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A New Empirical Expression of the Breakdown Voltage for Combined Variations of Temperature and Pressure

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Abstract**—**In aircraft applications, according to the nature of electrical equipment its location may be in unpressurized area or very close to the engine; thus, the environmental conditions may change from atmospheric pressure to less than 100 mbar, and the temperature may be higher than the ambient one as in most real working conditions of electrical equipment. Then, the classical Paschen curve has to be replotted since these parameters may affect the discharge ignition voltage. In this paper, we firstly investigate the domain of validity of two corrective expressions on the Paschen's law found in the literature, in case of changing the air environment and known as Peek and Dunbar corrections. Results show that these corrections are no longer valid for combined variation of temperature and pressure. After that, a new empirical expression for breakdown voltage is proposed and is validated in the case of combined variations of temperature and pressure.

Keywords**—**Gas breakdown, gas density, Paschen curve, temperature effects

I. Introduction

ELECTRICAL and electronic equipments in aircraft applications must be designed to operate over a wide range of pressure and temperature. According to the nature of electrical equipment, its location may be in unpressurized area; thus, the environment conditions may change from atmospheric pressure to less than 76torr, and the temperature rises close to the reactors and may be higher than the ambient one. In our study for this application, we are interested in combined variations of temperature and pressure, which is the case of equipment in unpressurized area and near the reactors.

The electric breakdown strength of gases and vapors from high pressures to vacuum is the subject of a very extensive literature. A very old but still useful description of breakdown in gases is that known as the Paschen law [1].Paschen theory is established under normal conditions of pressure, temperature (T_0 = 293K, p_0 = 760 Torr) and an absolute humidity of 11g/m^3 [2]-[3]. This law essentially states that the breakdown voltage of a gap is a function of the product of the gas pressure p and the gap length d [$V_B=f(pd)$].

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The product pd is a measure of the number of collisions that an electron makes while crossing the gap. Thus, an analytical expression may be found for the breakdown voltage:

$$V_B = B\frac{pd}{C+\ln pd} \quad with \quad C = \ln\left(\frac{A}{\ln(1+\frac{1}{\gamma})}\right) \tag{1}$$

Where A and B are gas dependent coefficients found experimentally. The value of A and B for air are valid for the range of E/P between 150-600 V.Torr^{-1}.cm^{-1} as A = 15 Torr^{-1}.cm^{-1}, B = 365 V.Torr^{-1}.cm^{-1} [3], and $\gamma = 3*10^{-3}$, therefore C is equal to 0.95.

However, it is well known that the breakdown voltage of the air gap is affected by atmospheric conditions, mainly by the combination of air pressure p and temperature T. Under certain conditions, the Paschen theory is not valid anymore.

Discussions on the effects of temperature and pressure on the breakdown voltage are usually focused on the variation of the relative air density given by the relation:

$$\delta = \frac{P}{P_0} * \frac{T_0}{T} \tag{2}$$

where p and T are the current pressure and temperature, and p_0 = 760 Torr and T_0 = 293K values corresponding to the standard atmospheric condition.

Considering a breakdown voltage V_0 under p_0, T_0 conditions, the IEC rules [4] for the adjustment of the voltage V under any p, T condition, use the relation:

$$V = V_0\delta^m \tag{3}$$

where m is an exponent which depends on the gap geometry and on the voltage form (AC, impulse or DC) being applied.

The 1973 standard specify that m is equal to 1 for air gaps up to length of d=1m.Thus in the case of different ambient conditions, the expression of the breakdown voltage is corrected and spells [5]:

$$V(P,T,Hr) = \delta * V(P_0,T_0,Hr_0) \tag{4}$$

According to expression (4) the breakdown voltage decreases as gas density is decreased from standard with temperature increase. This correction is known by Peek correction.

Another correction is found in the literature, which is Dunbar correction [6]. If the Dunbar correction leads to satisfying results for high temperatures at atmospheric pressure, this is not the case for Peek correction and for simultaneous changes in temperature and pressure.

We propose in this paper a new empirical expression for the breakdown voltage in case of combined variations of temperature and pressure, and correlated with experimental data. The domain of validity of this new corrective expression for combined pressure and temperature variation is also studied.

