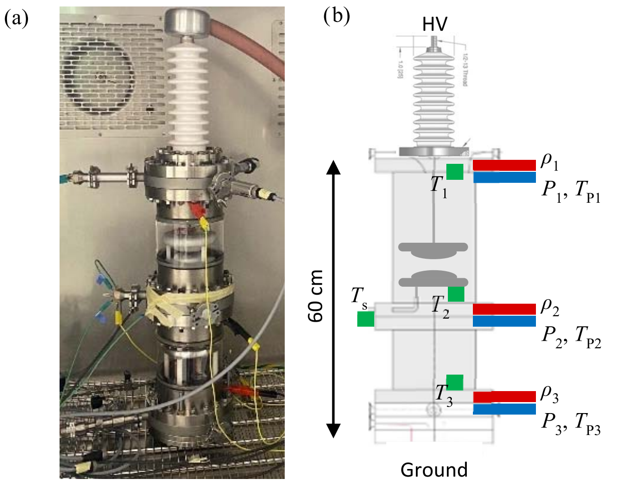

Fig. 1. Test object used to measure the dielectric properties of C5-FK mixture. (a) Picture of the test object. (b) Schematic representation of the test object and numbering of the sensors.

[11], [12]. There is however only limited literature exploring the dielectric performance of alternative gaseous insulation media below the dew point of the mixture. In [13], it was reported that the dielectric withstand of a voltage transformer insulated with a mixture of C4-FN with CO_2 and O_2 does not collapse abruptly when cooling the equipment below the dew point of the insulating mixture, even in the presence of visible condensation droplets; a systematic quantification of the dielectric performance of the gas mixture below its dew point was however not presented.

In this article, we investigate the dielectric properties of a mixture of C5-FK with synthetic air at low temperature, with particular emphasis on the region below its dew point. In Section I, we describe the method used to measure the dielectric strength of the mixture and its thermodynamic properties. In Section III, we introduce a semiempirical model used to analyze the experimental results. We present in Section IV the dielectric withstand measurement results for both power frequency (ac) and lightning impulse (LI) voltage stresses [14] obtained over a wide temperature range. Finally, in Section V, we compare the results to the predictions of our model and discuss the discrepancies.

II. EXPERIMENTAL METHOD

A. Test Object

The test object used to perform the dielectric testing is a sealed hollow cylinder with an inner diameter of 15 and 60 cm height, as shown in Fig. 1. The cylinder is comprised of two glass sections with steel parts at the top and bottom. The high-voltage (HV) feedthrough from the company Hositrad is rated up to 100-kV dc. The HV is brought to the test object with an HV cable rated up to 100-kV ac and 300-kV dc. The ground feedthrough is a standard 1.5-mm^2 copper cable, which is then connected inside the climate chamber to a thick copper braid. In all our measurements, the surfaces of the electrodes are kept horizontal and HV is always applied from the top.

The two electrodes have a Rogowski profile and a diameter of 80 mm. The gap between them is 10 mm, which leads to a uniform field with theoretical field enhancement of less than 1% at the edges of the electrodes. In order to decrease scatter coming from statistical time lag and avoid the impact of a possible deterioration of the surface quality with increasing number of dielectric breakdowns, the electrodes were sandblasted [15]. The measured surface roughness Rz is 42 μm. At the end of the experiments, the electrodes were inspected visually; no evidence of deterioration was found, and the breakdowns were found to be happening randomly on the electrode surface. The electrodes are mounted on plastic rods, so the thermal conductivity between them and the exterior surfaces of the test object is rather poor. In this way, no condensation should happen on the electrodes since they will be the last element to cool down. This is the same expected behavior in real switchgear products, where the cooling happens from the exterior during both potential situations (transport or turn-off). In particular in the latter case, the conductors under load will be considerably warmer than the outside of the device.

All the materials used in the fabrication of the test object are compatible with C5-FK. The test object is leak tight up to 1.5 bar and down to at least −40 °C.

The test object was placed in a climate chamber, Binder MKFT 720, which allows to cool our test object down to −70 °C with control of humidity down to 10% for temperatures above 5 °C. Before starting any cooling, the humidity is brought down to a minimum to avoid any frost formation or ice buildup inside the climate chamber. The temperature ramps are −2 °C/h for a temperature above −15 °C and −1 °C/h for temperatures below. After every cooling ramp, the test object is kept at constant temperature for at least 2 h before dielectric testing. In this way, we could ensure that the thermal equilibrium was reached.

