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# Electrical Breakdown Voltage In a Mixed Gas

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Properties of electrical breakdown voltage in a mixed gas are investigated based on Townsend criterion. The breakdown temperature $T_b$ and voltage $V_b$ are obtained in terms of the gas mixture ratio $\chi$. As an example, we investigate electrical breakdown properties in neon gas mixed with xenon. It is shown that the breakdown voltage decreases, reaches the minimum value at $\chi = 0.02$ and then increases again, as the mixture ratio $\chi$ increases from zero to unity. A preliminary experiment of AC-plasma display panel (PDP) is carried out for neon gas mixed with a few percent of xenon to verify some of the theoretical models. The experimental data agree qualitatively well with theoretical predictions.

KEYWORDS: breakdown voltage, mixed gas, PDP, electrical discharge

One of the most important issue of the industrial applications of plasma is reduction of the electrical breakdown-voltage in high pressure gas. As an example, we consider the electrical discharge system in high-pressure inert-gas in connection with its applications to the plasma display panel (PDP).[1–3] Reduction of the breakdown voltage in a low pressure gas by the Penning effects was reported in previous literature,[4] where one hundredth of one percent of argon gas is mixed with neon. However, the plasma display panel is operated at high-pressure gas and the breakdown voltage reduction in a mixed gas is mostly accomplished by collision-frequency decrease. The UV light emitted from xenon discharge plasma is converted into fluorescence, which provides an image on TV screen. The discharge plasma is generated by the electrical breakdown. Reduction of the discharge voltage is therefore the key element in enhancing the electrical efficiency of PDP. The electrical efficiency enhancement in turn prolongs the panel lifetime. Size of xenon atoms is relatively large so that electrons in the plasma are highly collisional. Therefore, electron mean free-path is small in xenon gas, requiring high breakdown voltage. Plasma generation in a mixture of xenon and light-atom gases may not need high breakdown voltage. We therefore investigate electrical discharge properties in a mixed gas.

The ionization energy of heavy atoms is usually low, although their atomic size is large. Plasmas are generated from ionization of neutrals by the impact ionization of electrons, which have their kinetic energy higher than ionization energy. Electrons with energy higher than ionization energy collide with neutrals, ionizing them. Therefore, it is easy to ionize neutrals with less ionization energy. Meanwhile, electron energy-gain in large-size neutrals is difficult due to small mean free-path. The electrons can easily get their kinetic energy in a light-atom gas mixed with heavy atoms. Once having enough kinetic energy, they collide with heavy atoms of low ionization energy, producing additional electrons and ions.

Electron kinetic energy is estimated from its temperature $T_b$, which at breakdown is obtained from sparking criterion[5] (also known as the Townsend criterion)

$$\alpha d = \ln(1 + 1/\gamma), \tag{1}$$

in a gas without electron attachment where $\gamma$ represents the secondary electron-emission coefficient (also known as Townsend's second ionization coefficient[5]) of low energy ion bombardment at the cathode. The ionization rate $\alpha$ in eq. (1) is known as Townsend's first ionization coefficient, and is defined as the number of ionizing collisions made on the average by an electron as it *travels one centimeter in the direction of* the electric field $E$. The electron travels with the drift velocity $v_d$ in the direction of the electric field $E$. The ionization rate $\alpha_{th}$ in unit time of neutrals by plasma electrons is expressed as

$$\alpha_{th}(T) = n_n \int_0^\infty \sigma(\epsilon) v g(\epsilon) d\epsilon \tag{2}$$

where $v$ is velocity of plasma electron corresponding to the electron energy of $\epsilon$, $\sigma(\epsilon)$ is the ionization cross section of neutrals by electrons and $n_n$ is the neutral density that is $2.5 \times 10^{19}$ particles per a cubic cm at one atmospheric pressure with room temperature. Therefore, the ionization rate $\alpha$ in eq. (1) for unit length is related to the ionization rate $\alpha_{th}$ in eq. (2) for unit time by $\alpha = \alpha_{th}/v_d$. The energy distribution function $g(\epsilon)$ of plasma electrons in eq. (2) can be a complicated function, depending on individual experimental conditions. However, for the time being, we assume a thermal distribution where the electron temperature $T$ is related to the mean electron energy $\langle\epsilon\rangle$ by $\langle\epsilon\rangle = 3T/2$. The electron temperature $T$ is typically in units of eV. We have also assumed that the breakdown electric field $E$ in eq. (1) is provided by two planar electrodes separated by distance $d$ in units of cm.

