Pressure and Temperature effects on the Paschen curve

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***Abstract*- In aircraft applications 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 100 mbar, and the temperature may vary up to 180°C near the aircraft engine. Since all these parameters may affect the discharge ignition voltage, the classical paschen curve has to be replotted according to these parameters. In this paper we firstly investigated the domain of validity of two corrective expressions on the paschen's law found in the literature, in case of changing the air environment: Peek and Dunbar corrections. After that, the effect of the low pressure combined to high temperature on the breakdown voltage at the left of the Paschen minimum has been investigated. Results show two different behaviours of Paschen curve related to temperature and pressure that can be explained by the variation of the breakdown mechanisms, and supported by measuring the energy dissipated in the electric discharge by means of the Lissajous figures at different conditions. Consequently, it was demonstrated that the electrical breakdown in gases occurs due to the gas or vacuum mechanism managed by the temperature and/or the pressure**

I. INTRODUCTION

In aircraft applications the electrical and electronic equipment 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 condition may change from atmospheric pressure to less than 100 mbar, and the temperature is raised close to the reactors and may be higher than the ambient. In our study for this application, we are interested in combined variations in temperature and pressure particularly, low pressures combined with high temperatures (case of equipment in unpressurized area near the reactors), which may correspond to the left part of the Paschen minimum.

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 (case air) is established under normal conditions of pressure, temperature: T_0 = 20 ° C, P_0 = 760 mmHg at 0 ° C (760 Torr), absolute humidity 11g/m3. Hence the necessity of introducing correction factors in case of changing the air environment. In the literature we can found two corrective expressions: Dunbar and Peek corrections[2-3].

In this paper we firstly investigated the domain of validity of these two corrective expressions, and then we examine the validity of the Paschen law by means of plotting the Paschen curves within the same pressure range for different temperatures. It will be demonstrated that depending on temperature, two different mechanisms of electrical breakdown can occur left of Paschen minimum.

II. BACKGROUND

A. Breakdown voltage

To determine Discharge Inception Voltage (DIV) for uniform field, empirical data is taken from the literature, and Paschen's law is used to approximate DIV theoretically [4,5]. The law essentially states that the breakdown characteristics of a gap are a function of the product of the gas pressure p and the gap length d [V_B=f (pd)]. The product pd is a measure of the number of collisions an electron makes by 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 $V.Torr^{-1}.cm^{-1}$ [5] and $\gamma = 10^{-2}$, therefore C is equal to 1.18.

B. Aeronautic environment impact

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 breakdown voltage for simulating a given operating altitude and temperature can be calculated by using two corrective expressions: Peek and Dunbar corrections.

Peek correction is based on the gas density "δ" and the expression is deduced from ideal gases law with volume being constant. The gas density, is affected by the temperature as well as the pressure of the gas and it is defined, following the IEC procedure [6], as the ratio of the air density during the test

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to that at the standard reference condition of air and pressure (p=760Torr and T=293K).

$$\delta = \frac{P}{760} * \frac{293}{T} \qquad (2)$$

Where p and T are the air pressure and temperature in the experiment.

Thus in the case of different ambient conditions, the expression of the breakdown voltage is corrected and spells [2]:

$$V(P,T,Hr) = \delta * V(P_0, T_0, Hr_0) \qquad (3)$$

According to expression (3) the breakdown voltage decreases as gas density is decreased from standard with temperature increase.

Dunbar correction is based on the relationship below derived from the ideal gas law [3]:

$$P_t = P_0 \frac{273 + t_t}{273 + t_0} \qquad (4)$$

t_0 : operating temperature in degrees Celsius
t_t :test temperature in degrees Celsius (usually room temperature)
P_0 : operating pressure in torr
P_t : test chamber pressure in torr
This pressure expression is then substituted in equation (1).

