Contribution to the Study of Surface Discharges Under Aeronautic Pressure Constraint

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RESUME –The aim of this work is to present the results of flashover voltage (FOV) of various solid insulating materials used in connectors for aircrafts. The effect of air pressure, insulating materials and electric field direction are investigated and analysed.

Keywords—Surface Discharges - Aeronautic – High Voltage - Electrical Insulating Materials – Electric Field Direction – Air Pressure – Flashover Voltage.

1. INTRODUCTION

The recent advancements in more electric aircraft and all electric aircraft impose higher voltages that stress the electrical insulation systems [1]-[3]. One of the consequences is the surface electrical breakdown (or flashover -FO). The final result is the apparition of an electric arc at the surface of the insulating material. The surface state of the material (clean, polluted, humidified) and its intrinsic characteristics, the voltage waveform, the electric field configuration and direction, and the air pressure are the major parameters defining the inception and the propagation of surface discharges.

In the standard IEC 60664-1 [5], clearance distances for various altitudes for aeronautical applications are defined. But, for creepage distances (CRD), set apart that only atmospheric pressure (sea level) is considered, the standard gives the CRD in contrast to the withstand voltage for different pollution degrees and material groups based on tracking resistance. For determining the CRD, only arc tracking resistance—as defined by comparative tracking index (CTI) tests in standard IEC 60112 [6] is used. On the other hand, the CTI tests do not indicate the effect of altitude.

Despite the limited work in the literature related to surface discharges in the aeronautical context, some recently published works have presented interesting results on surface discharges in the aeronautical context [7]-[13]. In [9]-[11], different electrode shapes were used for investigating the effect of air pressure and insulating materials on partial discharge inception voltage (PDIV) and FOV while keeping the CRD constant. The results showed that PDIV, FOV and the morphology of the surface discharges depend on air pressure. The results also showed that during the pre-flashover stage, the surface discharge behaviour is "glow and diffuse" for pressures between 90 mbar and 500 mbar, and "micro-filaments" above 500 mbar. Despite those recent works, the effect of tangential and normal electric fields have not been deeply investigated yet."

This study contributes to a better understanding of the effect of air pressure, the direction of the electric field and the nature of the insulating material on the surface dielectric strength.

2. EXPERIMENTAL SETUP & METHODOLOGY

The experimental setup is illustrated in the Figure 1. It constitutes of high voltage generator TREK 10 kV/40 mA, a climate chamber where pressure and temperature are controlled and the experimental cell is installed; and include a differential voltage probe, a partial discharge sensor (Jack-SMA), a high frequency current transformer (Bergoz), a high performance oscilloscope and a fast camera. The experimental cell is designed for setting the CRD by adjusting the distance between the electrodes (stainless steel). The electrodes are semi-cylindrical blocks with hemispherical shape at the extremities and are placed over the insulating material sample. The system is operated with a MATLAB code offering the possibility to control the voltage ramp speed and recording both PDIV and
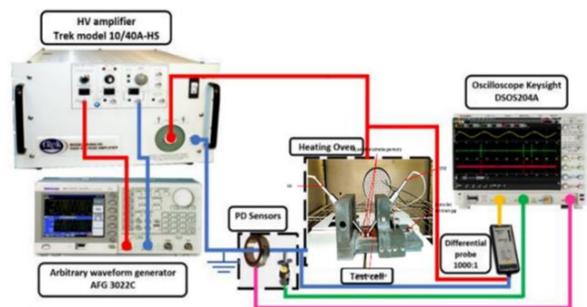

FOV.

Fig. 1. Experimental Setup.

The used insulating materials are silicone rubber, filled PEEK and PEKK and their characteristics are presented in Table 1. All the tests are achieved with dry and clean condition corresponding to pollution degree 1 according to IEC 60664-1 [5]. The ac (50 Hz) voltage ramp speed is fixed at 50 V/s and

the pressures are (mbar): 90-250-500-750-1000. Two electric field directions are considered: tangential TE and combined CE
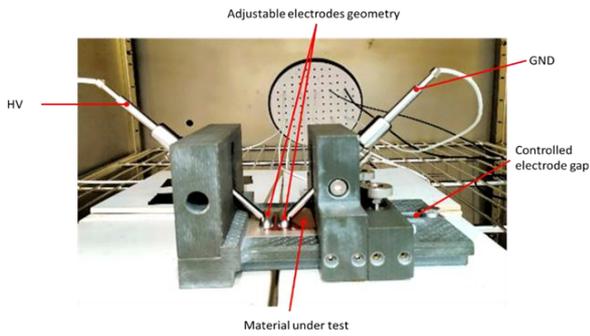
(back-electrode under the sample) as illustrated in Figure 3-a.