Bulk plasma experiments were conducted for various neutral gases. The ionization cross section $\sigma(\epsilon)$ of these neutrals versus electron energy $\epsilon$ has been well documented. For example, the ionization cross section $\sigma(\epsilon)$ of argon neutrals by electrons is documented experimentally in ref. 6. The maximum ionization cross-section occurs near the electron energy $\epsilon = 100$ eV for most of the gas species. Typical ionization energy $\epsilon_i$ is about 15 eV for these gases. The ionization energy of argon atoms is $\epsilon_i = 15.76$ eV. For electron temperature $T$ considerably less than the ionization energy $\epsilon_i$, the ionization rate $\alpha = \alpha_{th}/v_d$ in eq. (1) can be obtained from eq. (2) and is approximately given by

$$\alpha(T) = 2n_n \frac{v_{th}}{v_d} \frac{q}{\sqrt{\pi}} (\epsilon_i + 2T) \exp\left(-\frac{\epsilon_i}{T}\right), \tag{3}$$

where $q$ is the increase rate of ionization cross section and $v_{th}$ is the thermal velocity. The increase rate $q$ is in units of $cm^2/eV$ and the energy $\epsilon_i$ and temperature $T$ are in units of eV. The increase rate $q$ represents the profile of the ionization cross section, including its size. An equation similar to eq. (3) was first obtained in ref. 7.

Assuming that the gas consists of two species $X$ and $N$, the ionization rate for this mixed gas can be expressed as

$$\alpha(T) = 5\times 10^{19}\frac{p}{\sqrt{\pi}}\frac{v_{th}}{v_d}\left[(1-\chi)q_N(\epsilon_N+2T)\exp\left(-\frac{\epsilon_N}{T}\right)+\chi q_X(\epsilon_X+2T)\exp\left(-\frac{\epsilon_X}{T}\right)\right], \tag{4}$$

where $p$ is the pressure in units of atmosphere, and the symbol $\chi$ denotes the normalized mixture ratio of the gas species $X$. As an example of eq. (4), we have obtained the ionization rate of air consisting of nitrogen and oxygen molecules with the ratio of four to one. The ionization rate of air predicted by eq. (4) agrees remarkably well with data obtained experimentally.[8] Substituting eq. (4) into eq. (1), the electron temperature $T_b$ at the breakdown is obtained from

$$5\times 10^{19}\frac{v_{th}}{v_d}\frac{pd}{\sqrt{\pi}}\left[(1-\chi)q_N\epsilon_N\exp\left(-\frac{\epsilon_N}{T_b}\right)+\chi q_X\epsilon_X\exp\left(-\frac{\epsilon_X}{T_b}\right)\right]=\ln\left(1+\frac{1}{\gamma}\right) \tag{5}$$

where we have neglected the terms proportional to $2T_b$ in comparison with the ionization energies. Once the gas mixture ratio $\chi$ is known, the electron temperature $T_b$ at the breakdown can be determined from eq. (5) in terms of the parameter $pd$.

The mean free path $\lambda$ of electrons in the mixed-gas molecules is inversely proportional to the product of scattering cross section and neutral number density. That is

$$\begin{aligned}\frac{1}{\lambda} &= [\sigma_N(1-\chi)+\sigma_X\chi]n_n\\ &= 2.5\times 10^{19}[\sigma_N(1-\chi)+\sigma_X\chi]p,\end{aligned} \tag{6}$$

where $\sigma_N$ and $\sigma_X$ denote the scattering cross sections of species $N$ and $X$, respectively, and $p$ is the gas pressure in units of atmosphere. The electrons are accelerated by the electric field $E$ (in unit of volt/cm), gaining kinetic energy of $\lambda eE$ before they collide with neutrals. These slow elections are scattered isotropically in collisions with molecules, thermalizing their gained energy. This process repeats until they establish their temperature $T = \xi\lambda eE$, where $\xi$ is the thermalization form factor of electron energy. Therefore, the electron temperature is proportional to the product of the mean free path $\lambda$ and the electric field $E$ and is expressed as

$$\frac{1}{T} = 2.5\times 10^{19}\frac{\sigma_N p}{\xi E}[1+\zeta(T)\chi], \tag{7}$$

where the relative ratio $\zeta$ of the scattering cross section is defined by

$$\zeta(T) = \frac{\sigma_X-\sigma_N}{\sigma_N}. \tag{8}$$

The electron temperature in eq. (7) is well known and corresponds to the approximation for the mean free path. Remember that the Maxwellian distribution has been used in obtaining eq. (2) for simplicity of subsequent analysis. The Maxwellian distribution originates from a constant value of the free collision frequency for electrons. The form factor $\xi$ can be found by properties of gas species and by thermalization properties of electrons. The collision cross section of neutrals is sensitive to the electron energy. This property may also play an important role in defining the form factor $\xi$.

