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Properties of high-pressure discharge plasmas

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Abstract. Plasma properties during and immediately after electrical breakdown in a high-pressure gas are investigated. A simple scaling law of electrical discharge at high pressure is obtained. Introducing the normalized net ionization rate ξ, the electron temperature at breakdown is described uniquely in terms of the ionization properties of the gas, the second ionization coefficient γ at the cathode, and the parameter pd, where p is the gas pressure and d is the system dimension. The electron attachment process plays a decisive role in the breakdown phenomenon for a high-pressure gas, whereas it is not important in low-pressure discharges. An analytical expression for the high-pressure plasma density is obtained by making use of the electron rate equation. A simple analytical expression for plasma generation in a high-pressure gas provides important scaling laws in the d.c. electrical discharge system, where the electron attachment process is negligible. It is found that the logarithm of the electron density at breakdown is proportional to the discharge time τ_b, and is inversely proportional to the pulse risetime and the gap distance d between the two electrodes. The plasma density at breakdown is also an increasing function of the gas ionization energy ϵ_i.

1. Introduction

Estimation of electron energy and density at electrical breakdown is one of the most important issues in applications of various electrical discharge plasmas in high-pressure gases. For example, a coronal discharge system (Uhm and Lee 1997a,b) at atmospheric pressure has been investigated in connection with its applications to NO_x and SO_x reduction from emission gases (Chang et al. 1991; Higashi et al. 1992; Fujii et al. 1993; Hoard and Balmer 1998). Electrons in corona discharge plasma excite neutral gas species, which in turn are involved with effective chemical reactions. However, the excitation level of neutrals depends on the electron density and temperature in the plasma. Therefore a correct estimate of electron energy and density in a coronal discharge plasma is important for the determination of ongoing chemical reactions. The plasma display panel (PDP) is another application of a discharge plasma in a high-pressure gas (Slottow and Petty 1970; Weber 1987; Cho et al. 1998). Ultraviolet light emitted from the discharge plasma is converted into fluorescence, which provides an image (e.g. for a television screen). The efficiency of the ultraviolet emission is very sensitively dependent on the electron density and temperature in the discharge plasma. Correct determination of the energy gain mechanism of electrons in the discharge plasma will guide us in enhancing the electrical efficiency of PDPs. The electron energy and density of the electrical discharge from spark plugs in car engines, and the electron energy and density in lightning, are also of interest in our daily life. This paper investigates plasma properties during and immediately after electrical breakdown in a high-pressure gas.

The plasma properties may change after breakdown. This change may be due to space-charge effects, which can be identified as the plasma sheath near the electrodes, the space-charge potential caused by ambipolar diffusion, and the magnetic force due to the discharge current. We have found that these have a negligible influence on the electron energy. Thus the electron energy at breakdown may still accurately represent the energy after breakdown. In reality, electrical breakdown at high pressure is a very complicated phenomenon. It is almost impossible to describe a high-pressure discharge analytically when all physical aspects are taken into account. Therefore the present study considers only the most important aspects, namely ionization and attachment, obtaining a simple scaling law for a high-pressure discharge. The purpose of this paper is not to give a comprehensive understanding of electrical discharges at high pressure. Rather, it aims to derive of a simple scaling law that will be useful for a quantitative understanding of high-pressure discharges in a limited number of cases.

The electron temperature in a high-pressure plasma is obtained from the Townsend criterion (Howatson 1965) in Sec. 2. Several points are noteworthy in the analysis of the breakdown electron temperature. First, the electron temperature at breakdown is uniquely expressed in terms of the ionization properties (ϵ_i and q) of the gas, the second ionization coefficient γ at the cathode, and the parameter pd, where p is the gas pressure and d is the system dimension. Secondly, in a low-pressure gas, electron attachment does not have a significant effect on the electron temperature T_b and electric field E_b at breakdown, while in a high-pressure gas, the attachment process plays a decisive role in the breakdown phenomenon. Thirdly, the electron temperature at breakdown decreases as the parameter pd increases. An analytical expression for the high-pressure plasma density is obtained in Sec. 3, using the electron rate equation and neglecting electron attachment. A simple scaling law for the plasma density shows that an increase in the discharge time enhances the plasma density significantly. The logarithm of plasma density in the scaling law is inversely proportional to the gap distance d between the two electrodes. Finally, we also note from the scaling law that the plasma density at breakdown is an increasing function of the ionization energy.