Fig. 2. Creepage cell

(a): Electrodes and Electrical Field Orientations.
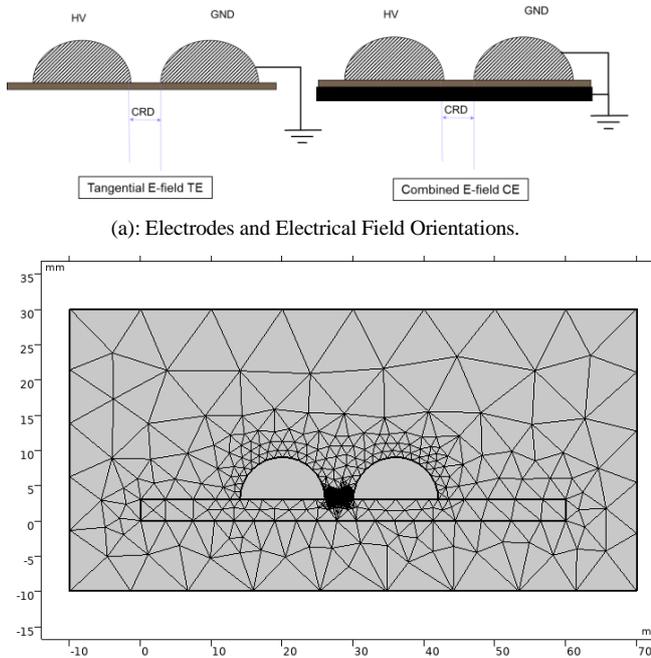
(b): Meshing.
Fig. 3. Electrodes arrangement and meshing.

The procedure is to apply the voltage until the appearance of the first several surface partial discharges. At this moment, the PDIV is recorded and the voltage continued to increase until FO and the FOV is recorded. The procedure is repeated 5 times per sample per pressure. In this paper, only average peak values of FOV are presented.

A FEM simulation (COMSOL Electrostatic software tool) have been achieved for evaluating the characteristics of both electric field (E-field) orientations (Fig. 3-a). The characteristics of the system are illustrated in Table 1.
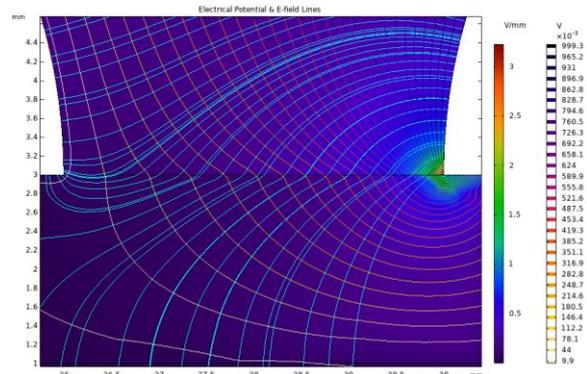
Table 1. Characteristics of the materials and the electrodes.

Element	Permittivity	Shape and Dimensions
Electrodes	1	Diameter 6 mm Length 40 mm
Dielectric B-PEEK	5.6	Square 75 mm x 75 mm x 3 mm

Dielectric Silicone (SiR)	4.4	Square 65 mm x 65 mm x 3 mm
Dielectric PEKK	3.5	Disc Diameter 60 mm Thickness 3mm
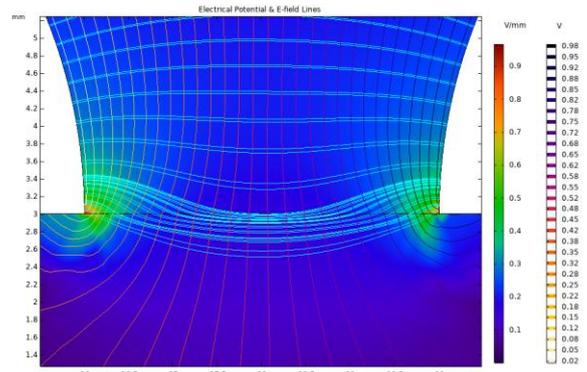
(a)   TE orientation.