II. Experimental Set-Up

Many spacecraft electric power subsystem component are required to operate in various low pressure and/or high temperature environments during launch, flight and reentry. Thus for discharge inception voltage test purposes, it is possible by our experimental setup to simulate any altitude or temperature in a room temperature containing gas at an appropriate pressure.

The experimental setup of discharge detection is shown in Fig. 1, with a pair of stainless steel electrodes (3). After each experiment, the electrodes surface area is reconditioned. The thickness of the electrode gap is adjusted with a micrometer gauge (4) after conditioning the vacuum (pressure, temperature, and humidity). A computer wholly controls the temperature of the environmental chamber (7). The temperature was made to vary from −65 ∘ C up to 150 ∘C and is controlled with a precision of +/ − 2 °C. The air in the chamber is the atmospheric air. The chamber is first vacuumed to the desired value of pressure, and then, the temperature is fixed. For the experiments, the pressure was altered from 760 $*10^{-3}$ to 760 torr, while the interelectrode gap was fixed at 1 mm. Then, the voltage is applied and is then raised slowly until the point of breakdown is reached under ac supply (50 Hz). Breakdown voltage is measured with an oscilloscope. This oscilloscope is Tektronix TDS3054B with a bandwidth of 500 MHz and a sampling rate of 5 GS/s. Partial discharge is a very fast phenomenon, which is considerably slowed down because of the impedance presented by our supply. We can then consider that the bandwidth of our oscilloscope is sufficient.

This setup also allows measuring partial discharge activity under combined stresses induced by the atmospheric parameters corresponding to the aeronautical environment.

The Rogowski/plane configuration of the electrodes used in our experiments is presented in Fig. 2

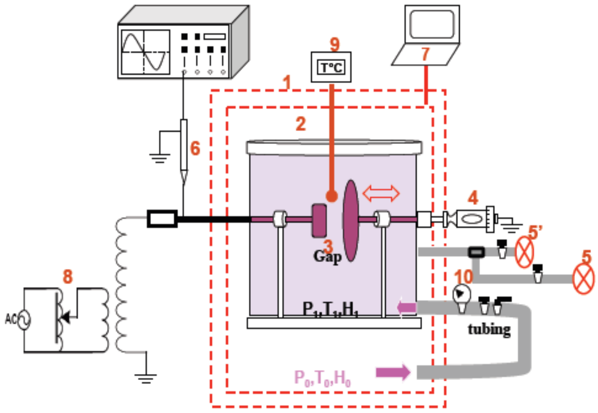


Fig. 1 Schematic experimental set-up and circuit diagram for breakdown voltage: 1-climatic chamber; 2-vacuum; 3-Gap; 4-micrometer gauge; 5- pump; 6 - voltage gauge; 7-computer;8-voltage source;9-temperature gauge,10 - pressure gauge

Fig. 2 Stainless Steel electrodes: Rogowski/plane electrode configurations

III. Results And Discussion

In this section, we will firstly examine the effect of low pressure combined to high temperature on the electrical breakdown mechanism at the left of the Paschen minimum, and then we will investigate and compare the experimental values obtained at room temperature with the theoretical Paschen curve and those at higher temperature with the Dunbar and Peek curves. In the last part, we will propose a new corrective expression of the Paschen's law for breakdown voltage in the case of combined variations of temperature and pressure.

A. Electrical Breakdown mechanism

At room temperature, it has been demonstrated [6] that the mean free path of electrons is smaller than the interelectrode gap (*d*=1mm), therefore the electrical breakdown follows the gas mechanism. It can be seen from Fig.4 that experimentally obtained values of the breakdown voltage at the right of this point correspond to the curve numerically calculated with (1) whereas those at the left of the Paschen minimum are approximately constant and equal to that obtained at $(pd)_{min}$. In this case, it is possible that the breakdown occurs along a line whose length multiplied with pressure corresponds to the value of the *pd* product at minimum. This phenomenon is explained by the edge type breakdown, when the discharge current selects a longer but energetically more favourable distance along the field lines $d_1, d_2, .. d_i$ (see Fig . 3).

