TOWARD A NEW THEORY OF ELECTRICAL BREAKDOWN IN AIR

J J LOWKE

CSIRO Materials Science and Engineering, PO Box 218, Lindfield NSW 2070, Australia.
John.Lowke@csiro.au

ABSTRACT

It is found that electrical corona in air is initiated when one electron can grow by ionization to only ~10^4 electrons. This criterion applies for both wires and points, for positive and negative polarity, and for radii varying from 0.1 mm to over 20 cm. It is proposed that this criterion corresponds to the development of significant numbers of the vibrational states of molecular nitrogen, which are metastable. De-excitation collisions of these metastables with electrons significantly increase electron energies to make possible ionization for lower electric fields and initiate breakdown.

1. INTRODUCTION

There are two well established theories of electrical breakdown. The first, "The Townsend Breakdown Criterion" [1], maintains that to establish a continuous discharge, each electron at the cathode must be replaced at the cathode in the discharge process. Such replacement processes could be photo-emission at the cathode by ultra violet photons from the discharge, or secondary emission of electrons from the cathode by the impact of positive ions. But experimental observations of the onset of corona, usually the precursor to full electrical breakdown, indicate that this initiating voltage is largely independent of the polarity of the applied voltage [2], and also largely independent of the electrode material [3,4]. A second breakdown theory is "The Streamer Breakdown Criterion" [5] which states that breakdown proceeds when space charges are sufficient to distort the local field and influence ionization. When electron avalanches are of the order of 10^8, a plasma avalanche of electrons and ions will have enhanced electric fields at the leading and trailing edges of the avalanche because of the enhanced electron density at the anode side of the avalanche and an enhanced positive ion density at the trailing edge of the avalanche. These enhanced fields can increase ionization so that the plasma can develop streamers to bridge the gap between cathode and anode.

Previously published values of the onset electric field for corona are analysed in Section 2 where it is found that there is corona onset after a single electron grows by ionization to 10^4 electrons rather than the 10^8 electrons usually specified for streamer development [5]. In Section 3, characteristics of vibrational excitation of molecular nitrogen are described. It is proposed that the de-excitation of these metastable states by collisions with electrons leads to significantly increased electron energy and thus ionization. In Section 4 the total breakdown process is described in terms of five separate stages. These stages incorporate the Townsend and Streamer mechanisms, but with a preceding stage involving the excitation of the metastable states of nitrogen which have a large influence in making ionization possible at much lower electric fields and constitute a most important step in the initiation of electrical breakdown.

2. ANALYSIS OF CORONA INITIATION

There have been many previous measurements of the voltages for the onset of corona for different radii of cylinders or cables, points or spheres, for different electrode materials and also for positive and negative polarity. These experimental results of surface electric fields as a function of radius are shown in Fig. 1 for cylinders and Fig. 2 for hemispheres on a cylinder. For some of the results of Fig. 2 it was necessary to do a numerical solution of Poisson's equation to determine the surface electric field at the sphere from measured voltages for corona onset to account for the influence of electrode separation.

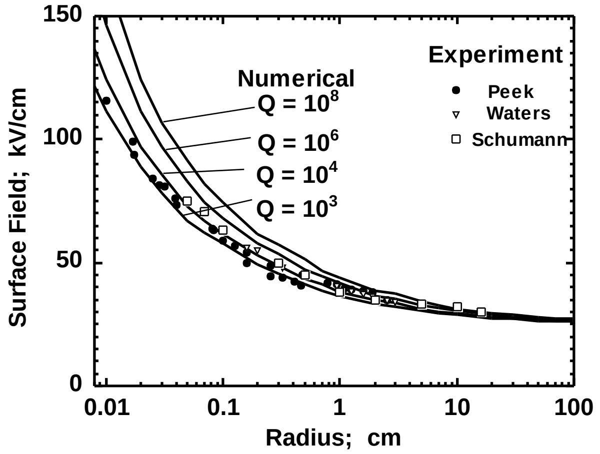

Fig. 1 Measured corona onset fields for cylinders.