(b)   CE orientation.

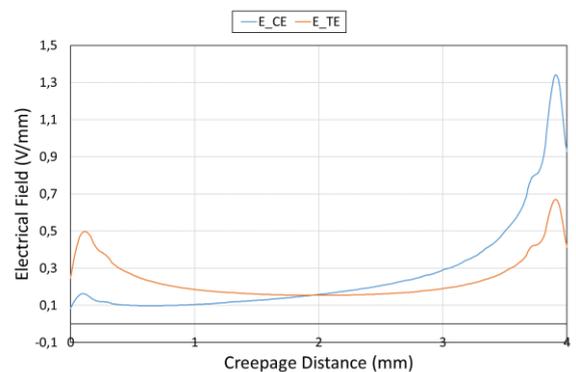Fig. 4. Electric field mapping and equipotential lines distribution based on COMSOL simulation

Fig. 5. Electrical field distribution along the CRD for both E-field orientations.

3. RESULTS & DISCUSSION

Fig.6 illustrates the results of FOV as a function of air pressure of each insulating material for both E-field orientations. The first remark is that FOV increases with air pressure for both configurations whatever the insulating material and E-field orientation. The second observation is that FOVs corresponding to TE orientation are higher than the ones for CE orientation for all insulating materials. The main reason is that the E-field lines penetrate deeply in the solid dielectric

in the case of CE orientation compared to TE orientation where the E-field lines are close to the surface (Fig. 4). On the other hand, according to Fig. 5, CE orientation electric field magnitude at the triple point of HV electrode is higher than the TE orientation ones. This implies that the CE orientation is the worst case.

Fig. 7 presents the comparison between the materials versus the air pressure for both E-field orientations. The results show that for TE orientation, PEKK presents the best performances, followed by SiR, and the last one is B-PEEK. In the case of TE orientation, at 90 mbar, the insulating material does not affect considerably FOV values in opposition of the upper pressures. For 250 mbar, both of SiR and B-PEEK present close FOV values. In the case of CE orientation, in the range 90 mbar – 250 mbar, FOV of all the insulating material are similar. B-PEEK presents the lowest FOV at 500 mbar while SiR and PEKK are close. Above this pressure, PEKK presents the highest FOV values, followed by SiR.

Regarding the materials performance classification for both E-field orientation, PEKK presents the best performances, followed by the SiR and the B-PEEK. There is a correlation between FOV and permittivity of the materials classification.

Based on Paschen's law, the breakdown voltage of a uniform gap is governed by

$$V_b = \frac{Bpd}{\ln\left\{ Apd \Big/ \ln\left(\frac{1}{\gamma}\right) \right\}} \qquad (1)$$

where A is the saturation ionization in gas, B is the energy of excitation and γ is the coefficient of secondary ionization. For dry air, these parameters have the following values: A = 15 $(\text{torr. cm})^{-1}$, B = 365 $\text{V}(\text{torr. cm})^{-1}$, and $\gamma = 0.01$ [19-20].

In the following, Eqt (1) is applied for a uniform gap with 4 mm clearance and compared with flashover experimental data as illustrated in Figures 6 and 7. Results of Figure 6 show that Paschen's law are close to flashover data only at low pressure (90 mbar) for the CE orientation. For higher pressures, the difference between flashover data and Paschen's law increase with the pressure rising. In Figure 7, corresponding to TE orientation, flashover data are lower than Paschen's law results whatever the pressure. Those results give indication about the probable flashover discharge physics. Indeed, for TE orientation at low pressure, the flashover propagation seems controlled by the secondary emission from the metallic electrodes and the solid dielectric. When the pressure increases, the secondary emission is mainly controlled by the dielectric up to 250 mbar. When pressure rise up 1000 mbar, the photo-ionization probably plays a role in the secondary emission as suggested in a previous work [11]. Regarding the CE orientation, the results suggest that the secondary emission is controlled by the solid dielectric and the photo-ionization.

