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ORIGINAL RESEARCH PAPER

# Temperature-dependent partial discharge characteristics of high temperature materials at DC voltage for hybrid propulsion systems

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**Abstract**

The safe and reliable operation of insulation material used in key high voltage components under extreme environmental conditions represents the major concerns for manufacturers and operators of More Electric Aircrafts (MEA). Surface discharge occurring in high current carrying components in DC power system diminishes the insulation material's performance and life, especially at high-temperature conditions. Here, the surface discharge behaviour of two commonly used high-temperature insulation materials, ethylene-tetrafluoroethylene (ETFE) and polyetheretherketone (PEEK) is studied at different temperatures under ramp and DC voltages. Extracted partial discharge (PD) features are presented and the impact of voltage polarity on surface discharge propagation is discussed. Our studies reveal that, while both materials exhibit non-linear PD behaviour with respect to their electrical conductivity, ETFE generally shows PDs with higher intensity at high temperature above 100°C with a higher possibility of surface discharge due to its lower permittivity. Overall, the PD mechanism in high-temperature, DC voltage applications is explored, and a basis for the selection of high-temperature PD suppressing materials is developed.

## 1 | INTRODUCTION

The vision of electrified propulsion with enhanced fuel efficiency and lower operation cost has inspired many studies [1–3]. However, primary and secondary distribution systems—responsible for transporting the power from the generation system to the converters, and from the converters to the loads respectively—are subjected to the harsh environmental conditions such as pressure, humidity and temperature variation, etc. Transition from the traditional power distribution system to the MEA requires a reliable electrical insulation system at a higher voltage level and higher power density under the above-mentioned conditions. Therefore, surface discharge as the main deteriorating factor of insulation of wires and cables has raised serious concerns about the expected lifetime of insulation system in the aerospace industry.

Among the main agents of surface discharge, the ionised gas particles around triple junctions, accumulated charges on the interface and in the insulation bulk, all having a significant contribution in the formation of the conductive and thermal channels that can facilitate the initiation of surface discharge over the insulation. Changes in the bulk property of the insulation material as well as the operating environment condition can introduce distinctively different partial discharge (PD) behaviours. For example, the DC conductivity of polymers has been recognized as one of the main insulation properties, whose value depends on temperature and electric field. In other words, the

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operating temperature can change the conductivity of insulation, and in turn introduce space charge accumulation, leading to a higher electric field gradient across the insulation [4–8]. Moreover, the electrical insulation properties have a significant impact on charge transport, injection, accumulation and recombination, affectingt the PD inception voltage and surface flashover. Also, the conductivity of the dielectric materials as one of the main factors affecting the charge behaviour has a non-linear dependency on temperature and can vary over several orders of magnitude from ambient to higher operating temperatures [9]. Under overload operation, heat can be transferred to the compartment where all the wires and cables are installed and increase the temperature in the compartment. Therefore, higher surface discharge intensity at elevated environmental temperatures can accelerate the degradation process of the insulation materials. Du et al. have studied the surface charge behaviour of some polymeric materials which shows the deeper trap level and lower trap density of charges at higher temperatures due to higher dissipation rate of energised electrons and ions [10, 11].

High-temperature insulation materials are widely used in the aerospace industry due to their excellent long-term chemical and mechanical resistance. Authors have already studied the PD behaviour of fluoropolymer-based insulated wires under AC and DC voltage at ambient and low pressure [12]. In addition, comprehensive investigations of the electrical properties of high-temperature materials including PI, PTFE, PEEK, FEP and ETFE have been thoroughly conducted and presented [13–15]. The non-linear conductivity dependency of these materials discussed in our previous work [13], however, characteristic of PDs initiated on the insulation surface due to non-uniform electric field intensity, as well as the temperature effect on this phenomenon, remain to be investigated thoroughly. In this paper, two commonly used insulation materials in the aerospace industry belonging to fluoropolymer and polyketone families, that is ETFE and PEEK were used for PD analysis at different temperatures under the ramp and DC voltages for both polarities. Possible causes for differences in recorded results and extracted PD features have been discussed.

## 2 | EXPERIMENT SETUP

### 2.1 | Test setup

The test samples are ETFE and PEEK flat plaques in size of size 8 × 8 cm and thickness 240 μm, are placed between brass electrodes. High voltage electrode is in a cylinder form of diameter 2cm and height 5cm, with smooth edges, while the ground electrode is another cylinder of 5 cm in both diameter and height. The whole test cell was housed inside an oven to adjust the compartment air temperature. Four temperature levels, that is, 25°C, 75°C, 100°C and 130°C, were chosen for the PD test, performed for 20 min after the temperature has reached a stable value. The relative ambient humidity was around 25%. A virgin sample was used for each test at different temperature levels, and both sides of the sample were cleaned using 75% anhydrous ethanol prior to the test to remove possible surface charges.