B. Sensors

In order to monitor the thermodynamic properties of the gas mixture, a pressure-temperature-density ($pT\rho$) measurement system, more thoroughly described in [16] and [17], was used. Measurements were performed at three heights (40, 280, and 540 mm) from the bottom of the test object, shown in Fig. 1. Temperature was measured using K-type thermocouples, pressure measurement was performed using Keller PAA-33X sensors with a range of 0–3 bar, and the density was measured using Trafag 8775 RS485 sensors. Additionally, the temperature of the test object surface was measured using a K-type thermocouple (T_s in Fig. 1).

The density sensor operates by measuring the difference of oscillation frequencies Δf of a quartz resonator in the gas medium inside the sensor and a reference resonator in vacuum

$$\Delta f = A\rho + B\sqrt{\rho} + D.$$

In order to use the density sensors to determine the concentration of C5-FK in the test object atmosphere, the sensors were calibrated to obtain the A, B, and D coefficients. Calibration was performed in nitrogen atmosphere with gas pressures ranging from 30 Pa to 140 kPa and temperatures ranging from −40 °C to 20 °C by using the total gas pressure p and gas temperature T and the gas density ρ measured at one of the

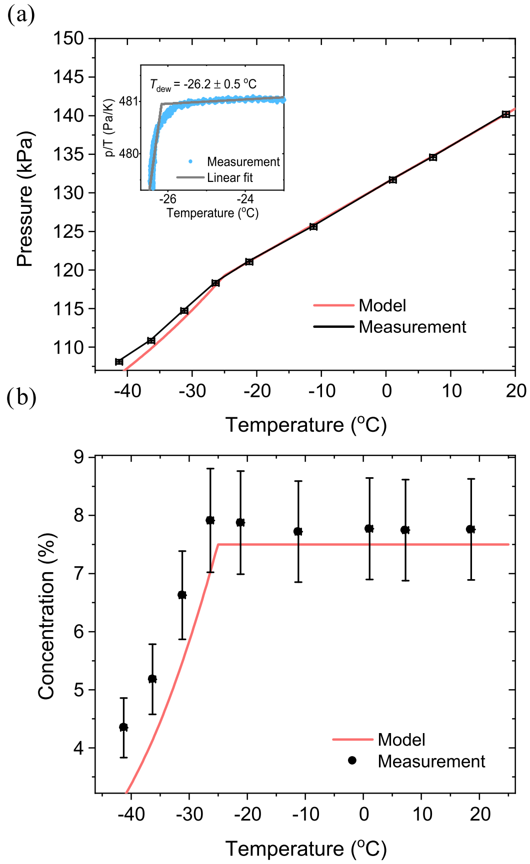

Fig. 2. Temperature-dependent properties of the gas mixture. (a) Pressure versus temperature. Dew point measurement using pressure over temperature versus temperature (inset). (b) C5-FK concentration versus temperature. The red curve represents the ideal gas model. The error bars shown are calculated using the standard deviation derived from the errors arising from the calibration coefficients, the pressure, and the temperature measurement inaccuracies.

three measurement points. The C5-FK partial pressure in the measurement point can be determined as

$$p_{\mathrm{C5-FK}} = \frac{RT\rho - M_{\mathrm{air}}\,p}{M_{\mathrm{C5-FK}} - M_{\mathrm{air}}}$$

where R is the universal gas constant, and $M_{\mathrm{C5-FK}}$ and M_{air} are the molar masses of C5-FK and air, respectively. Using the partial pressure, the concentration of C5-FK can be estimated as

$$c_{\mathrm{C5-FK}} = p_{\mathrm{C5-FK}}/p.$$

C. Gas Mixture Properties

C5-FK has a boiling temperature of 26.9 °C at atmospheric pressure; therefore, it is used in a mixture with a carrier gas to maximize performance [18]. For medium-voltage switchgear, the minimum operational temperature often is -25 °C [19], and a pressure below or around 140 kPa absolute at 20 °C is used to minimize complications arising from higher pressure gas enclosures. The target gas mixture used in the experiments summarized here is 7.5 mol% C5-FK, 74 mol% N_2, and 18.5 mol% O_2 at filling temperature of 20 °C and total pressure of 140 kPa absolute; it was prepared by sequential filling of the test object at room temperature. Using the ideal gas law, the partial pressure of C5-FK at -25 °C is 8.9 kPa, which is the saturation vapor pressure of C5-FK at this temperature; the targeted dew point of the mixture is therefore -25 °C.