Based on those results, it seems clear that Paschen's law is not applicable for flashover voltage calculation. This is why an empirical approach is preferred. In fact, from the experimental results, it is possible to deduce an empirical relationship of FOV as function of air pressure

$$FOV = Ap^a \qquad (1)$$

where p is the air pressure, and A and a are the interpolation parameters which depend on insulating materials and electrical field orientation.

$$A = K_1 \varepsilon_r^2 + K_2 \varepsilon_r + K_3 \qquad (2)$$
$$a = k_1 \varepsilon_r^2 + k_2 \varepsilon_r + k_3 \qquad (3)$$

Table 2 presents the values of the parameters A and a for each insulating material. From Table 2, it is possible to deduce by interpolation the relationship between the parameters A and a, and the insulating materials permittivity and the result show that A and a can be approximated with a polynomial law as a function of the permittivity ε_r accordingly.

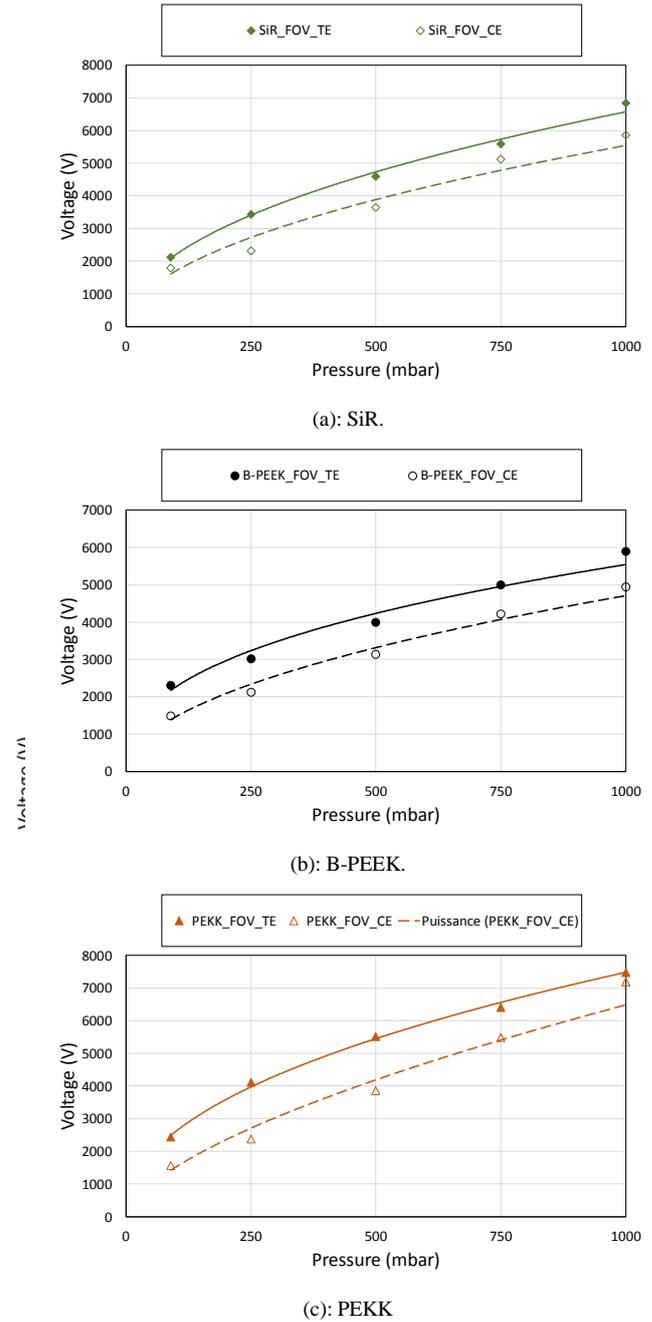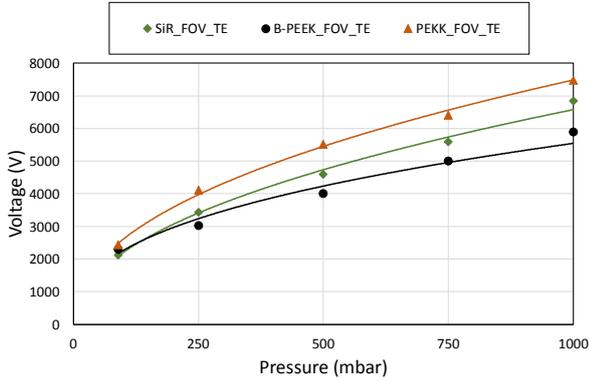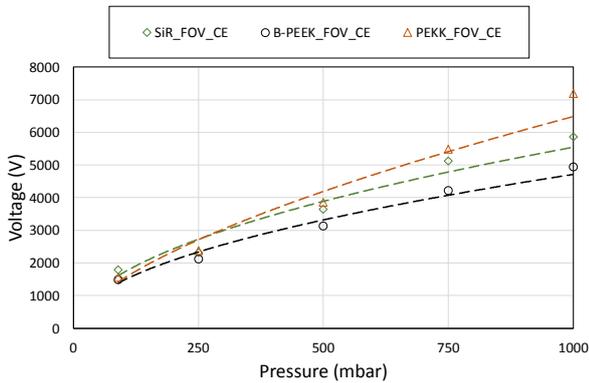(a): SiR.