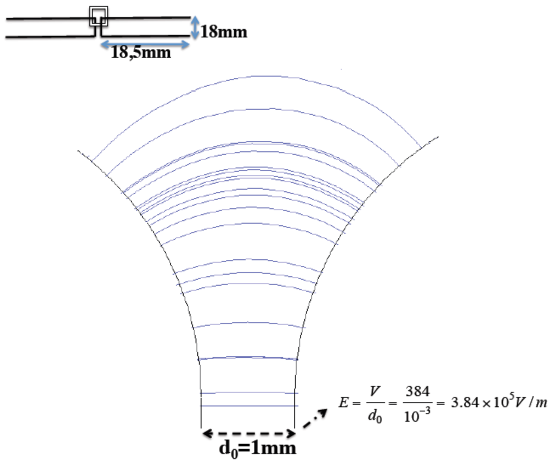


Fig. 3 Electrode systems with edge field lines (of the lengths d_i, i=1,2....) obtained by the charges simulation method (d_0=1mm,V=384V)

In other words, an electrical breakdown occurring along a field line $d_i > d_0$, (i.e., in the region of the non-homogenous electric field [8]) is due to gas mechanism: it can no longer be associated with uniform field and thus the measurements do not correspond to the Paschen curve data.

Taking into account theses considerations, and considering a constant voltage value equal to 384 V for $p<p_{min}$, the so modified Paschen curve leads to a good correlation with the experimental values as presented in Fig.4.

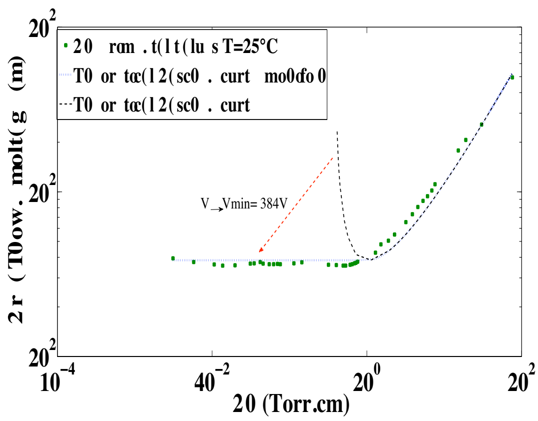


Fig. 4 Comparison between the experimentally obtained results for breakdown voltage at room temperature and the modified theoretical Paschen curve (Rogowski/plane,d_0=1mm)

While for temperatures higher than room temperature, the voltage breakdown increases on the left part of the curve as shown on Fig. 5. As for the theoretical Paschen curve, a minimum appears again for $(pd)_{min}$, which is equal in our experimental results to 7.6 Torr.ccm independently from the configuration of the electrodes. These results are obtained by varying the pressure for a constant inter-electrode gap (d_0=1mm) and for different electrode configurations.

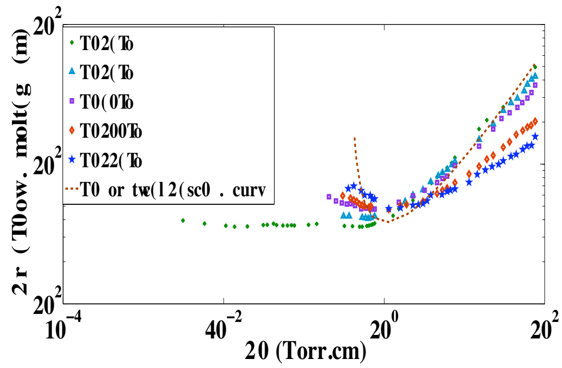


Fig. 5 Experimentally obtained results for breakdown voltage at different temperatures (d_0=1mm) (rogowski/plane)