### 2.2 | PD test circuit and test procedure

Unlike PD test for AC voltage, no consensus has been reached regarding the DC PD test algorithm and data analysis; however, conventional PD measurement techniques in accordance with IEC 60,270 have been suggested for performing PD test under DC [9, 16]. Since the recorded PDs in DC test would be much smaller in magnitude than the AC test with also a much lower repetition rate, we have analysed all recorded PDs to ensure the validity of PD data and to reject external noises. All tests were performed inside a Faraday cage with a noise level lower than 15 PC. This noise magnitude is slightly higher than the suggested threshold by IEC 60,270, due to the higher sensitivity and capability of the instrument in measuring wide frequency range (16 kHz–48 MHz) with respect to IEC standard bandwidth (115–440 kHz).

AC PD circuit was equipped with a rectifier including the diode and smoothing capacitor set (90.4 nF) for rectification with negligible ripples [12, 14]. Figure 1 shows the PD circuit and test procedure followed in each test. We have already introduced different PD pattern representations based on time and frequency information of recorded PD data for the DC PD test [12, 14]. However, in this paper, other PD parameters such as PD count, and accumulative PD pulse magnitude (i.e. summation of the magnitude of preceding PD pulses) calculated from PD data for both polarities, are presented and discussed.

In each test, the voltage is increased with the rate of 200 V/s up to ±4 and ± 6 kV separately, and then, is fixed at a constant voltage value. The total recording time is 15 min; however, PD pulses initiated from the ramp voltage and during the fixed voltage have been separated. We detected the higher PD repetition rate and magnitude within the initial 30–40 s of the ramping time interval (as defined in Figure 1). However, this high repetition rate is reduced significantly in a couple of seconds after reaching the maximum voltage level in each test. In order to have a safe margin between the PDs that occurred

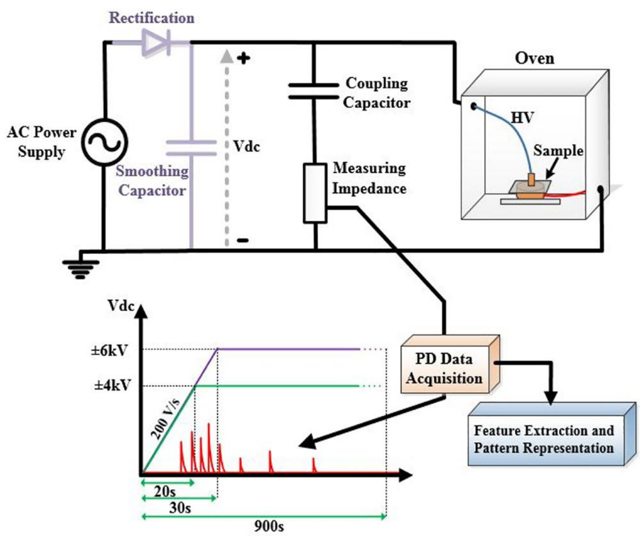


**FIGURE 1** Partial discharge (PD) test setup

during voltage ramping and the rest of the recording time, all the detected PDs in the first minute of recording are assigned to the voltage ramping interval, and the rest of the detected PDs to the stable fixed voltage interval.

As shown in Figure 1, PD measurement was carried out for a 15-min duration after the voltage ramping. The voltage ramping rate for all tests was adjusted to 200 V/s which takes 20 and 30 s to reach 4 and 6 kV, respectively. In order to evaluate the impact of electric field intensity on surface discharge behaviour at different temperatures, 4 kV and 6 kV were applied in a separate test on virgin samples. Also, both positive and negative polarities at the same voltage levels were separately applied to the new samples by inverting the diode in order to study positive and negative streamer discharge progression over the samples' surface. In this section, different parameters of recorded PD data such as PD number, PD pulse magnitude, accumulative PD pulse magnitudes have been presented for both ramp and DC voltage tests. Although the ramp voltage and its rate prior to the fixed DC voltage have a history effect on the PD behaviour during fixed voltage test due to the surface charge accumulation and the free charge liberation from the metal electrode, PD pulse magnitude and repetition rate are significantly different during voltage ramp and fixed voltage duration. Therefore, we conduct the above-mentioned testing procedure on all the samples to study the DC PD test to compare the insulation performance of dielectric materials at the same condition.

## 3 | RESULTS

Figure 2 shows detected PD sequences and accumulated PD pulse magnitudes over one entire test procedure. Higher PD repetition rate with ascending PD pulse magnitude due to PDs with higher magnitudes are observed during voltage ramp. As can be seen, PD progression is continued for longer than 20 s (duration of voltage ramping up to 4 kV) and it settles down in less than a minute. The same trend was observed for tests up to 6 kV with a ramping duration of 30 s. Hence PD data recorded after 1 min of test, with different characteristics, has been assigned for DC voltage test.

