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Paschen curves for metal plasmas

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Abstract. The Paschen curve for D.C. electric field-driven sources like conductively coupled plasmas is examined. The considered plasma gases are metals. The minimum breakdown requirement is related to the ionization energy and the collision cross section of the considered plasma. The dominant collisions to consider may depend on the plasma source.

1. Introduction

The Paschen curve uses two coefficients A_0 and B_0 [1–5], usually experimentally obtained, to determine at which applied electric voltage V a plasma will be self-sustaining after its generation for a given pressure times distance between the electrodes. The Paschen curve determining at which voltage breakdown occurs shows a minimum.

Experimental data for A_0 and B_0 are not available for metal plasmas. Examining the first Townsend coefficient α, analytic expressions for the two parameters A_0 and B_0 can be obtained, see [6].

Here, the Paschen curves for metals and more specific the minimum of the breakdown curve are examined. This minimum of the breakdown curve is related to the ratio of the two Paschen parameters. This minimum is therefore dominated by the ionization energy of the considered gas. This outcome is of practical importance indicating that metal plasmas are much easier to ignite than ordinary plasmas like argon, air, or nitrogen plasmas.

The minimum in the Paschen curve is also related to the collision cross section. In Sec. 4 we will show that the dominant collision mechanism indeed influences the ease to ignite a zinc plasma.

2. The Paschen curve

The Paschen curve of the Townsend discharge [1–5] is used to predict gas breakdown inside electric field-driven plasma sources. The electric field is drawn from a voltage difference V between two electrodes at a distance d. These electrodes form a gap in which the gas is at pressure p. Two coefficients are used to describe the Townsend discharge.

The first Townsend coefficient α describes the success rate for accelerated electrons to collide and ionize the background gas. The first Townsend coefficient depends on two parameters A_0 and B_0,

$$\alpha = A_0 p \exp\left(-\frac{B_0 pd}{V}\right). \tag{2.1}$$

The parameters A_0 and B_0 have been determined experimentally for the most common plasma gases like argon and nitrogen, for example by Cobine [7]. For other plasmas, these parameters can be theoretically determined as performed by Burm [6]. The parameters A_0 and B_0 are roughly constant over the full range of voltages and pressures for any given gas [1].

The second Townsend coefficient γ describes the success rate of newly created electrons at electrodes. Created positive ions may collide with the cathode creating new electrons, the so-called secondary electrons, out of electrodes.

The Paschen curve [1–5] relates the required voltage V versus pressure p times electrode distance d in order to burn a self-sustaining plasma inside the gap,

$$V_{\text{breakdown}} = \frac{B_0 pd}{\ln(A_0 pd) - \ln\left(\ln\left[\frac{\gamma+1}{\gamma}\right]\right)}. \tag{2.2}$$

In order to determine the conditions at which breakdown occurs most easily, i.e. the breakdown minimum, the derivative of expression (2.2) has been taken and set to zero. The minimum breakdown voltage,

$$V_{\min} = \exp(1)\frac{B_0}{A_0}\ln\left(\frac{\gamma+1}{\gamma}\right) \tag{2.3}$$

is obtained at

$$pd_{\min} = \frac{\exp(1)}{A_0}\ln\left(\frac{\gamma+1}{\gamma}\right). \tag{2.4}$$

Note that $V_{\min}$ is directly related to the ratio of the Paschen parameters, $\frac{B_0}{A_0}$.

3. Paschen parameters

In [6] analytic formulas have been presented in order to estimate the values of the two Paschen parameters A_0 and B_0,

$$A_0 = 0.224\frac{e^4}{16\pi\epsilon_0^2 E_{12}^2}\frac{3}{kT_h} \tag{3.1}$$

and

$$B_0 = \frac{5}{4}\frac{\pi a_r^2}{kT_h}\frac{E_{12}}{e}, \tag{3.2}$$

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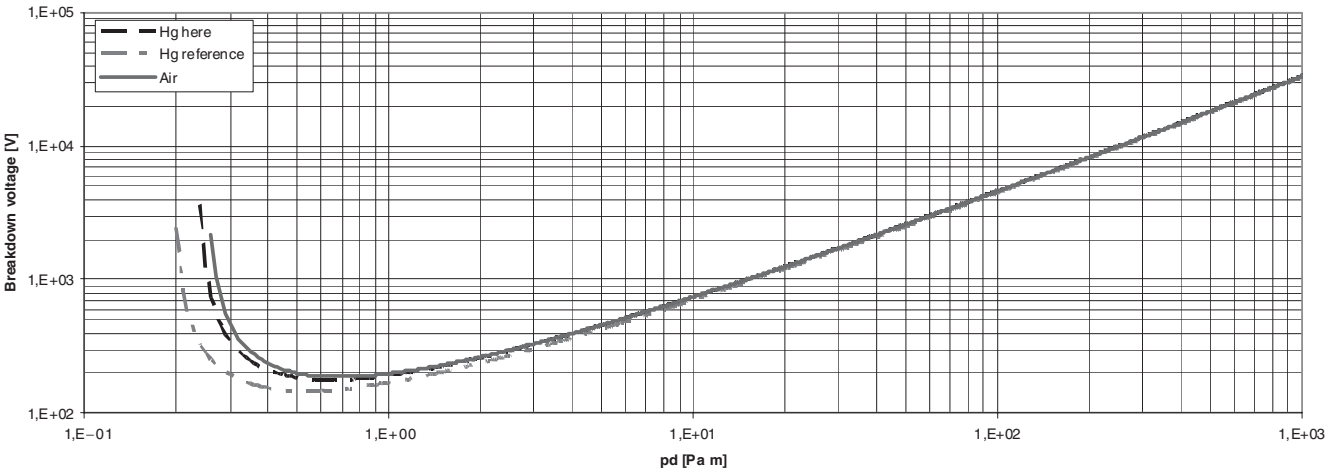