According to the ideal gas law (pV = nRT where V is the volume of the gas, T the temperature and R is a constant), an increase of the temperature leads to a decrease of the gas density and hence the mean free-path of electrons increases and begins to be comparable and even higher than the gap length. In this case, the gas breakdown occurs due to a mechanism called the vacuum mechanism [7]. There are several well-established physical mechanisms, which can initiate the breakdown of a vacuum gap; in our measurement carried out in a low vacuum, the initiation of electrical breakdown is not due to the Fowler–Nordheim theory of field emission from the cold pure metal surface. Indeed, this type of electrode emission requires a threshold electric field about 10^{-9} V. m^{-1} (in high vacuum), which is very much higher than the field values calculated in our experiments. The maximum breakdown voltage obtained on the left of the Paschen minimum for temperatures above 25°C for a gap of 10^{-3}m (1 mm) being 600 V, the field values calculated in our experiments cannot exceed 10^5 V.m^{-1} (in low vacuum). The phenomenon that we have observed can be explained, if we refer to the literature [9]–[10], by a decrease in the work function of the local region of the cathode, due to the availability of the adsorbed gases on the cathode. Thus, a temperature rise causes the dissociation of the neutral contaminants increasing significantly the number of mobile ions in the interelectrode area. These ions in collision with molecules from adsorbed gas layers provide a sufficient quantity of charged particles. While moving through the interelectrode region in opposite directions, these charged particles ionize new particles on their way, which finally leads to gas breakdown [8]. Electrons causing the discharge remain confined in the gap and electrical breakdown occurs in the central part of the inter-electrode area (i.e. in the region of a homogenous electrical field [8]).

In this case we can notice from Fig. 5 that the Paschen theory is not valid anymore. It is well known that the breakdown voltage of the air gap is affected by atmospheric conditions, principally by the combination of air pressure p and temperature T. Hence the classical Paschen curve has to be replotted according to these parameters. Two corrective expressions on the Paschen's law were found in the literature: Dunbar and Peek corrections. In the next section we investigated the domain of validity of these expressions at atmospheric pressure and then for combined variations of temperature and pressure, in order to check if there correlate with our experimental results.

B. Dunbar and Peek corrections

A correction found in the literature and proposed by Dunbar [6] is based on the relationship below derived from the ideal gas law

$$p_t = p_0 \frac{T_t}{T_0} \quad (5)$$

where T_t is the test temperature (usually room temperature), and p_t the operating pressure which is then substituted in (1), so leading to "Dunbar curve" shown on Fig. 6.

We have compared curves obtained from Dunbar and Peek corrections with experimental results measured at atmospheric pressure for different temperatures. It is observed from Fig. 6 that these experimental values obtained by varying the distance between the electrodes at a constant temperature and at atmospheric pressure are superimposed to the Dunbar curve, for higher temperatures (for example T=120°C in Fig. 6).

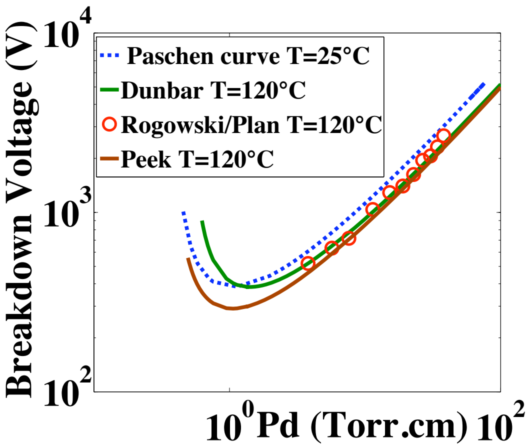


Fig. 6 Comparison of experimental results with the theoretical curves for breakdown voltage at atmospheric pressure for different temperatures,T=120°C (Rogowski/plan)

However, for combined variations of temperature and pressure shown in Fig. 7, the experimental points obtained by varying the pressure at constant inter-electrode gap and a fixed temperature (T=120°C), no longer follow the behaviour of the Dunbar curve neither that of Peek curve.