The environmental temperature has a non-linear impact on PD activity. It is observed that the PD count or accumulative magnitude not only increase linearly with temperature, but also the trend of changes for these two parameters versus temperature has not been found to be the same. More detailed information about the differences and possible cause is illustrated using the following results presented in this section.

For the voltage ramping interval, Figure 3 shows accumulated PD pulse magnitude values calculated at different temperatures for both PEEK and ETFE, with both polarities. Figure 3(a) shows the accumulative PD pulse magnitude results up to 4 kV, which has a similar trend observed during voltage ramping up to 6 kV as given in Figure 3(b). The magnitude of PD pulses that occurred at 6 kV is higher than 4 kV as expected. However, a significant increase can be seen at 130°C and positive polarity, especially for ETFE. Also, the PD magnitude trend when increasing the temperature at negative polarity generally has less change than that at positive polarity.

Number of detected PDs corresponding to the results in Figure 3 can be found in Table 1 for both test samples at different test conditions. As can be seen, in most cases, the number of PDs occurred for positive polarity is generally higher than that at negative polarity at all temperatures, the same as accumulative PD pulse magnitude results. Results show that the number of PDs has an opposite trend for PEEK and ETFE. Also, a similar trend is observed for both polarities for each dielectric material. On increasing the temperature, PD count ascends and then descends for PEEK in both polarities; while under the same condition, this parameter first decreases and then increases for ETFE.

This trend can also be seen clearly in accumulative PD pulse magnitude at 6 kV. Another significant observation is that this number of PDs is respectively lower for ETFE at

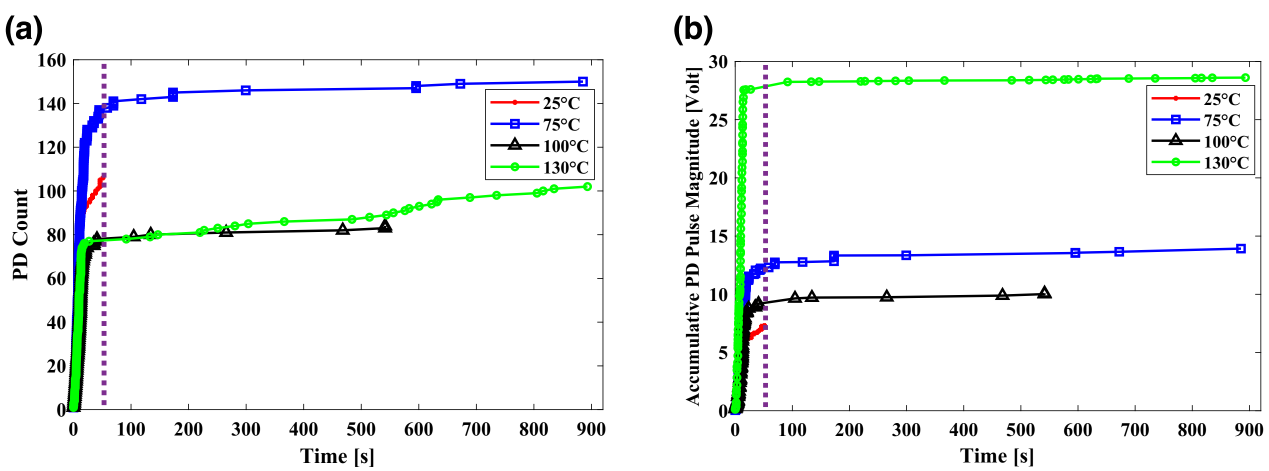


**FIGURE 2** Partial discharge (PD) count (a) and accumulative PD pulse magnitude (b) plots during positive ramp and DC voltage test up to 4 kV for PEEK at different temperatures