Figure 1. Paschen curves for mercury as deduced here and by von Engel [10]. The curve for air is included as reference to show that the Paschen curve for mercury lies close to the Paschen curve for air.

with e being the electron charge, ϵ_0 the dielectric constant of vacuum, E_{12} the first step excitation energy considered to dominate ionization, k the Boltzmann constant, T_h the heavy particle (ions and atoms) temperature, and a_r being the atomic radius. Expressions (3.1) and (3.2) have been successfully tested against experimentally obtained values [6].

In the derivation of parameters, step ionization is considered dominant. Further, the collision cross section considered in [6] is that of hard spheres, $\sigma_c = \pi a_r^2$, which is a logical choice considering ordinary plasmas from gases like argon, air, and nitrogen. The ionization degree in these plasmas is relatively low. The considered copper plasmas in [6] to identify breakdown locations are in fact short-living plasma sparks. The ionization degrees in these copper plasmas are also very low.

Examining the ratio $\frac{B_0}{A_0}$ yields

$$\frac{B_0}{A_0} = \frac{20}{3}\frac{a_r^2}{0.224}\left(\frac{\pi\epsilon_0}{e}\right)^2\left(\frac{E_{12}}{e}\right)^3 = 8.97\cdot 10^{17} a_r^2\left(\frac{E_{12}}{e}\right)^3. \tag{3.3}$$

Note that the ratio depends severely on the ionization energy (actually the energy required for the first step) and also but less severe on atomic radius. The atomic radius shows up since hard sphere collisions are considered dominant, as discussed above. Substituting expression (3.3) in expression (2.3) indicates that the minimum in the Paschen curve is strongly related to the ionization energy of the gas.

4. Results

Note that considering modern lamps containing metal halides, like, for example in [8], the metal halides contribute to the visual spectrum. No special hardware is required to ignite these metal halides. One may therefore expect that metal plasmas are easier to ignite than ordinary plasmas such as argon, air, or nitrogen plasmas.

From all metal plasmas, relative much breakdown data are available for mercury [7, 9, 10], which may be explained by the fact that mercury plasmas are of interest for the light industry. Coefficients A_0 and B_0 have been calculated for a breakdown occurring in a mercury gas at room temperature. A relative large atomic radius has been used, $a_r = 0.176$ nm, as is typical for mercury. The first step excitation energy E_{12} is set equal to 9.5 eV, which is just below the ionization energy of 10.4 eV. This value is obtained by considering the energy levels of mercury. The level density increases enormously between 9.5 eV and 10.4 eV. Further, electrodes made from tungsten ($\gamma = 0.0678$) have been considered.

The obtained coefficients A_0 and B_0 are 11.7 $\mathrm{Pa^{-1}\,m^{-1}}$ and 278.99 V $\mathrm{Pa^{-1}\,m^{-1}}$, respectively, which are in agreement with Reece Roth [9] reporting $A_0 = 14.6$ and $B_0 = 277.5$ for mercury. The obtained minimum breakdown voltage $V_{\min} = 178$ V and breakdown location $pd_{\min} = 0.64$ Pa m are in agreement with von Engel [10] but strangely enough not in agreement with [9]. von Engel [10] finds that $V_{\min} = 147$ V and $pd_{\min} = 0.53$ Pa m. Reece Roth [9] refers to [7] reporting $V_{\min} = 520$ V and $pd_{\min} = 2.7$ Pa m for mercury. However, using $A_0 = 14.6$ and $B_0 = 277.5$, Reece Roth [9] should find $V_{\min} = 142$ V and $pd_{\min} = 0.5$ Pa m. Similarly, as reported by von Engel [10], we find the Paschen curve for mercury, which is laying just below the Paschen curve for air, see Fig. 1.

Comparing our results with those from Reece Roth [9], when his values for A_0 and B_0 are used, we quickly find 20–30% deviations between the Paschen curves. These deviations may give an impression about the accuracy of the predicted Paschen curves.