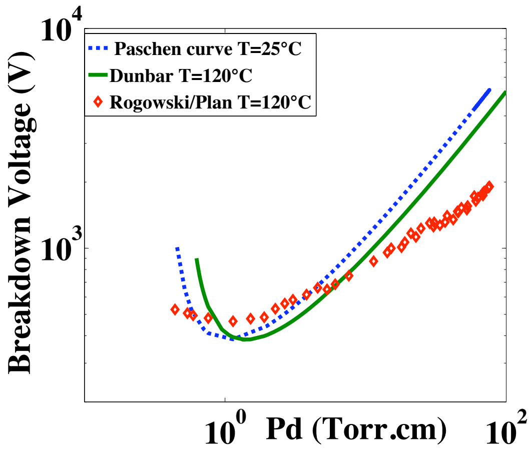


Fig. 7 Comparison of experimental results with the theoretical curves for breakdown voltage with combined variations of temperature and pressure (d_0=1mm) (Rogowski/plan), T=120°C

As a conclusion concerning these corrections, we can mention that, Dunbar correction correlate better to our results than Peek correction at atmospheric pressure, however these two corrections are not suitable for combined variations of temperature and pressure. To further validate our experimental points and to be sure that the variations between the voltage values for different temperatures at a given pressure, are not due to uncertainty of measurements, the experiments were repeated several times. A good reproductively of our results are obtained, and the uncertainty in the breakdown voltage was ≈ 4%. In addition, for example the difference obtained at atmospheric pressure between the breakdown voltage for 50°C and 100 °C was 1782V. This value could not be referred as an uncertainty values. So, based on our experimental data, we tried to extract a new empirical formula, which can be applied under these conditions in the case of vacuum mechanism (T>25°C). This expression is presented in the next section.

C. Proposed correction factor

As mentioned in the introduction (3), the adjustment of the breakdown voltage is calculated from an initial value of the breakdown voltage in normal conditions multiplied by a power of the density.In our study, we have adopted the same procedure. However, since at the left of the Paschen minimum, it was demonstrated that the breakdown voltage is approximately equal to V_{min}=384V for pressures below $(pd)_{min}$ rather than the value calculated according to (1), we use as a reference this modified Paschen's law called $V_{Paschen.mod}$. This so modified Paschen curve is also shown on Fig. 4.

For four different values of temperature: 35-50-80-150°C, we have measured the breakdown voltage V_{meas} for a constant gap (1mm) between the electrodes by varying the pressure. For each experimental point, we calculate the gas density. The resulting ratio $V_{Paschen.mod}/V_{meas}$ is plotted against δ for the four mentioned temperatures. In Fig. 8, we present for example the variation of two temperatures 35°C and 50 °C versus the relative air density.

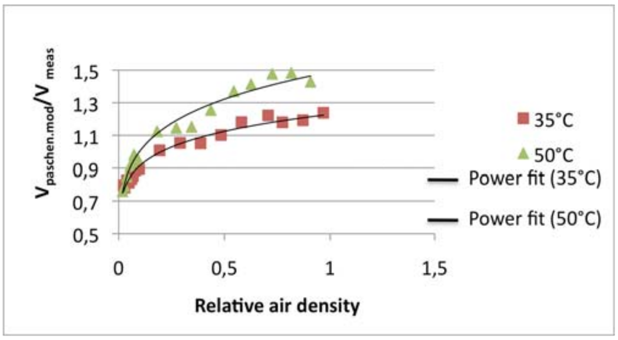


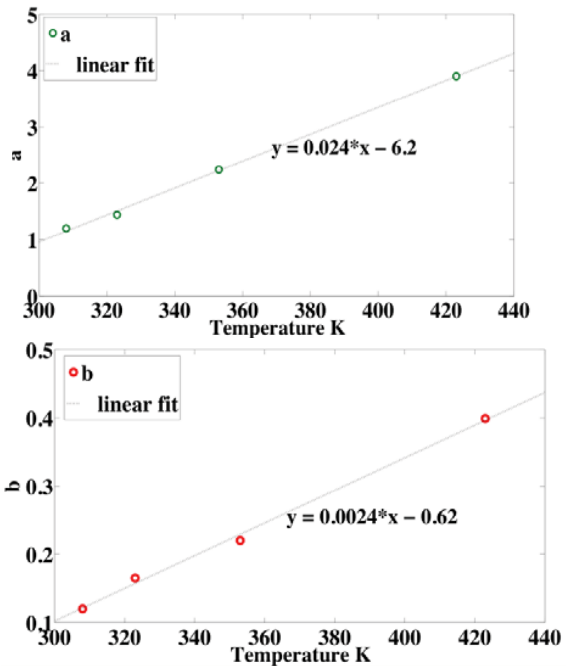
Fig. 8 Ratio of $V_{Paschen\ mod}/V_{meas}$ Vs. relative air gap density for different temperatures