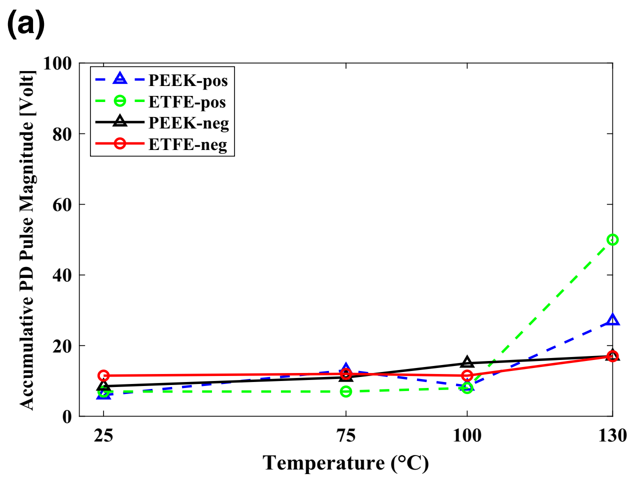


**FIGURE 3** Accumulative PD pulse magnitude for ramping voltage at different temperatures up to: (a) 4 kV, (b) 6 kV

**TABLE 1** Detected number of PDs during ramping the voltage at different temperatures

| | PEEK | | | | ETFE | | | |
|---|---|---|---|---|---|---|---|---|
| Temperature | +4 kV | +6 kV | −4 kV | −6 kV | +4 kV | +6 kV | −4 kV | −6 kV |
| 25°C | 106 | 126 | 96 | 197 | 145 | 257 | 88 | 158 |
| 75°C | 141 | 322 | 97 | 255 | 37 | 97 | 77 | 120 |
| 100°C | 78 | 243 | 99 | 185 | 99 | 265 | 57 | 144 |
| 130°C | 78 | 98 | 109 | 180 | 337 | 1582 | 119 | 303 |

Abbreviations: PD, partial discharge; PEEK, polyetheretherketone; ETFE, ethylene-tetrafluoroethylene.

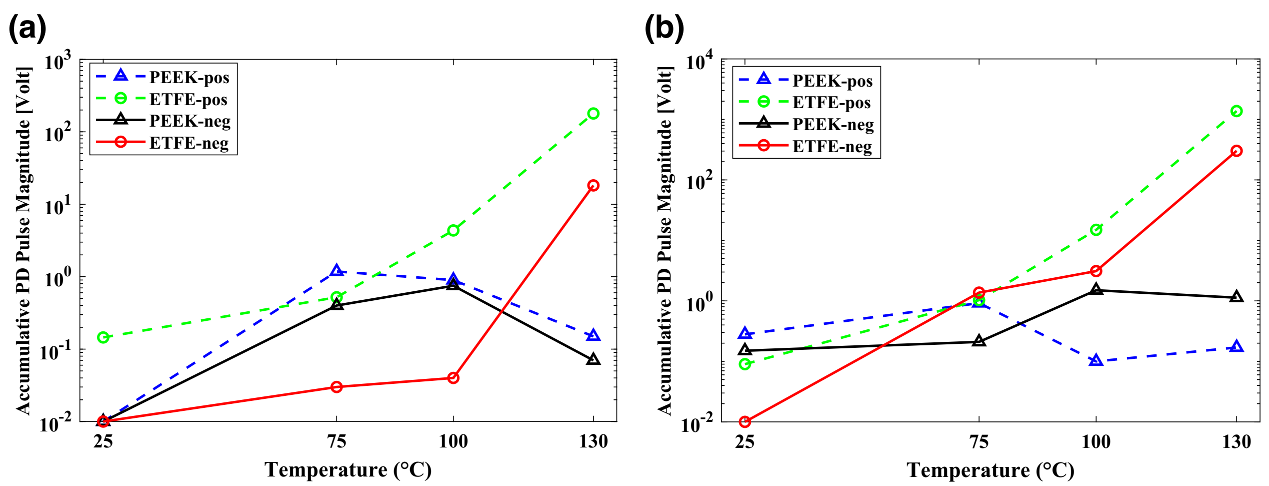


**FIGURE 4** Accumulative partial discharge (PD) pulse magnitude for the fixed DC voltage at different temperatures up to: (a) 4 kV, and (b) 6kV

temperatures around 75°C and at temperatures higher than 100°C. Also, PEEK has a lower PD count at temperatures higher than 100°C compared to lower temperatures, that is 25°C and 75°C. Our conductivity tests show non-linear behaviour at temperatures higher than 130°C, hence it is not suggested to assume any uniform increasing or decreasing trend at higher temperatures. For example, a downward trend of detected PD numbers at 130°C can be changed at temperatures beyond this value [13].

Figure 4 shows a log plot of accumulative PD pulse magnitudes calculated during 14 min at the fixed DC voltage (zero values are assigned with a log value of 0.01 for better representation of the stacked line graph). The accurate number of detected PD pulses ($n$) and accumulative PD pulse magnitude values ($Q_T$) shown in Figure 4 are given in Table 2. A similar PD pulse magnitude trend is observed for DC voltage as presented for a ramp voltage in Figure 3. This parameter for positive polarity is higher at 75°C for PEEK and decreases at