D. Dielectric Testing

1) AC Power Frequency: The ac dielectric testing is done with a commercially available Haefely KIT 4.0 system. The maximum rated output voltage of the HV transformer is 100 kV rms at 50 Hz and 100 mA of current. The voltage is increased with a ramp of 1 kV/s until breakdown. The transformer is stopped as soon as the source current of the transformer is more than 3.4 A. For every temperature step, 20 breakdowns are recorded. Each breakdown only inputs a very small amount of current (<100 mA) to the gas, and therefore, no decomposition is observed.

For the recorded breakdown voltage, we use the survival function $\hat{S}(V)$ and the empirical cumulative distribution function (ECDF) calculated by Kaplan–Meier estimator [20]. The 95% confidence intervals are calculated from Greenwood's formula [21]. This method allows to have a nonparametric approach, where we do not predefine a theoretical breakdown voltage distribution. We also show the first breakdown of the sequence to monitor possible history effect. For comparing between different temperatures, we use the mean of the distribution with a standard error of the mean and normalize the mean with values obtained above the dew point.

In order to verify the setup and test procedure, we perform an ac dielectric breakdown experiment for pure synthetic air at 140 kPa. We find a breakdown level of 303 ± 1 V/cm/kPa with a 1-cm gap at 140 kPa for both 20 °C and after cooling the gas down to -40 °C. The results are perfectly in line with the known dielectric withstand of air [22].

2) Lightning Impulse: The LI setup uses the same transformer as the ac setup with a two-stage Marx generator. The setup is designed to generate a voltage pulse of shape as defined by the IEC norm [14], [19]. The pulse front-time T1 is 2 μs and the time to half-value is 50 μs. The peak value is 95 kV ± 3% to always ensure breakdown in order to use the always breakdown method, also called assured disruptive discharge [14]. We use the same analysis methodology with Kaplan–Meier estimator as described for the ac breakdowns. We make 75 breakdowns per temperature to ensure a good statistic. We verified that the results obtained with this method are comparable to those obtained using another standard measuring technique ("up–down method") as previously shown in [23].

III. SEMIEMPIRICAL MODEL

To analyze our results, we use a semiempirical model, where the gas mixture is deliberately modeled as an ideal gas. The limitations of this approach are well documented [5]. Given the low pressure considered here and the typical scatter associated with dielectric withstand measurements, this simple approach is however more than appropriate to guide the interpretation of our results.

Our hypothesis for the behavior of the dielectric withstand below the dew point of the mixture is that it is the dielectric withstand of a mixture with lower C5-FK concentration, i.e., one where the partial pressure of C5-FK in the gas mixture is limited by the saturation pressure of the fluid at temperatures below the dew point. Since the dielectric withstand of mixtures of C5-FK and air increases monotonically with increasing C5-FK content [5], [11], we expect the dielectric performance to be independent of temperature above the dew point and to slowly decrease as the gas temperature is brought below the dew point.

We use the vapor pressure curve from [8] and the dielectric withstand for various concentration from [5] and [11] in the following way. We first calculate the total pressure versus temperature without condensation using the ideal gas law

$$p_1(T) = p_{\text{fill}} \frac{T}{T_{\text{fill}}}$$

where p_{fill} and T_{fill} are, respectively, the pressure and temperature during filling, and T is the temperature in Kelvin. The partial pressure of C5-FK in the mixture can then be calculated using the vapor pressure curve

$$p_{\text{C5-FK}}(T) = \min\left(C_{\text{C5-FK,fill}}\, p_1(T),\ p_{\text{VP,C5-FK}}(T)\right)$$

where $C_{\text{C5-FK,fill}}$ is the concentration (mole fraction) of C5-FK after filling, and $p_{\text{VP,C5-FK}}$ is the vapor pressure of C5-FK at a given temperature. This equation is easily understood: below the dew point, the molar fraction of C5-FK is limited by the vapor pressure of the fluid, above, by the concentration at filling. The total pressure is then

$$p(T) = p_1(T) - \left(C_{\text{C5-FK,fill}}\, p_1(T) - p_{\text{C5-FK}}(T)\right)$$