III. Experimental Set-Up

The experimental set up and the diagram circuit of discharges detection is shown in figure 1.A climatic chamber with width 580 mm, depth 450mm and height 750mm contains a test cell (dimater:29mm, height:29mm) where a pair of stainless steel electrodes is installed.The electrodes gap separation is adjusted with the micrometer gauge. The gap is fixed after the vacuum conditioning (pressure, temperature and humidity). The temperature and the absolute humidity of the environmental chamber are controlled by the computer. Then, the voltage is applied, which is then raised slowly until the point of breakdown is reached under AC supply 50Hz. Breakdown voltage is measured using an oscilloscope. This setup also allows measuring partial discharge activity under combined stresses caused by the atmospheric parameters corresponding to the aeronautical environment.

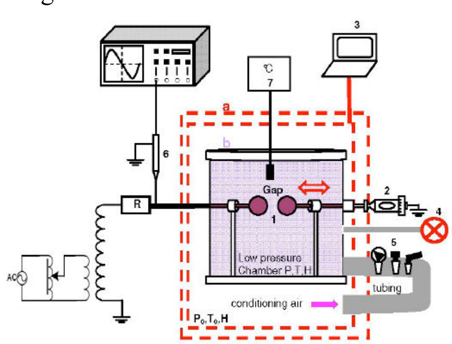
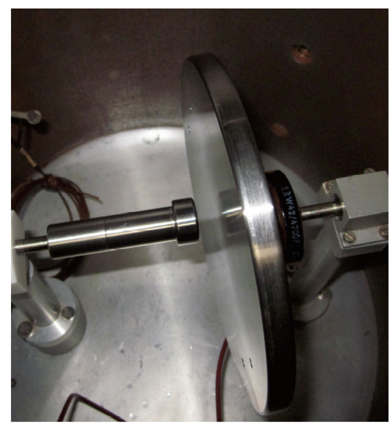


Fig 1. Schematic experimental set-up and circuit diagram for breakdown voltage:a-climatic chamber; b-vacuum; 4 - pump; 5 - pressure gauge; 6 - voltage gauge; 7 -temperature gauge

The energy consumed by the discharge is measured by connecting a capacitor between the bottom electrode and the ground in series with the device under test (see figure 2.a). This capacity C must be large enough (approximately nF) to be able to collect all the charges coming out from the equivalent cell C_e (approximately pF). A digital oscilloscope records the voltage, the charge and the Lissajous figure. The Lissajous figure is obtained on the oscilloscope screen by plotting the transported charge on the Y-axis versus the applied voltage on the X-axis (see figure 2.b).

a)



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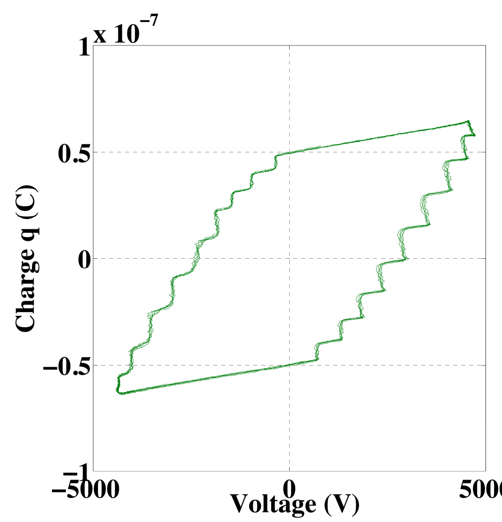


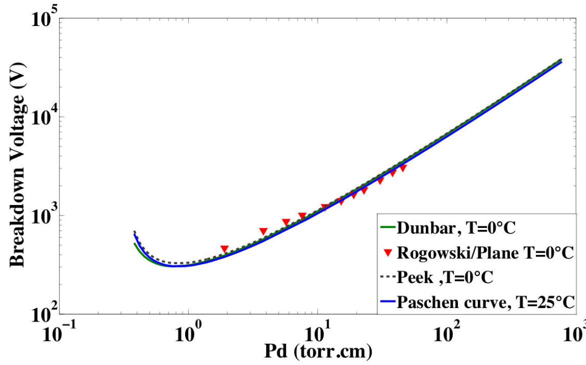
Fig 2: a) Experimental setup, b) Example of the Lissajous figure.

The electrode configuration used in our experiments is presented in figure 2.