The breakdown voltage $V_b = Ed$ is calculated from eq. (7) and can be expressed as

$$\xi V_b = 2.5\times 10^{19}\sigma_N T_b[1+\zeta(T_b)\chi]pd, \tag{9}$$

where the electron temperature $T_b$ is obtained from eq. (5) in terms of the parameter $pd$. Equation (9), together with eq. (5) is one of the main results of this article and can be used to obtain the breakdown voltage in a mixed gas. The breakdown voltage $V_b$ can be considerably reduced by an appropriate choice of the gas species whose ionization energies and collisional cross sections can provide optimum condition. For completeness of analysis, we estimate the ratio $v_{th}/v_d$ of the thermal velocity to the drift velocity for electrons. The electron drift velocity in weakly ionized plasmas is given by

$$v_d = \frac{\lambda eE}{mv_{th}}, \tag{10}$$

for $v_{th}/v_d \gg 1$ typical in high-pressure discharge. Here, $m$ is the electron mass. Making use of the electron temperature $T = \xi\lambda eE = (1/2)mv_{th}^2$ and eliminating the electric field in eq. (10), we can show that the thermalization form factor $\xi$ is related to the ratio by $v_{th}/v_d = 2\xi$.

As an example, we consider neon gas mixed with xenon. The neon gas mixed with a few percent of xenon is used in the plasma display panel (PDP) for apparent reasons shown later. We assume that the subscript $N$ and $X$ in eq. (5) represent the neon and xenon species. The increase rate $q_N$ and $q_X$ of ionization cross section for neon and xenon are given by[6] $q_N = 1.2\times 10^{-18}\,\mathrm{cm^2/eV}$ and $q_X = 3.12\times 10^{-17}\,\mathrm{cm^2/eV}$, respectively. The ionization energies for these gas species are given by[6] $\epsilon_N = 21.5\,\mathrm{eV}$ and $\epsilon_X = 12.2\,\mathrm{eV}$. Making use of the power parameter $a$ defined by $a = \epsilon_N/\epsilon_X$, and carrying out a straightforward calculation, we obtain

$$\left[(1-\chi)U^a+\frac{q_X\epsilon_X}{q_N\epsilon_N}\chi U\right] = \frac{\sqrt{\pi}\ln(1+1/\gamma)}{10^{20}q_N\epsilon_N\xi pd}, \tag{11}$$

from eq. (5), where the function $U$ is defined by

$$U = \exp\left(-\frac{\epsilon_X}{T_b}\right) = \exp\left(-\frac{12.2}{T_b}\right), \tag{12}$$

for xenon gas. Once value of the unknown $U$ is found, the corresponding temperature can be obtained from eq. (12).

The thermalization form factor $\xi$ is not known for neon and xenon. The thermalization form factor[8] of air consisted of diatomic molecules is found to be $\xi = 3$. We expect that thermalization form factor for majority of experimental gas at high pressure, where the electron temperature is about 1 eV, is in the range of $2 \lesssim \xi < 6$. However, the electron breakdown-temperature in eqs. (11) and (12) is a logarithmic dependence of the form factor $\xi$. Therefore, corrections of electron temperature associated with a correct value of the form factor is negligibly small. As an example, we consider PDP cells, assuming that the secondary electron-emission coefficient $\gamma$ at the cathode is $\gamma = 0.2$. Assuming that the thermalization form factor of neon is $\xi = 3$, the right-hand side of eq. (11) is calculated to be $3.8 \times 10^{-3}$ for $p = 1$ atmosphere and $d = 0.1$ cm, which are typical to PDP applications. The number $3.8 \times 10^{-3}$ is a very small value, thereby generating a small value of $U$ in eq. (11). Note that the parameter $q_X\epsilon_X/q_N\epsilon_N$ in eq. (11) is 14.8 which is a considerably large value. Therefore, the term proportional to $\chi U$ in the left-hand side of eq. (11) dominates over the term proportional to $U^a$ even for a relatively small value of the mixture ratio $\chi$, where the power parameter $a = 1.77$. We remind the reader that the term proportional to $\chi U$ in the left-hand side of eq. (11) originates from the contribution of xenon ionization, whereas the term proportional to $U^{1.77}$ originates from neon contribution. Ions are mostly generated from the ionization of xenon due to a low ionization energy, as expected. Therefore, the electron breakdown-temperature $T_b$ is mostly decided by the xenon ionization energy. The typical electron energy $\langle\epsilon\rangle$ at breakdown is about $\langle\epsilon\rangle \approx 3.75$ eV corresponding to the breakdown temperature $T_b = 2.5$ eV. The collisional cross sections of neon[9] and xenon[10] gases for the electron energy of $\langle\epsilon\rangle = 3.75$ eV are given by $\sigma_N = 2.5 \times 10^{-16}\,\text{cm}^2$ and $\sigma_X = 3 \times 10^{-15}\,\text{cm}^2$, respectively. Therefore, the parameter $\zeta$ defined in eq. (8) is given by $\zeta = 11$ for $T_b = 2.5$ eV. The breakdown voltage $V_b$ in eq. (9) is proportional to the collisional cross section $\sigma_N$ of neon for a small value of mixture ratio $\chi$. Although the ions are generated from xenon gas, the breakdown voltage in eq. (9) is mostly determined from collisional cross section of neon, which is one-twelfth of collisional cross section of xenon for the electron energy of $\langle\epsilon\rangle = 3.75$ eV. In this regard, the breakdown voltage can be considerably reduced by mixing neon with xenon.