and the concentration of C5-FK versus temperature is

$$C_{\text{C5-FK}}(T) = \frac{p_{\text{C5-FK}}(T)}{p(T)}.$$

It is well documented that the dielectric withstand of a gas mixture cannot be reliably calculated through a weighted sum of the contribution of individual gas components [24]. To estimate the dielectric withstand of the mixture of air and C5-FK as the fraction of C5-FK is changed in uniform field conditions, we therefore use the measurements of the critical field various concentrations coming from the round-robin test performed in [5] and also the swarm experiments in mixtures of C5-FK and N_2[11] to capture the synergy effect between C5-FK and air at low C5-FK concentrations, assuming that the dielectric withstand at any given temperature normalized with the one obtained at room temperature after filling is

$$E_{\text{crit,mix}}(T) = E_{\text{crit,C5-FK/air}}(C_{\text{C5-FK}}) / E_{\text{crit,C5-FK/air}}\left(C_{\text{C5-FK,fill}}\right)$$

where $E_{\text{crit,C5-FK/air}}$ is the dielectric withstand of mixture of C5-FK with air or N_2 obtained by interpolating various concentrations coming from [5] and [11]. This model supposes that: 1) the condensate part of C5-FK does not contribute to the dielectric properties of the mixture; 2) that the relative dependence of the critical field of the C5-FK mixture with synthetic air at 140 kPa is the same as when only N_2 is used as background gas (for [11]); and that iii) the relative impact of changing the C5-FK composition does not significantly vary as the pressure is increased from 10/100 kPa [5], [11] to 140 kPa here. It is known that the absolute critical field in mixtures of C5-FK and air can differ by roughly 5% from the one in mixtures of C5-FK and N_2 [25]. The different measured dielectric withstands versus C5-FK concentration show some deviation from each other, and thus, we will show a range for the expected withstand with temperature.

IV. RESULTS

A. Thermodynamic Properties of Mixture

Fig. 2 shows the thermodynamic properties of the mixture during a cooling down phase. The pressure–temperature curve shows a clear kink around the dew point of the mixture around −25 °C. The p/T curve shows that the dew point is at −26.2 °C ± 0.5 °C. The concentration of C5-FK as measured with the density sensor decreases from 7.8% ± 0.9% at 20 °C to 4.4% ± 0.5% at −40 °C. The pressure follows the ideal gas law above −25 °C. However, the model and the experimental data seem to be diverging below the dew point, where the model predicts approximately 1%–2% lower C5-FK concentrations than the experimental data at the lowest temperature reached. The measured dew point of −26.2 °C ± 0.5 °C is slightly lower than expected. The model curve of the concentration is within the error bars of the experimental measurements besides the concentration below the dew point.

During the cooling down and heating up phases, the concentrations measured using each of the three, vertically distributed, density sensors differ by less than 0.2%, which is well within the error bar of these sensors. Thus, we conclude that no stratification occurs in the test object as the temperature is ramped up or down and that the mixture remained homogeneous after thermal stabilization. Therefore, we will only use the bottom sensors during the rest of this article.

B. AC Power Frequency Dielectric Withstand

We plot the ECDF for the ac dielectric withstand in Fig. 3(a). First, the distribution of the breakdowns at one given temperature happens in a range of less than 2-kV rms, which shows that the electrodes have a well-defined breakdown level. The breakdown levels below −30 °C are clearly lower than the ones measured at higher temperatures. In order to verify the reproducibility of these measurement, a second set of measurements were done with the same gas but going from 20 °C to −40 °C directly without any intermediate step. The temperature was kept at −40 °C for 30 h to ensure a complete thermal equilibrium. The result of this second measurement, labeled −40 °C V2, is fully in line with the first one, which shows that temperature cycling does not affect the dielectric performance at low temperature.

Fig. 3(b) shows the mean value of the ECDF with the error bars, which are the standard error of the mean. Below −25 °C, the dielectric withstand decreases, reaching 85% of its room-temperature value at −40 °C. The results obtained while ramping-up the temperature are within the error bars of those obtained when the temperature was being decreased.