Zinc plasmas for deposition of corrosion protective layers are considered next. In case of these zinc plasmas it is important to notice that zinc vapor is produced by a thermal heating device. A capacitively coupled plasma device is initiating the gas breakdown. The so produced zinc plasma has a high ionization degree in contrast with

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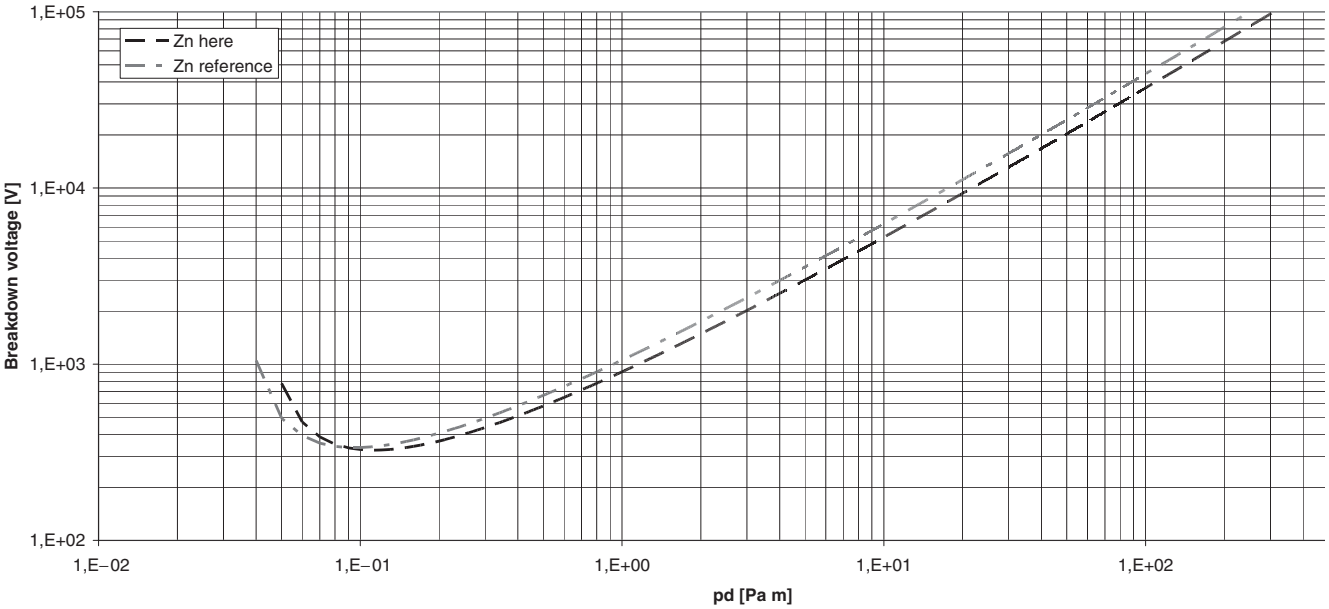


Figure 2. Paschen curves for zinc as deduced here and experimentally obtained by Rajasekaran and Naidu [11].

normal plasmas like argon, air, or nitrogen plasmas or the mercury plasma discussed above. The Paschen curve of the zinc plasma is influenced such that the dominant collision cross section becomes the Coulomb interaction due to that the zinc vapor is originating from the thermal heating source. In [6] the Paschen curve parameters A_0 and B_0 are deduced considering atomic collisions with the background gas as the dominant collision type. Therefore, the atomic radius a_r shows up in the formula for parameter B_0.

Coefficients A_0 and B_0 have been calculated for a breakdown occurring in thermally heated zinc vapor. A relative large atomic radius has been used, $a_r = 0.87$ nm, for considering Coulomb interaction at a temperature of 0.55 eV. The temperature is typically valid for the source and has been measured with optical emission spectroscopy. The first step excitation energy E_{12} is set equal to 4.0061 eV. This value is much lower than the ionization energy caused by many energy states between the first step excitation level and ionization. Further, electrodes made from steel ($\gamma = 0.0691$) have been considered.

The obtained coefficients A_0 and B_0 are 65.9 Pa^{-1} m^{-1} and 2876.79 V Pa^{-1} m^{-1}, respectively. The obtained minimum breakdown voltage, $V_{\min} = 325$ V, and breakdown location, $pd_{\min} = 0.11$ Pa m, are in agreement with that of Rajasekaran and Naidu [11], who report experimentally obtained data for zinc from a heat pipe, see Fig. 2. Rajasekaran and Naidu [11] reports $V_{\min} = 336$ V and $pd_{\min} = 0.095$ Pa m. The obtained minimum voltage is much higher than the minimum breakdown voltage calculated from atomic collisions (about 10 V).

The low ionization energy of zinc causes that a zinc gas breakdown occurs easily. However, the large dominant collision cross section due to that the zinc vapor is generated by a thermal heating device counterbalances most of this effect.

5. Conclusions

The minimum voltage to force breakdown in a gas is strongly related to the ionization energy of the considered gas and is further related to the radius of the dominant collision cross section.

It can be concluded by examining the Paschen curves for two metal vapors (Hg and Zn) that metal vapors are easier to ignite than ordinary plasmas, like argon, air, and nitrogen, due to their much lower ionization energies. However, the dominant collision mechanism can reduce the ease of gas breakdown severely, for example in case of a zinc plasma created in a heat pipe.

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