2. Electron temperature in a high-pressure plasma

Electrons in the presence of a strong electric field are accelerated, gaining kinetic energy. Plasma is generated by electron impact ionization, where high-energy electrons collide and ionize neutrals in the discharge gas, creating secondary electrons and ions. Thus the ionization produces additional electrons. In many cases, the ionization rate α of the discharge gas can be expressed as

$$\alpha(E/p) = hp \exp\left(-g\frac{p}{E}\right), \tag{1}$$

where E is the electric field and p is the gas pressure. With α being in units of cm^{-1}, and E and p in units of $\mathrm{V\ cm^{-1}}$ and atm respectively, the coefficients h and g are in units of $\mathrm{cm^{-1}\ atm^{-1}}$ and $\mathrm{V\ cm^{-1}\ atm^{-1}}$ respectively; h and g are obtained from experimental data. The ionization rate α is known as Townsend's first ionization coefficient (Howatson 1965). Equation (1) agrees well with experiment in many cases, but only over the limited range of E/p corresponding to the Townsend discharge range. For example, for air, $h = 3.5\times10^3\ \mathrm{cm^{-1}\ atm^{-1}}$ and $g = 1.65\times10^5\ \mathrm{V\ cm^{-1}\ atm^{-1}}$, these values being rated for E/p in the range $1.25\times10^3\ \mathrm{V\ cm^{-1}\ atm^{-1}} < E/p < 2\times10^5\ \mathrm{V\ cm^{-1}\ atm^{-1}}$ (Wagner 1971; Price et al. 1972; Sigmond 1984; Uhm and Lee 1997a,b).

Meanwhile, the ionization rate α of neutrals by plasma electrons with temperature T much less than the ionization energy ϵ_i can also be expressed as

$$\alpha(T) = \alpha_{\mathrm{th}}(T) = 2n_0\frac{q}{\sqrt{\pi}}(\epsilon_i + 2T)\exp\left(-\frac{\epsilon_i}{T}\right), \tag{2}$$

where ϵ_i and T are both in units of eV. The rate of increase of the ionization cross-section q in (2) is in units of $\mathrm{cm^2\,eV^{-1}}$, and can be obtained from experimental data documented in Rapp and Englander-Golden (1965). Equation (2) was first obtained by Zeldovich and Raizer (1966). It is easy to analytically estimate the ionization rate from (2) for known values of ϵ_i and for a given gas.

The electrons accelerated by the electric field may not necessarily have a Maxwellian energy distribution. Indeed, theoretical calculations for helium breakdown indicate that the electron velocity distribution is anisotropic for large values of the parameter E/p (Riemann 1992; Richley 1999). However, an earlier experiment (Crompton et al. 1953) showed that a Maxwellian distribution represents the electron energy state reasonably well for air breakdown at high pressure. Taking the neutral number density to be given by $n_0 = 2.5\times10^{19}\ p\ \mathrm{cm^{-3}\ atm^{-1}}$ at pressure p, we obtain

$$Q\exp\left(-\frac{\epsilon_i}{T}\right) = \exp\left(-g\frac{p}{E}\right) \tag{3}$$

from (1) and (2). Equation (3) must be satisfied for the electric field throughout the Townsend discharge range. The constant Q in (3) is given by

$$Q = 5\times10^{19}\frac{q}{h\sqrt{\pi}}(\epsilon_i + 2T). \tag{4}$$

Recognizing that the electron temperature T in (3) is also an independent variable, (4) is valid only when the constant Q is very close to unity. We remind the reader that the electron temperature T in (4) is much less than the ionization energy ϵ_i in most experimental applications. Approximating the electron temperature T by its average value $\langle T \rangle$ in the Townsend discharge range, we find from (4) that

$$h = 5 \times 10^{19} \frac{q}{\sqrt{\pi}} (\epsilon_i + 2\langle T \rangle), \tag{5}$$

which gives a unit value of the constant Q in (4). The coefficient h is uniquely described in terms of the increase rate q and ionization energy ϵ_i of the gas species. Equation (3) can be equivalently expressed as

$$T = \frac{\epsilon_i}{g} \frac{E}{p}, \tag{6}$$

where the electron temperature T is proportional to the ionization energy ϵ_i and the electric field E in the Townsend discharge range. The electron temperature is also inversely proportional to the gas pressure p in this discharge range. Once the coefficient g has been measured experimentally, the electron temperature T in the Townsend discharge is uniquely described by the electric field and gas pressure. The mean electron energy $\langle \epsilon \rangle$ is 1.5 times the electron temperature in (6). The cross-section for scattering of neutral molecules by electrons is a function of electron temperature in general. Therefore it is difficult to define a mean free path λ of electrons that is inversely proportional to gas pressure. However, the electrons are accelerated by the electric field E, gaining kinetic energy λeE before they collide with neutrals. Therefore the electron temperature is proportional to the product of the mean free path λ and the electric field, and is expressed as $T = \zeta \lambda eE$, where ζ is the thermalization form factor of electrons and the electric field E. Note that the electron temperature $T = \zeta \lambda eE$ is similar to the expression in (6).