C. Lightning Impulse

We plot the same ECDF for the LI breakdown voltage measurements in Fig. 4(a). The situation is a bit different from

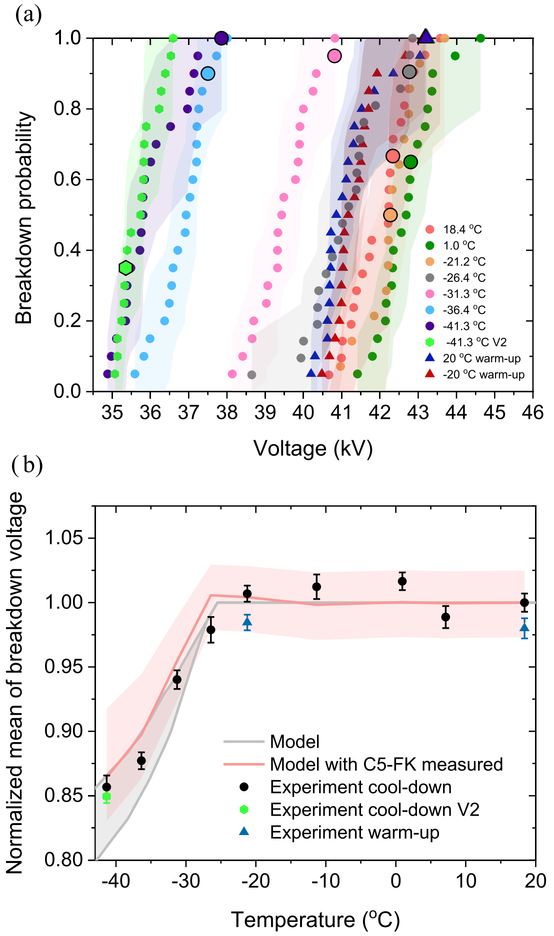

Fig. 3. AC dielectric breakdowns for various temperatures. (a) AC rms breakdown ECDF. The shaded color represents the 95% confidence intervals calculated with Greenwood's formula. The bold points are the first observed breakdown event of the sequence. (b) Normalized mean value of the ECDF with normalized standard error. The gray shaded area represents the range, where the model would predict the breakdown value to lie. The pink shaded area represents the breakdown range, where the measured C5-FK concentration is used as an input for the model.

the ac measurements, all the results are at a similar level, and only the first withstand measured at −40 °C seems to be higher than the rest. The slopes of the ECDFs also vary, contrary to the ac case where the slopes remained similar across the temperature range investigated. Again, the −40 °C measurement differs from the rest of the measurement data, with a much broader breakdown probability distribution than the one seen at higher temperatures.

In Fig. 4(b), we plot the mean of the ECDF the same way as for the ac withstand. Contrary to what has been found with the ac testing, the measured dielectric withstand after LI increases as the device is cooled down below the dew point. The error bars portraying the scatter in the data also increase. The results obtained after reheating up the test object to a given temperature fully overlap (considering the error bars) with the ones obtained when first cooling down the device. This confirms that condensation is a fully reversible process, and that in applications, the dielectric performance of equipment that would be cooled down below the dew point temperature is recovered once the temperature of the equipment goes back and stabilizes to the normal operating range. The second temperature cycling shows that the −40 °C measurement is slightly below the first −40 °C one and on the same level as the all the previous ones.

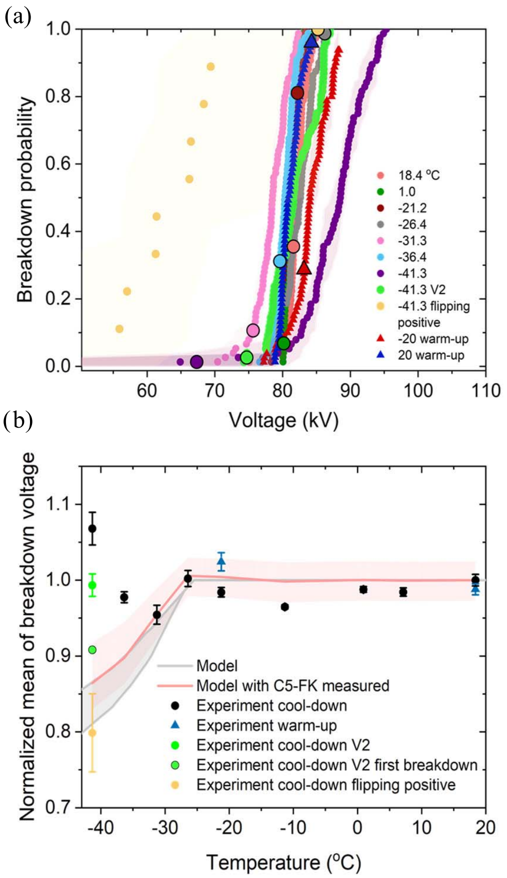

Fig. 4. LI dielectric breakdowns for various temperatures. (a) LI breakdown ECDF. The shaded color represents the 95% confidence interval calculated with Greenwood's formula. The bold points are the first observed breakdown events of the sequence. (b) Normalized mean value of the ECDF with normalized standard error. The gray shaded area represents the range, where the model would predict the breakdowns. The pink shaded area represents the breakdown range, where the measured C5-FK concentration is used as an input for the model.