**TABLE 2** Detected number of PDs and accumulative magnitudes for fixed DC voltage at different temperatures

| | PEEK | | | | | | | | ETFE | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | +4 kV | | +6 kV | | −4 kV | | −6 kV | | +4 kV | | +6 kV | | −4 kV | | −6 kV | |
| **Temperature** | ***n*** | $Q_T$ | ***N*** | $Q_T$ | ***N*** | $Q_T$ | ***N*** | $Q_T$ | ***N*** | $Q_T$ | ***n*** | $Q_T$ | ***n*** | $Q_T$ | ***n*** | $Q_T$ |
| 25°C | 0 | 0 | 1 | 0.28 | 0 | 0 | 2 | 0.15 | 2 | 0.15 | 6 | 0.09 | 0 | 0 | 0 | 0 |
| 75°C | 9 | 1.18 | 4 | 0.92 | 4 | 0.4 | 2 | 0.21 | 1 | 0.52 | 4 | 1.03 | 1 | 0.03 | 3 | 1.37 |
| 100°C | 6 | 0.9 | 0 | 0 | 5 | 0.75 | 3 | 1.5 | 32 | 4.35 | 154 | 14.94 | 1 | 0.04 | 9 | 3.11 |
| 130°C | 24 | 0.15 | 17 | 0.17 | 1 | 0.07 | 5 | 1.13 | 3,900 | 179 | 8,418 | 1,375 | 78 | 18.2 | 1018 | 302 |

Abbreviations: PD, partial discharge; PEEK, polyetheretherketone; ETFE, ethylene-tetrafluoroethylene.

higher temperatures, while it increases with temperature, especially at higher electric field intensity. For negative polarity, the highest PD pulse magnitude value for PEEK is at 100°C and it reduces at 130°C; however, this parameter has an upward trend for ETFE with respect to temperature and electric field density. A sharp increase of curve at 100°C is due to a higher calculated value at 130°C for ETFE. A lower vertical range is chosen in Figure 4 in order to demonstrate the trend at lower temperature values; however, accurate values especially at 130°C can be found in Table 2. The higher value of accumulative PD pulse magnitude for ETFE during ramp and DC voltage given in Figures 3 and 4 at 130°C can be associated with a higher PD repetition rate. Since the number of detected PD pulses for DC voltage is too low and can vary within 20% interval based on our repeated test results, it cannot be discussed for DC voltage unlike the ramp voltage results. Therefore, PD behaviour can be evaluated based on accumulative PD pulse magnitude values with both number and magnitude information of detected PD pulses. Also, it is noteworthy that the number of detected PDs and PD pulse magnitude are higher for positive polarity than negative polarity, similar to the results presented for ramp voltage.

In order to assess the PD activity during the whole process of the test including the voltage ramping and stable DC interval, PD pulse magnitude average plot versus recording time at different test conditions can be found in Figures 5 and 6.

PD pulse magnitude average at each PD incident point is defined by dividing the summation of recorded preceding PD magnitudes (which named accumulative PD magnitudes) by the number of detected PDs. The upward trend demonstrates the increase in PD pulse magnitude over time, especially during the voltage ramp. The curve is decreased and stabilised (flat section of the curve) when the voltage is adjusted in a defined fixed level and PDs with lower magnitude occur. A continuous ascending trend is observed in one of the cases arising from the fast progression of the streamer and transition from surface discharge to the creepage discharge. In most cases, plots have not been sketched to the end of the PD test runtime, which means that there is no further PD development and progression at the second stage of the test (fixed DC voltage). It should be noted that the incident time of the first recorded PD is the reference value for the test. Therefore, the time duration of the first stage where the PD pulse magnitude average increases is lower than the adjusted time for voltage ramping which is 20 and 30 s for 4 kV and 6 kV, respectively. Also, it can be seen that the possible PD continuation and stabilised plot can be achieved within 15-min recording time, which means that the proposed test time duration for DC test for adjusted and defined PD detection sensitivity is reasonable.

Overall, it can be found that the time scale in these plots makes it possible to investigate the continuation and propagation of PDs at the DC voltage which cannot be concluded from previous results presented in Figures 3 and 4. Generally, the PD continuation was not observed for both samples at 25°C. The PD activity at positive polarity has more consistency at 75°C for PEEK sample, and at 100°C for EFTE; while, there is a direct relation between PD consistency and temperature for extracted results at negative polarity. ETFE sample has a significantly higher PD repetition rate than PEEK at 130°C, and, this factor is much higher for positive polarity than negative polarity. Also, the possibility of PD continuation at positive polarity is generally higher than negative polarity.

## 4 | DISCUSSION

### 4.1 | DC conductivity

Different electrical properties of high temperature insulation materials including conductivity, space charge characteristic, surface flashover, surface anti-erosion properties and partial discharge behaviour at pressure variation have been thoroughly investigated and explained in our previous research works [13–15]. As explained in Section 1, conductivity is one of the influencing factors which can determine PD behaviour at DC voltage. Using the electrode configuration defined by the ASTM standard [16], DC conductivity measurement at different electric field values has been conducted for these samples inside the oven for wide range of temperatures (at 25°C, 50°C, 100°C and 150°C), as shown in Figure 7.