Based on the experimental data obtained for the four temperatures, a correction factor K is derived. As for each temperature the ratio $V_{Paschen.mod}/V_{meas}$ is estimated as a power law of the air gap density (see Fig. 8). This factor depends on two variables a and b, and the air density δ, so that:

$$K = \frac{V_{Paschen.\mathrm{mod}}}{V_{meas}} = a\delta^{b} \qquad (6)$$

The values of a and b for different temperatures are extrapolated from these curves and are represented on Fig. 9. In order to establish a relation between these two variables and the temperature, the values of a and b versus temperature are plotted.

a)



b)

Fig. 9 a and b values vs temperatures

As shown in Fig. 9, these two variables vary linearly with temperature, and two different expressions of a and b can be extracted:

$$a = 0{,}024 * T_i\ (K) - 6{,}2 \qquad (7)$$
$$b = 0.0024 * T_i\ (K) - 0{,}62 \qquad (8)$$

By introducing the corrective factor K to the expression of breakdown voltage (1), the new empirical expression of ignition voltage for combined variation of temperature (T_i) and pressure becomes:

$$V_{Ti} = \frac{V_{Paschen.\mathrm{mod}}}{K} \qquad (9)$$

Plotting the data points obtained for example at 100°C and 125 °C with the simulated curve checks the validity of the new expression. By varying the pressure, for higher temperatures, and an interelectrode gap of 1mm, we can notice form Fig. 10 that there is a good correlation between the simulated curves calculated with (9), and the experimental data.

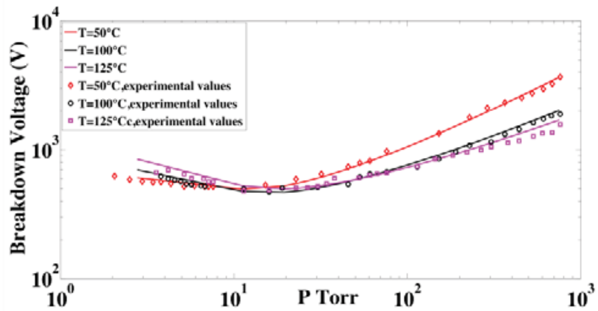


Fig. 10 Experimentally obtained points compared to the simulated curves

In order to verify the validity of this formula for different interelectrode gap, several tests were performed for different distances. Fig. 11 shows a good correlation between the experimental points obtained for *d*=350µm and the simulated curve (same results are obtained for different ineterelectrode gap).

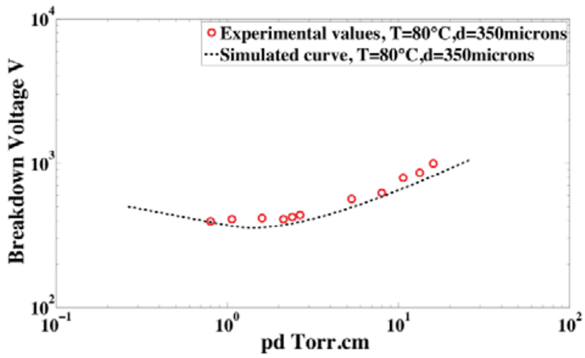


Fig. 11 Experimentally obtained points compared to the simulated curves, Rogowski/plane electrodes, T=80°C, d=350µm

IV. Conclusion

It has been demonstrated that for combined variations of temperature and pressure, two different breakdown mechanisms occur on the left of the Paschen minimum depending on temperature. At room temperature electrical breakdown is due to gas mechanism, whereas for higher temperatures, it is due to vacuum mechanism.

Dunbar correction is validated for temperature variations in atmospheric pressure regardless of the electrode configurations. Or in combined variations of temperature and pressure this correction is no longer valid.

In the case of combined variation of pressure and temperatures, a new empirical expression has been added and validated for different condition of temperature and electrode gap.

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