During this second temperature cycle, another measurement was done, where the polarity of the LI pulse was changed between every shot. The LI pulse is switched from positive to negative between every voltage application, always keeping the HV on the top electrode. Only eight shots per polarity were recorded. We only show the ECDF for the positive polarity because there is no proper baseline for the negative polarity for all other temperature measurements, but the results are very similar at a first approximation. The mean value of the normalized withstand when flipping the polarization is much lower than the one measured through consecutive breakdown tests with a constant polarity. A decrease of the dielectric withstand at −40 °C of about 20% is measured in this case, taking the room temperature results as reference. The error bars are also very large because of the reduced number of points.

In Fig. 4(a), the bold markers on the ECDF represent the first breakdown observation of the sequence. Interestingly, the two first breakdowns for the two −40 °C measurement are on the very low end of the distribution curve. The measurements below −30 °C also have the first breakdown below the 0.3 probability value, whereas for the other temperatures, the first points are more randomly distributed. Since this should be an independent random distribution, the probability having four points in a row that are below 0.3 is 0.8%. Therefore, this behavior might be a sign of some history effect.

V. DISCUSSION

A. Thermodynamic Properties of Mixture

The dew point of the mixture is about 1.2 °C ± 0.5 °C lower than expected. The main uncertainty remains during the filling process, which is done sequentially and leads to small errors since the partial pressure is different than the mole fraction [5]. There are two other theoretical sources of deviation: the first is the Poynting effect, which lowers the dew point [26]. Using the liquid molar volume of C5-FK of 1.7×10^{-4} m^3/mol, we find that the dew point should be shifted by −0.2 °C. This shift is insufficient to explain the difference with an expected value. The second source of deviation is that the gas mixture behaves differently than an ideal gas. The Peng–Robinson equation of state has been proposed to describe better the behavior of alternative gases [5] and its effect would also lead to a lowering of the dew point. The real gas model would also bring corrections to the total pressure and C5-FK content as a function of temperature, especially below the dew point. As the focus of this article is the dielectric properties of the gas mixture at low temperatures and since this behavior is already adequately captured in the ideal gas approximation, the full real-gas analysis of these results will not be pursued here.

B. AC Power Frequency

The model curve of the dielectric withstand, as described in Section III, is plotted in Fig. 3, we use as $E_{\mathrm{crit,C5-FK}}$ the data extracted from [5] and [11] using the lowest and the highest measurement to create a range. The ac dielectric withstand is clearly following the expected trend. We also plot in the same figure the model curve but using the C5-FK concentration measured with the $pT\rho$ method and the $E_{\mathrm{crit,C5-FK/N2}}$ from [11]. All the measurements below the dew point are well within the predicted range of the model and the model with measured C5-FK concentration.

The spreads of the ECDF of the ac measurement are constant when decreasing the temperature, which proves that the gas has the same behavior in low temperature as in high temperature for ac dielectric withstand. However, when looking at the first breakdown point of each sequence, four out of five points below −25 °C are higher than 0.9. The distribution of the first breakdown should be random inside the ECDF if the dielectric breakdowns are independent of each other. This small effect could be linked to the stronger anomalous behavior seen in the LI breakdowns.

C. Lightning Impulse

The LI measurement series shows an unexpected behavior at low temperatures. During our measurement, we used the always breakdown method with positive HV impulse. The results indicate that the dielectric strength of the mixture below the dew point stays constant or increases. As the electrodes create a uniform electric field, there should not be any space charge effect. The fact that increasing the stabilization time at −40 °C has an impact on the dielectric strength points toward an effect of condensation dynamic; however, there was no effect for the ac measurements.

Vapor supersaturation and mist of dielectric liquids have been proven to increase the dielectric strength for both ac and LI conditions [27], [28], [29], [30]. The dielectric liquids used in these investigations are C_2Cl_4, $C_8F_{16}O$, C_6F_{14}, and $(C_4F_9)_3N$.