These results show non-linear relation between conductivity and environmental temperature, especially for ETFE. Also, it shows the same trend for these two materials at

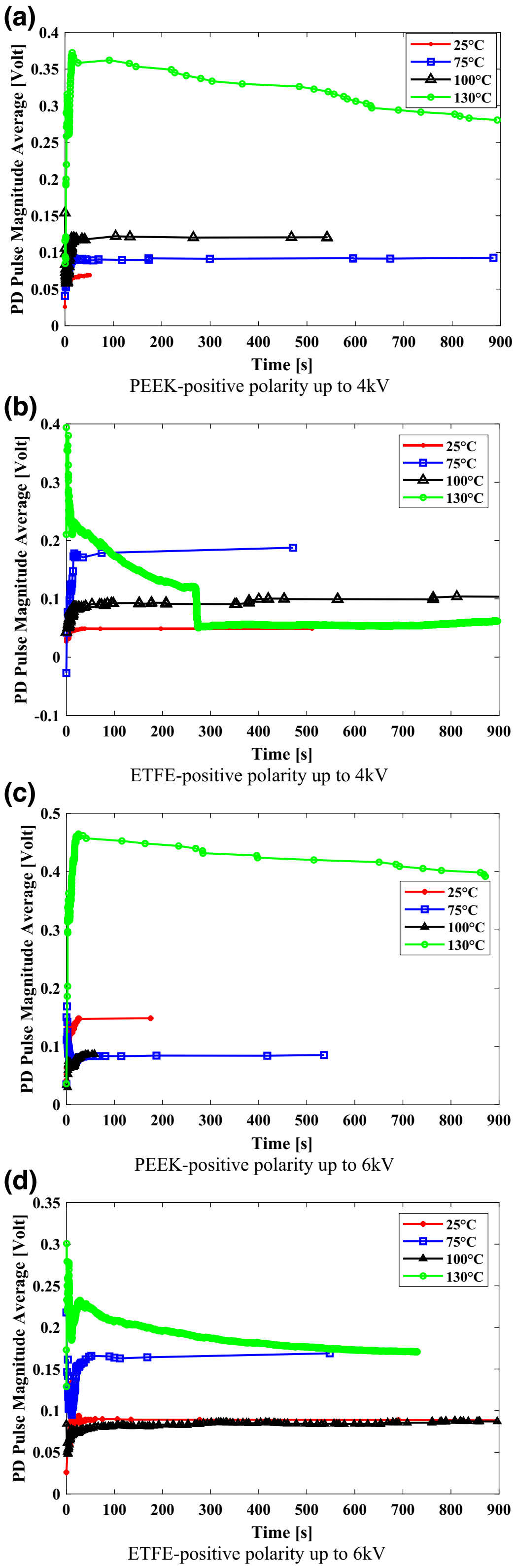


**FIGURE 5** Partial discharge (PD) pulse magnitude average plots over time for positive polarity at different temperature ranges

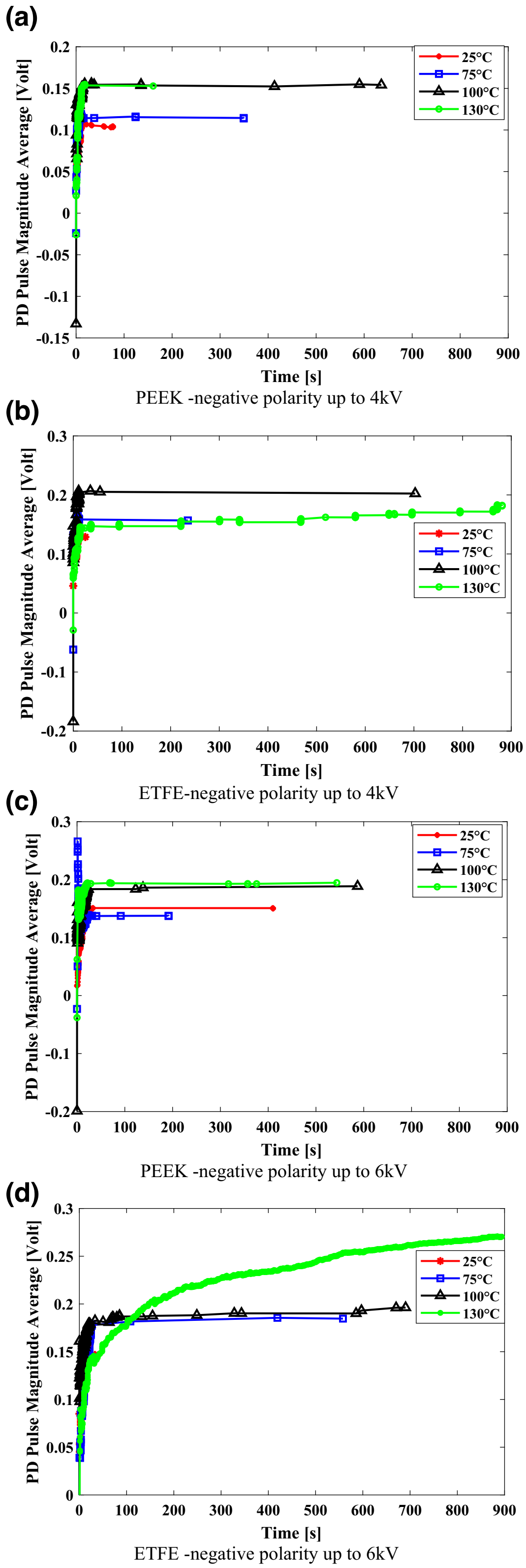


**FIGURE 6** Partial discharge (PD) pulse magnitude average plots over time for negative polarity at different temperature ranges