IV. Results And Discussion

A. Peek and Dunbar corrections

It is observed from figure 3a -3b that the experimental obtained values by varying the distance between the electrodes at atmospheric pressure for different temperatures are superimposed to the Dunbar curve for a temperature above 25°C (calculated from the expression (4)), and that of Peek for T < 25 ° C (calculated from the expression (3)) respectively, regardless of electrode configuration.



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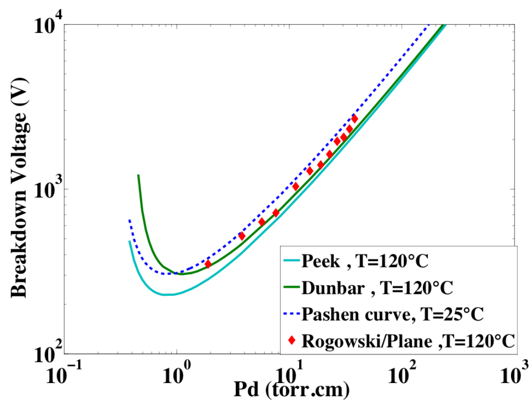

Fig.3. Experimentally obtained results for breakdown voltage at atmospheric pressure for different temperatures (d=1mm) a) T=0°C, b) T=120°C (rogowski/plane).

Whereas for combined variations for temperature and pressure shown in figure 4 we note that the experimental points no longer follow the behavior of the Dunbar curve for T> 25 ° C. Similar results are obtained for Peek correction (T<25°C).

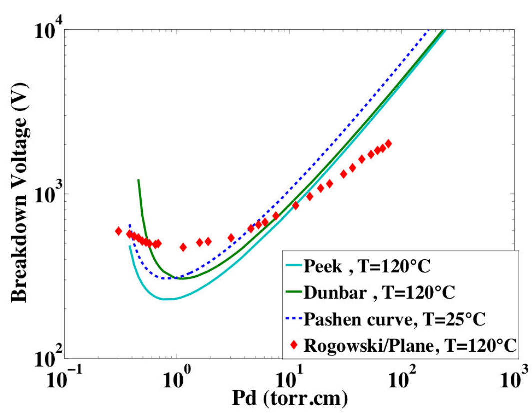

Fig.4. Experimentally obtained results for breakdown voltage at combined variations of temperature and pressure (d=1mm) (rogowski/plane).

B. Electrical breakdown mechanism

In our experiments, the main factor is the temperature that affects the electrical breakdown mechanism. Results obtained for combined variations of temperature and pressure show that the values of the breakdown voltage at room temperature at the left of the Paschen minimum is lower than these at higher temperature (see figure 5). It can therefore be inferred that, the breakdown occurs through two different mechanisms depending on temperature.

Experimentally from figure 5, we can notice that the voltage breakdown for higher temperature increases at the left of $(pd)_{min}$,which is equal in our experimental results to 10 mbar.mm independently from electrode configuration . These results are obtained by making pressure variation at constant inter-electrode gap (d_0=1mm) and higher temperatures for different electrode configurations.

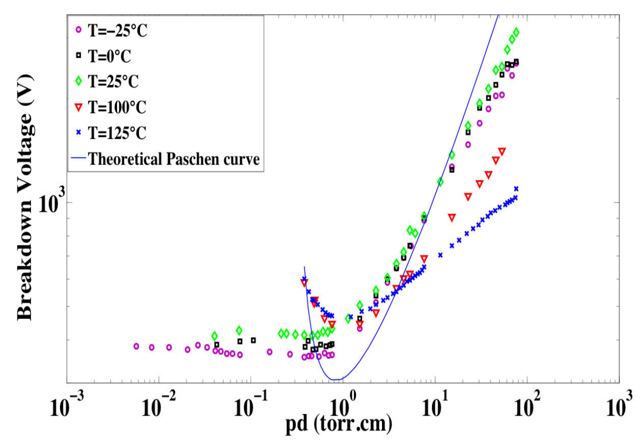

Fig.5. Experimentally obtained results for breakdown voltage at different temperatures (d=1mm) (rogowski/plane).