The breakdown electric field is obtained from the sparking criterion (also known as the Townsend criterion)

$$\exp[(\alpha - \beta)\, d] - 1 = \frac{\alpha - \beta}{\alpha \gamma} \tag{7}$$

(Howatson 1965), where β is the electron attachment constant of the gas and γ is Townsend's second ionization coefficient (Howatson 1965) at the cathode. In obtaining (7), we have also assumed that the electric field E is provided by two planar electrodes separated by a distance d. The electron attachment constant β of the gas species is generally expressed as

$$\beta(E/p) = up \exp\left(-s\frac{p}{E}\right) \tag{8}$$

(Sigmond 1984), where the coefficients u and s are measured experimentally. For example, the coefficients u and s for air are measured to be $u = 15\ \mathrm{cm^{-1}\,atm^{-1}}$ and $s = 2.5 \times 10^4\ \mathrm{V\,cm^{-1}\,atm^{-1}}$. (Wagner 1971; Price et al. 1972; Sigmond 1984; Uhm and Lee 1977a,b).

Substituting (1) and (8) into (7), the sparking condition can also be written as

$$\xi = 1 - \frac{u}{h} \exp\left[(g - s)\frac{p}{E}\right] = \frac{1}{hpd} \exp\left(g\frac{p}{E}\right) \ln\left(1 + \frac{\xi}{\gamma}\right), \tag{9}$$

where $\xi = 1-\beta/\alpha$ is the normalized net ionization rate. Eliminating the electric field E from (9), the net ionization rate ξ is calculated from

$$\frac{\xi}{(1-\xi)^{g/(g-s)}\ln(1+\xi/\gamma)} = \frac{1}{pd}\frac{h^{s/(g-s)}}{u^{g/(g-s)}}. \tag{10}$$

High-energy electrons, with energy higher than the ionization energy, ionize neutrals, whereas medium-energy electrons, with typical energy 5 eV, are captured by gas molecules. As can be seen from (6), the coefficient g is proportional to the ionization energy ϵ_i for specified electron temperature T and parameter E/p, which are also shared by the attachment process. Therefore the coefficients g and s are proportional to the ionization and attachment energies respectively of a given gas. Therefore, in general, the coefficient s is much less than the coefficient g. For example, the ratio of these coefficients for air is $s/g = 0.15$ (Uhm and Lee 1997a,b). We also note from Christophorou (1971) that the ionization cross-section is much larger than the attachment cross section, with $h \gg u$. The ratio of u and h for air is given by $u/h = 0.0043$. Physically acceptable values of the net ionization rate ξ in (10) for an electrical discharge lie in the range of $0 \leqslant \xi \leqslant 1$. Once the normalized net ionization rate ξ is known from (10) in terms of the gas ionization and attachment cross-sections, the breakdown field E_b and the electron temperature T_b at breakdown are given by

$$T_b = \frac{\epsilon_i E_b}{gp} = \frac{\epsilon_i}{\ln\left[\dfrac{\xi hpd}{\ln(1+\xi/\gamma)}\right]}, \tag{11}$$

from (6).

Several points are noteworthy from (10) and (11). First, the net ionization rate is unity ($\xi = 1$) in the absence of the attachment process ($u = 0$), as can be seen from (9). Secondly, the net ionization rate ξ approaches unity as the gas pressure parameter pd in (10) decreases. Thus we note from (11) that in a low-pressure gas, electron attachment does not have a significant effect on the electron temperature T_b and electric field E_b at breakdown. Electrons are generated by ionization (α) of neutrals and emission (γ) at the cathode, and depleted by electron attachment (β) of gas molecules. Even if there is not sufficient gas volume and material for ionization because of a small value of pd, electrons are still provided by emission from the cathode. On the other hand, the influence of electron attachment and therefore the electron depletion mechanism may disappear for a small value of the pressure parameter pd. Thirdly, because $s/g \ll 1$, the normalized net ionization rate ξ in (10) is much less than unity in a high-pressure gas characterized by a value of pd comparable to or larger than unity. It is obvious from the definition of ξ in (9) that the influence of the attachment process on the breakdown field increases as the value of ξ decreases from unity. Thus the attachment process plays a decisive role in the breakdown phenomenon for a high-pressure gas. Making use of data for the coefficients h, g, u, and s in air (Wagner 1971; Price et al. 1972; Sigmond 1984; Uhm and Lee 1997a,b), we find from (10) the factor $\xi/\ln(1+\xi/\gamma) = 0.16/pd$, which is indeed much less than unity for high-pressure air. Substituting