different electric field values, which implies that the applied voltage corresponding to the electric fields ranging from 10 to 30 kV/mm should not have a significant impact on the conductivity values. PD activity with higher intensity for ETFE at 130°C especially at positive polarity can be associated with higher conductivity values. Unlike ETFE, a slight change in

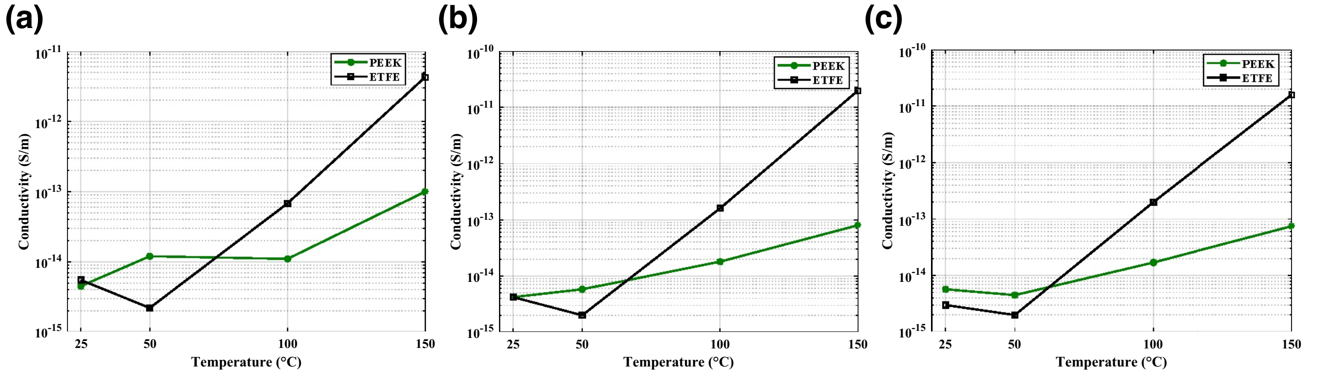


**FIGURE 7** Conductivity in the range of 25°C–150°C under different electric fields: (a) 10 kV/mm, (b) 20 kV/mm and (c) 30 kV/mm [13]

conductivity can be seen for PEEK between 50°C and 100°C which is generally compatible with obtained results for the second DC stage given in Table 2, indicating that the PD count can vary within 20% interval among repeated test results as mentioned before.

## 4.2 | Polarity impact

In order to discuss the influence of polarity on PD behaviour, the mechanism behind the dominant charges for both polarities as well as the streamers interaction with the interface of insulation materials should be investigated. Environmental gas pressure and composition affecting the photoionisation process and photoemission from the surface further complicate the problem. However, the impact of pressure has been separately discussed in our previous research paper [14]. A common agreement among the researchers about the positive and negative streamers in the gas based on the experimental tests and numerical modelling results is that positive streamers are relatively easier to initiate with respect to negative streamers [17, 18]; however, the interaction of the solid with the streamer at different temperatures requires a further discussion about the mechanism of both streamers along the dielectric surface.

To elaborate upon the theory of streamer discharge at different polarities, the electrons as the dominant charged particles in the anode-directed streamers in the negative polarity of voltage move away from the high voltage electrode with the electron drift velocity which is a function of the tangential electric field on the gas/solid interface of our configuration. When the temperature is not high enough, the dominant perpendicular electric field of electrode configuration increases the recombination process and the drift of charges into the solid bulk which can be a restraining factor for discharge across the surface. The same influence of electric field can be described for the cathode-directed streamer at the positive polarity of the voltage. Although positive ions have much lower mobility than electrons, charged particles with high energy at the streamer tip are propelled by photoemission and photoionisation process. Also, study results in [19, 20] show that the effect of secondary electron emission induced by the photons from the surface for both polarities is negligible which might not cause a significant difference in streamer development and PD properties for both polarities at higher temperatures. Other key factors defining the local electric field in the gas/solid interface, before and after each discharge incident, are the surface charge accumulation and charge decay which need to be deeply investigated in a separate study. To the best of the author's knowledge, the impact of temperature on these processes for positive and negative streamers has not been thoroughly studied which makes further discussions difficult.