According to the ideal gas law ($PV = nRT$ where V is the volume of the gas, T the temperature and R is a constant), increasing the temperature decreases the gas density and hence the mean free-path of electrons increases and begins to be comparable to the gap length. In this case electrical breakdown occurs due to a mechanism called the vacuum mechanism. There are several well-established physical mechanisms, which can initiate the breakdown of a vacuum gap. According to the theory, it is initiated by three phenomena which cause thermal instability of one of the electrodes [7,8, 9,10-11]: emission mechanism, accelerated electrode material micro-particles and through the avalanche effect in the adsorbed residual gas layer on the electrode. Or in our measurement carried out in a low vacuum, the initiation of electrical breakdown is not in accordance with the Fowler-Nordheim theory of field emission from the cold pure metal surface, since this type of electrode emission requires a threshold electric field about 10^9V.m^{-1}(in high vacuum) which is very much higher than the field values calculated in our experiments that is not in excess of 10^5V.cm^{-1}(in low vacuum) though we assume that the initiation of electrical breakdown is based on the avalanche breakdown hypothesis: : in collisions with molecules from adsorbed gas layers on the electrode or with molecules of impurities (contaminants), multiply charged particles are formed, which move through the inter-electrode region in opposite directions, ionizing new particles on the way, which finally develops into gas breakdown [12]. 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 [12])

While at room temperature when the mean free path of electrons is smaller than the interelectrode gap (d=1mm), the electrical breakdown mechanism of gas is applied .It can be seen from figure 5 that experimentally obtained values of the breakdown voltage at the left of the Paschen minimum are approximately equal to pd min and those at the right of this point correspond to the numerically calculated curve.

It is possible that the breakdown occurs along the 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 spark selects a longer but energetically more favourable distance along the field lines d_1, d_2 , .. d_i. In other words, electrical breakdown occurring along the field line $d_i>d_0$, (i.e., in the region of the non-homogenous electric field [12]) is due to gas mechanism and it can no longer be associated with uniform field and thus the measurements do not represent valid Paschen curve data.

C. Energy measurements

Depending on temperature, at the left of Paschen minimum, two different mechanisms of electrical breakdown could occur and the nature of the discharge differs. Qualitatively the physical picture of the type of discharge can be described in terms of energy supplied to the gap, thus to reinforce our interpretations we present the energy measurement.

Energy measurements for partial discharge for combined variations of temperature and pressure are carried out. We used the V-Q Lissajous method or (Manely method [13]), to determine the energy deposited into the discharge plasma.

According to figure 6, which shows the variation of energy versus pressure for several temperatures, It is noticed that at the left of the Paschen minimum the values of energies measured for T>25°C are at least one order magnitude higher than that at room temperature which characterizes the presence of two different discharge mechanism depending on temperature.

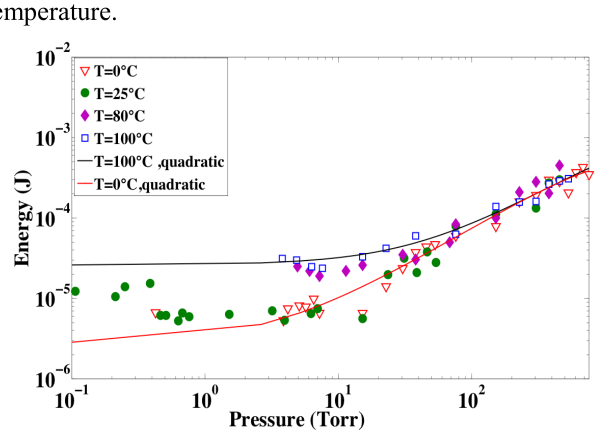

Fig 6.Experimentally obtained results for energy at different temperatures (d=1mm).

V. Conclusion

Peek and Dunbar corrections are validated for temperature variations in atmospheric pressure regardless of the electrode configurations. Or in combined variations of temperature and pressure these corrections are no longer valid.

It was demonstrated that the occurrence of gas or vacuum mechanisms for electrical breakdown at the left of Paschen minimum depends on the temperature.

At room temperature, electrical breakdown occurring along the field line $d_i>d_0$, (i.e., in the region of the non-homogenous electric field) is due to gas mechanism.

However for higher temperatures, electrical breakdown occurring in the central part of the inter-electrode area (i.e. in the region of a homogenous electrical field) is due to vacuum mechanism.

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