Using $C_7F_{16}O_4$, Okada *et al.* [27] showed that creating vapor with supersonic vibrators enhances the ac and LI dielectric strength and it is even more increased when the droplet density increases. In these tests, the LI dielectric strength sees a larger increase than the one seen when applying an ac voltage. The main hypothesis put forward in these articles is that there are fewer first electrons available for the avalanche effect. Harrold [29] and [30] also claims that there is supersaturation of the mixture in the presence of droplets, as can be explained through the Kelvin equation.

The main difference between the previously cited experiment and the ones summarized here is that we do not generate vapor or mist actively and they used sphere–sphere configuration. However, we do not actively create the mist, and the effect is still present after 30 h of thermal stabilization. After 30 h, more than 99.9% of the droplets with a diameter larger than 100 nm (fog or mist droplets are assumed to range from diameters of 0.1–200 μm) should have deposited from the test object atmosphere due to the gravitational settling [31]. Another difference with the works cited above is that here the results differ qualitatively whether an ac or LI voltage shape is used.

Important insights can be gained from the experiment, where the polarity of the voltage pulse is flipped between each application of the voltage. In this measurement series, the LI dielectric breakdown level is much closer to the prediction of the model and significantly below the level measured when using positive polarity impulses only. We observe that the first breakdown for every data series with temperature below −30°C occurs on the lower tail of the ECDF.

Our hypothesis is that the first breakdown can resuspend some of the deposited droplets that are charged by the breakdown. Additionally, small, local increase of the test object temperature due to the first breakdown can cause a volatilization of a small amount of the condensed C5-FK and formation of droplets at the test object gas space. We do not expect a large increase of temperature since the current input is very small in our tests. The charging of these droplets would shield the electrodes and thus reduce the field at the electrodes and increase it in other less critical areas. Therefore, the following LI shots with the same polarity would happen at higher voltages. We observe that the first breakdown below the dew point is rather on the lower tail of the ECDF, which would agree with this charging hypothesis.

In the case where the voltage polarity is flipped after every voltage pulse, this charging has a detrimental effect and would lead to a decrease of the LI dielectric withstand. To the best of our knowledge, the previously reported experiments on the dielectric performance of mists have not investigated the effect of alternating the pulse polarity after each breakdown. Our hypothesis explains the difference seen in their experiment between LI and ac.

Another interesting aspect is that the first breakdowns in the ac tests are in the upper tail for temperatures that are below the dew point. One could interpret this using the same charging hypothesis, the first breakdown charges the droplets in the gas, and therefore, since the ac has positive and negative waveforms, the electric field is enhanced for the other polarity than the first breakdown. Therefore, the first breakdown is usually at higher voltages than the following breakdown.

VI. CONCLUSION

We have shown that a mixture of C5-FK with synthetic air at 140 kPa behaves close to an ideal gas above the dew point. The ac dielectric withstand behaves like a mixture with lower concentration, and at −40 °C, the dielectric withstand is 85% of the one at 20 °C. We find that the dielectric withstand under LI stays constant or increases below the dew point, which we attribute to our testing method and a charging of the condensate part of the gas. This charging effect was confirmed by changing the polarity of each impulse: in this case, the subsequent dielectric withstand at −40 °C falls to the predicted 80% of the dielectric withstand of 20 °C, in line with the results obtained with ac voltages.

We conclude that at −40 °C, the C5-FK mixture with a dew point of −25 °C loses only 20% of its dielectric performance, both under ac and LI stresses when the condensation does not happen on the electrodes. The implications of this finding in applications are that the switchgear devices using such mixtures as environmentally friendly insulation medium and rated for a −25 °C minimum operating temperature can still be operated at temperatures as low as −40 °C, because there is still significant margin between the operating voltage and the test voltages, whereof still 80% can be reached. As condensation and evaporation of C5-FK are fully reversible, it was shown that the dielectric withstand after heating is fully recovered.

To understand the higher LI dielectric withstand, we made the hypothesis that the first breakdown puts in suspension some droplets that are then charged. In order to verify this hypothesis, one could verify the presence of droplets in the gas after the first impulse and measure their size distribution. For the ac power frequency, one could also analyze whether the breakdown happens on alternating polarity to confirm the possible charging effects.

ACKNOWLEDGMENT

The authors would like to thank Axel Kramer and Mariya Porus for their help with the sensor choice and the data acquisition system. They would also like to thank Maik Hyrenbach and Ole Granhaug for the fruitful discussion on C5-FK properties.

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