Generally, our results in Figures 5 and 6 show relatively higher repetition rate during the recording time, a higher value of average PD pulse magnitudes at highest temperature (130°C) as well as a higher possibility of PD continuation for positive with respect to the negative surface discharges. The main reason behind this observation could be the fact that the high localised dense positive charges on positive streamers' tip released with higher energy and magnitude at higher temperatures on the surface making them easier to be detected, while the electrons show more diffusive behaviour with lower charge density in negative streamers' tips. Also, simulation results show that positive streamers hover over the dielectric surface without attaching to the surface, because the electron ionization requires some distance to happen and to feed the positive streamer tip for further development during the discharge process [20–22]. This shows less interaction of positive streamers with the dielectric surface, and possibly less trapping and recombination of positive ions. However, this hypothesis requires extensive studies for verification.

## 4.3 | Gas/solid interface

Interaction of the charged particles (i.e. electrons, and positive and negative ions) in the air during the discharge process such as diffusion, recombination and drift have a short-term memory effect. While, the presence of solid dielectric introduces more complicated charged particle activities with short- and long-term effects which can significantly affect the streamer progression over the dielectric surface. The major factors determining the PD behaviour in the gas/solid interface are as follows:

- Electric field components: The perpendicular component of the electric field lines is mainly concentrated around the so-called triple junction region and forces free electrons to ionise the gas required for ion-bombardment for the discharge process. Liberated positive ions with lower drift velocity intend to drift towards the solid surface in the attached electrode configuration to the dielectric, while electrons drift away from the surface due to the tangential electric field because of their higher velocity. Therefore, the streamer on the dielectric surface is driven by the tangential electrical field component which forces the charged particles to propagate along the surface [19]. That being so, the increase in applied voltage and electric field intensity has a significant impact on the bombardment of the dielectric with liberated dominant charges, higher drift and energy of charge particles due to high tangential electric fields at the streamer tips; and in turn, the intensity of PDs including PD count and their magnitude as can be seen for PD results at a higher voltage (±6 kV) compared to to the lower voltage (±4 kV).
- Dominant charge polarity: these dominant carriers are defined by applied voltage polarity which has been discussed in Section 4.2. A positive streamer initiated under positive polarity can force the positive ions to drift towards the dielectric along the perpendicular electric field and bombard the surface, and then, the streamer development occurs along the dielectric surface. The intensified tangential electric field at the head of the streamer can push the positive ions forward until charged particles are not sufficient to ionise the gas due to recombination and drift of positive ions attributable to the perpendicular electric force, while, the free electrons liberated from the cathode, spread easily on the surface and drift away from the cathode. These electrons have more chance to be injected into the dielectric and recombine with holes in the traps. As discussed earlier, positive streamers with less interaction with the dielectric surface have shown a higher chance of repetition at higher temperatures with respect to the negative streamers as shown in Figures 5 and 6.
- Dielectric permittivity: It has been found that the attraction of the streamer to the dielectric during surface discharge propagation is mainly due to the electrostatic interaction. The speed of this attraction depends on the maximum electric field of the streamer due to the net charge at the streamer head. These charges polarise the dielectric surface and increase the electric field between the dielectric and the streamer which results in faster attachment of the streamer to the dielectric surface. Also, a higher quantity of homo-charge accumulation for a dielectric with higher permittivity can weaken the ionization process ahead of the discharges as reported in [23]. Besides, the relative permittivity of ETFE with descending trend from 2.55 at 25°C to 2.45 at 130°C (measured at 1.15 kHz in [24]) is lower than the permittivity of PEEK reported around 3.3 [25]. Taking into account the factors aforementioned, the PD continuation with a lower possibility for PEEK with respect to ETFE during the second stage of the tests on the samples can be partially associated with higher permittivity of PEEK than ETFE. However, high PD intensity at 130°C with respect to other temperatures for both samples is due to higher conductivity at this temperature as discussed in Section 4.1.

## 5 | CONCLUSIONS

In this paper, the surface discharge behaviour of two commonly used insulation dielectric, PEEK and ETFE, is investigated and presented at different temperatures. Our main findings are summarised below:

(i). High electrical DC conductivity and its gradient can be two main factors in facilitating the PD occurrence; however, the dependency of this parameter to the temperature and non-linear trend of measured conductivity make the evaluation of the PD performance of these two materials more difficult, except for temperatures higher than 100°C under which ETFE shows significantly higher conductivity than PEEK.

(ii). Magnitude of positive and negative streamers for PEEK is increasing first and then decreasing with a peak between 75°C and 100°C for both ramp and DC voltage, while this value for ETFE shows a uniformly rising trend for elevated temperatures.

(iii). The lower permittivity of ETFE with respect to the PEEK has been considered as the reason behind the possible PD continuation that is, higher observed PD pulses during the second stage of the test for fixed DC voltage.

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