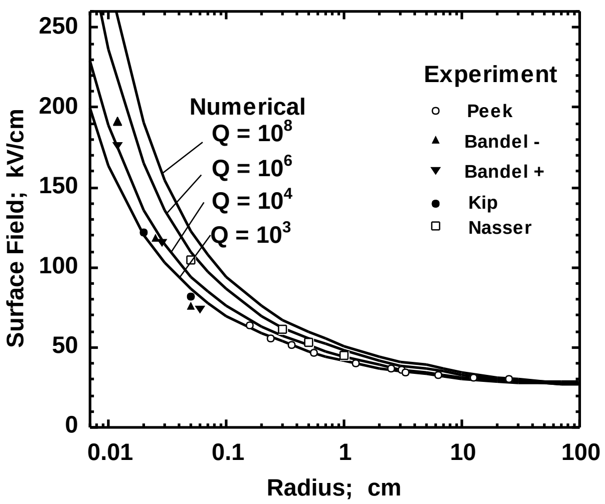

Fig. 2 Measured corona onset fields for spheres and points.

As in an earlier paper [6], also shown in Figs 1 and 2 are curves for various values of Q where

$$Q = exp\{\int(\alpha-\eta)dr\}. \qquad (1)$$

The integral is taken along a line perpendicular to the electrode surface where the net ionization coefficient α-η is positive; α is the ionization coefficient, η is the attachment coefficient and r is the radial coordinate. Q represents the number of electrons to which a single electron would increase through ionization in moving from the surface of either a cylindrical or spherical cathode. It is noted from Figs. 1 and 2 that the curves for Q = 10^4 give a fair fit for all radii for both spherical and cylindrical electrodes. This avalanche size is much lower than that required for space charge fields to produce streamer propagation.

The development of corona suggests the onset of a strong ionization mechanism within the gas and independent of the electrodes. For electric fields of less than 25 kV/cm, electrons become rapidly attached to form negative ions as attachment coefficients are then larger than ionization coefficients. However, independent experimental measurements indicate that once initiated, it is possible for glow discharges to operate in air for electric fields as low as 5 kV/cm, or values of E/N of 20 Td., e.g. for corona discharges [7], pre-breakdown discharges [8] and discharges in low pressure nitrogen [9]; E is the electric field and N is the gas number density. In a previous paper [10] it has been shown that the metastable $a^1\Delta_g$ oxygen molecules, through their ability to detach electrons from O_2^- ions, have a strong role in enabling discharges to operate at lower electric fields than 25 kV/cm, but an additional ionization mechanism is still necessary.

3. VIBRATIONAL STATES OF NITROGEN

It is proposed that excitation of the vibrational states of nitrogen have a major role in increasing ionization at low E/N. These states are metastable, with a lifetime at atmospheric pressure of the order of a millisecond [11], which is large compared with the times for corona development of less than a microsecond. The excitation potential of the first vibrational level is 0.29 eV, and excitation can be represented by

$$N_2(v=0) + e \rightarrow N_2(v=1) + e$$

Further excitations can then occur by electrons as these states are long lived metastables:

$$N_2(v) + e \rightarrow N_2(v+1) + e$$

Furthermore successive excitations can occur through collisions of the metastable states among themselves [12]:

$$N_2(v) + N_2(v) \rightarrow N_2(v+1) + N_2(v-1)$$

Up to 60 quantum levels can be achieved [13], and population density distributions among these excited states is approximately a Boltzmann distribution [12]. Energy levels of the nitrogen molecule are illustrated in Fig. 3, the energy of the 60th vibrational level being ~ 9.7 V [13].

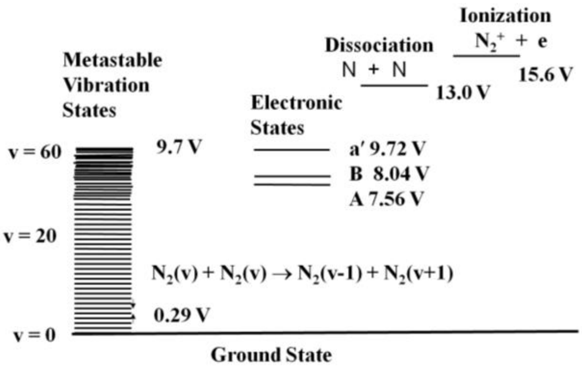

Fig. 3 Energy levels of molecular nitrogen.