(b): B-PEEK.

(c): PEKK

Fig. 6. Variations of FOV with air pressure of each insulating materials and both electrical field orientations.

Table 2. Values of the parameters A and a of Equation (1).

Parameters	A		a	
E-field	TE	CE	TE	CE
B-PEEK	248.470	83.472	0.4742	0.6301
SiR	378.560	160.660	0.3886	0.5127
PEKK	318.120	142.210	0.4572	0.5068

(a) TE orientation

(b) CE orientation

Fig. 7. Variations of FOV with air pressure for all insulating materials for each electrical field orientations.

Table 3. Values of the parameters of Equations (2) and (3).

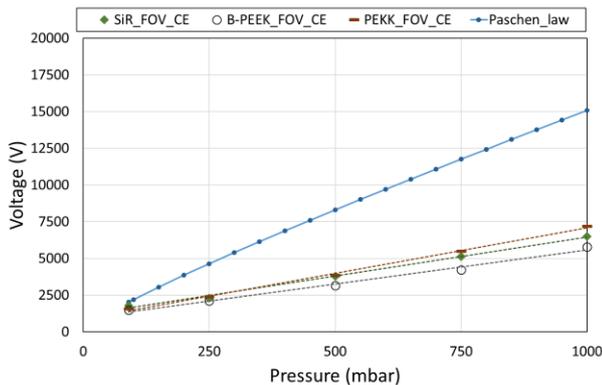| Parameters	K_1	K_2	K_3	k_1	k_2	k_3
TE	-76.749	659.08	-1035.5	0.0636	-0.5647	1.6420
CE	-37.624	311.92	-483.38	0.0418	-0.3200	1.1119

Fig. 8. Comparison of Paschen's law and FOV for various air pressure and 4 mm gap for all insulating materials for CE orientations.
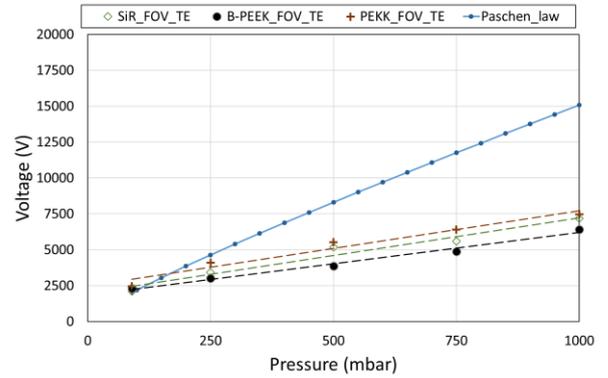

Fig. 9. Comparison of Paschen's law and FOV for various air pressure and 4 mm gap for all insulating materials for TE orientations.

4. CONCLUSIONS

This work aimed to investigate the influence of the electrical field orientation and the nature of electrical insulating material on FOV under aeronautic air pressures. The main conclusions are:

- FOV increase with air pressure and correlate with used the insulating materials permittivity.
- The configuration CE is the worst case.
- In the range of pressure 90 mbar to 250 mbar, FOV of all materials are close.
- Paschen's law is not applicable for FOV calculation.
- The relationship between FOV and air pressure can follow a power law where the parameters depend on material characteristics and electrical field orientation.

The determination of the variation of the parameters A and a of FOV's equation is the next step of this work.

5. ACKNOWLEDGEMENTS

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