Substituting proper numbers into eqs. (11), (12) and (9) for neon gas mixed with xenon, we obtain

$$[(1-\chi)U^{1.77} + 14.8\chi U] = 3.8 \times 10^{-3}, \tag{13}$$

$$T_b = \frac{12.2}{\ln(1/U)}, \tag{14}$$

and

$$\Gamma_b = \frac{\xi}{pd}V_b = 6.25 \times 10^3 T_b(1 + 11\chi), \tag{15}$$

where the normalized discharge voltage $\Gamma_b$ is in units of volt and the anode-cathode distance $d$ is in units of cm. The solution $U$ in eq. (13) decreases drastically from 0.0421 to $2.97 \times 10^{-4}/\chi$ as the mixture ratio $\chi$ increases from zero to unity. Therefore, the electron breakdown temperature $T_b$ decreases monotonically from 3.86 eV to 1.5 eV as the mixture ratio $\chi$ increases from zero to unity. As mentioned earlier, value of the solution $U$ is much less than unity.

In order to verify the theoretical model in eq. (9) for the breakdown voltage, we have carried out a preliminary experiment of AC-PDP, where three-electrodes system is used.[3] The anode and cathode are covered with a dielectric layer whose thickness is about 30 $\mu$m and are parallel to each other in front glass. The sustaining discharge in the AC-PDP occurs between these parallel sustaining electrodes. These electrode width and cell pitch are kept to be 300 $\mu$m and 1080 $\mu$m, respectively, while gap distance between electrodes varies from 50–200 $\mu$m for optimum efficiency of PDP operations. The neon (Ne) is used as a main filling gas, and a small amount of xenon gas is introduced. The anode and cathode in PDP cells are placed on a co-plane in PDP experiment. Therefore, they do not see each other. On the other hand, we have assumed that the anode and cathode plane-electrodes in the theory face each other with the gap distance of $d$. In this regard, a quantitative comparison between the theoretical prediction and experimental data may not be easy. Shown in Fig. 1 are plots of the breakdown voltage $V_b$ versus the gas mixture ratio $\chi$. The closed rectangular dots are experimental data obtained for $pd = 3.15$ Torr-cm. Taking into account of the curved electric field in coplanar electrode, the effective value of parameter $pd$ is $pd = 16$ Torr-cm corresponding to 0.022 atm-cm. The curve obtained from eq. (9) in Fig. 1 is simply the least square fit of experimental data assuming $\xi/pd = 85$. Both theory and experiment indicate that the minimum breakdown voltage occurs around the mixture ratio of $\chi \approx 0.02$. The breakdown voltage decreases to its minimum at $\chi \approx 0.02$ and then increases again, as the gas mixture ratio $\chi$ increases from zero to unity. We remind the reader that the mixture ratio $\chi = 1$ means the xenon gas only. As pointed out earlier, quantitatively comparing a theoretical result with experimental data may not be easy. However, the experimental data agree qualitatively well with theoretical predictions.

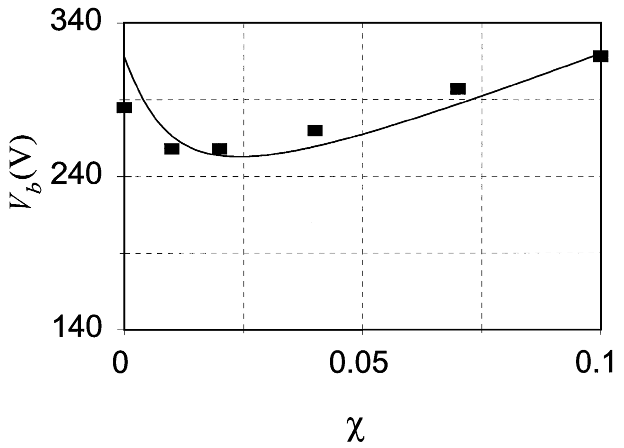


Fig. 1. Plots of the breakdown voltage $V_b$ versus the gas mixture ratio $\chi$. The closed rectangular dots are experimental data obtained for $pd = 3.15$ Torr-cm. The curve obtained from eq. (9) is simply the least square fit of experimental data assuming $\xi/pd = 85$.

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