The distribution of the number densities of these excited vibrational states corresponds to a temperature that is not the gas temperature but the temperature of the electrons. This temperature, is ~ 20,000K even at the low value of *E/N* of 20 Td, as the "characteristic energy" or value of D/μ is 1.8 eV; *D* is the diffusion coefficient and μ the electron mobility.

Electrons lose energy by exciting vibrational states, but at equilibrium, from the principle of "detailed balance", there are an equal number of collisions where electrons gain energy through the de-excitation of excited states by x levels; i.e.

$$N_2(v) + e \rightarrow N_2(v\text{-}x) + e$$

These collisions are referred to as "collisions of the second kind" or "super elastic collisions". De-excitation of highly excited states of nitrogen by collisions with low energy electrons increases the number of electrons in the high energy region of the electron distribution function and has a major effect in increasing ionization.

Calculations of this effect have been made by using the computer code "ELENDIF" [14] to compare solutions with and without the effect of super-elastic collisions. Cross sections for nitrogen [15] and oxygen [16] that were used had 9 vibrational levels for nitrogen and 8 for oxygen. Fig. 4 shows the calculated distribution function at E/N = 20 Td for air and it is seen that the population density of electrons with energies above 5 eV are increased by four orders of magnitude. Fig. 5 shows the calculated ionization coefficients in air which at 20 Td are also increased by four orders of magnitude. Similar results have been obtained by other authors to explain the low electric fields in low pressure nitrogen discharges [17].

Electron avalanche sizes of 10^4, when accounting for the small volume occupied by the avalanche, correspond to densities of the order of 10^8/cc. Excitation rates of the nitrogen metastable vibrational states for E/N<300 Td are orders of magnitude higher than ionization rates, as shown in Fig. 6. The calculated metastable densities for an electron avalanche size of 10^4 are of the order of 10^{16}/cc. It is proposed that this density is sufficient to cause an increase in the total ionization rate for avalanche sizes above 10^4 and explain the onset of corona.

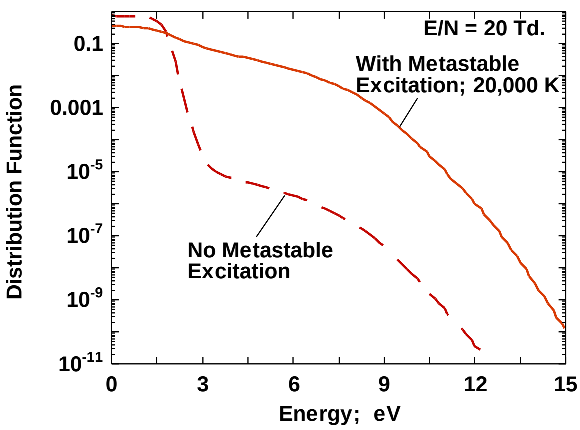

Fig. 4 Calculated distribution functions for electrons in air, showing the effect of electron excitation of the vibrational states.

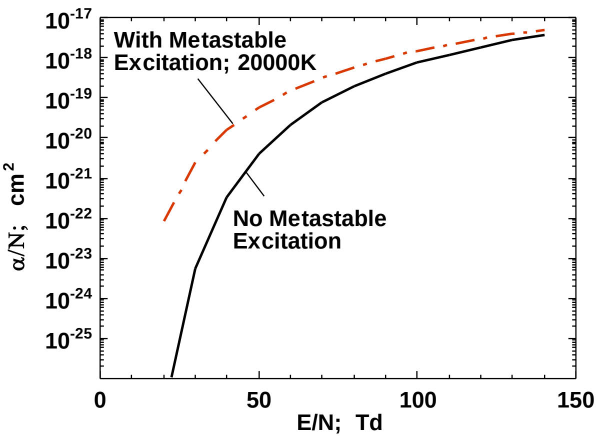

Fig. 5. Effect of excitation collisions of vibrational states on ionization coefficients in air.

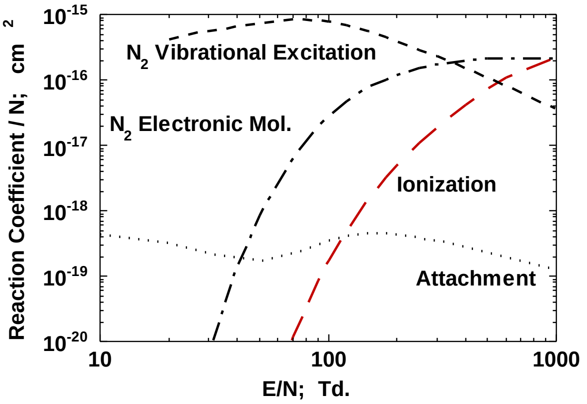

Fig. 6. Calculated excitation rates for various processes in air, with a vibrational temperature of 300 K.

4. STAGES OF BREAKDOWN.

Rather than electrical breakdown consisting of one complex process for which there are rival theoretical explanations or criteria for inception, the view is presented that the breakdown process consists of five separate physical processes which generally occur in succession. Complete breakdown does not proceed if conditions for any one of these processes is not fulfilled.

The five processes are:
(1) An electron must be present in a high field region to initiate by ionization an avalanche.
(2) The avalanche must be able to grow to exceed ~ 10^4 electrons so that then sufficient vibrational states of nitrogen are excited which greatly enhance ionization.
(3) Space charge effects for large avalanche sizes induce streamer development.
(4) Cathode processes are initiated fulfilling the Townsend breakdown mechanism.
(5) Gas heating from the corona causes a glow to arc transition where the arc bridges the electrode gap in what is referred to as a “leader”.

REFERENCES

[1] F Llewellyn-Jones *Ionization and breakdown in Gases*, Methuen, 1966.
[2] F W Peek Jr *Dielectric Phenomena in High Voltage Engineering*, McGraw-Hill, 1929.
[3] H W Bandel, “ Point to plane corona in dry air”, Phys. Rev. 84, 92-99, 1951
[4] W N English and L B Loeb, “Point-to-plane corona onsets”, *J. Appl. Phys.* 20, 707-711, 1949.
[5] H Raether H *Electron avalanches and breakdown in gases*, Butterworths, 1964.
[6] J J Lowke and F D’Alessandro, “Onset corona fields and electrical breakdown criteria”, J. Phys. D: Appl. Phys. 36, 2673-2682, 2003.
[7] C T Phelps and R. F. Griffiths, “Dependence of positive corona streamer propagation on air pressure and water vapor content,” J. Appl. Phys. 47, 2929, 1976.
[8] K Feser and R. C. Hughes, “Measurement of direct voltage by rod-rod gap”, Electra 117, 23-34, 1988.
[9] L Yu, L Pierrot, C O Laux and C. H. Kruger, “Effects of vibrational non-equilibrium on the chemistry of two-temperature nitrogen plasmas”, Plasma Chemistry and Plasma Processing 21, 483-503, 2001.
[10] J J Lowke, “Theory of electrical breakdown in air– the role of metastable oxygen molecules”, J. Phys. D: Appl. Phys. 25, 202-210, 1992.
[11] R C Millikan and D R White D R, “Systematics of vibrational relaxation”, J. Chem. Phys. 39, 3209-3213, 1963.
[12] M Capitelli, G Colonna, O De Pascale, C Gorse, K Hassouni and S Longo(2009), “Electron energy distribution functions and second kind collisions”, Plasma Sources Sci. Technol. 18, 014014, 2009.
[13] M Lino da Silva, V Guerra, J Loureiro and P A Sa, “Vibrational distributions in N2 with an improved calculation of energy levels”, Chemical Physics 348, 187-194, 2008.
[14] W L Morgan and B M Penetrante, “ELENDIF: a time dependent Boltzmann solver for partially ionized plasmas”, Computer Physics Communications 58, 127-152, 1990.
[15] A V Phelps and L C Pitchford, “Anisotropic scattering of electrons by N_2 and its effect on electron transport”, Phys. Rev. A 31, 2932-2949, 1985.
[16] S A Lawton and A V Phelps, “Excitation of the $b^1\Sigma^+_g$ state of O_2 by low energy electrons”, J. Chem. Phys. 69, 1055, 1978.
[17] H Brunet, P Vincent and J Rocca-Serra, “Ionization mechanism in a nitrogen glow discharge”, J. Appl, Phys. 54, 4951-4957, 1983.

Acknowledgement. The author is most indebted to Dr A V Phelps of JILA, Univ. Colorado in Boulder, USA, for discussions on electron-molecular collision processes.