$$\frac{\xi}{\ln(1+\xi/\gamma)} = \frac{1}{pd}\frac{h^{s/(g-s)}}{u^{g/(g-s)}} \tag{12}$$

into (11) for $\xi \ll 1$, the breakdown field can be approximately expressed as

$$\frac{E_b}{p} = \frac{g-s}{\ln(h/u)} \tag{13}$$

for a high-pressure gas. Equation (13) can also be obtained simply by putting $\alpha = \beta$, which is equivalent to taking $\xi = 0$ in (9).

For a discharge gas without electron attachment process ($u = 0$), the parameter ξ in (9) is unity, and the electron temperature in (11) at breakdown is simplified to

$$\ln\left(1+\frac{1}{\gamma}\right) = hpd\exp\left(-\frac{\epsilon_i}{T_b}\right) = 5\times 10^{19}\frac{q\epsilon_i\, pd}{\sqrt{\pi}}\exp\left(-\frac{\epsilon_i}{T_b}\right). \tag{14}$$

In obtaining (14), use has been made of (5) and the low-temperature property of $\langle T\rangle \ll \epsilon_i$, which is valid for most experimental applications. Equation (14) is valid only for a relatively high-pressure gas satisfying

$$hpd > 2.7\ln\left(1+\frac{1}{\gamma}\right). \tag{15}$$

Otherwise, (14) must be modified to include corrections associated with the derivation of (2) under the assumption of $T \leqslant \epsilon_i$. However, we must point out to the reader that a typical value of h related to the ionization cross-section is in the range of 10^3–10^4 cm^{-1}. Therefore the value of the parameter pd can be much less than unity without violating the validity of (15).

It is remarkable to note from (14) that the electron temperature at breakdown is uniquely described in terms of the ionization properties (ϵ_i and q) of the gas, the second ionization coefficient γ at the cathode, and the gas pressure parameter pd. In particular, the electron temperature at breakdown is almost linearly proportional to the ionization energy ϵ_i. A large ionization energy of the gas requires a high electron temperature for breakdown. We also note from (14) that the electron temperature at breakdown decreases as the parameter pd associated with gas pressure and system dimension increases. It is obvious from (1) and (2) that the ionization rate increases with pressure. Thus a high-pressure gas requires a low electron temperature for breakdown. It is further noted from (14) that the electron temperature at breakdown decreases as the ionization cross-section (q) increases, or as the anode–cathode gap d increases. Finally, we also observe that the electron temperature at breakdown decreases as the second ionization coefficient γ and the cathode increases. Remember that the coefficient γ is typically much less than unity ($\gamma \ll 1$). As an example, we consider argon PDP cells, assuming that the secondary electron emission coefficient γ at the cathode is $\gamma = 0.1$. The breakdown electron temperature is calculated from (14), and is given by $T_b = 2.7$ eV for $p = 1$ atm and $d = 0.1$ cm.

As mentioned earlier, electrical breakdown at high pressure is a very complicated phenomenon. For example, electrons experience elastic and inelastic collisions (Von Engel 1955; Uhm 1999). The cross-section for inelastic collisions of neutrals with electrons is sometimes very large owing to the physical properties of molecules, including resonant behaviour. Once electrical breakdown has occurred, a swarm of plasma electrons allows the formation of a significant population of both electronically and vibrationally excited states of neutral molecules (Uhm 1999). These molecular excitations also complicated the breakdown phenomenon. It is therefore very difficult to describe quantitatively electrical breakdown at high pressure, taking account of all these physical aspects, although there have been some previous qualitative investigations of high-pressure breakdown (Von Engel 1955; Uhm 1999). In this paper, we have concentrated on the most important parameters, namely ionization and attachment, and have obtained an analytical description of the breakdown phenomenon. This analytical approach gives a simple scaling law for high-pressure breakdown, providing a quantitatively measurable scheme. The analysis of high-pressure discharge in this paper may be extended to include other physical aspects.

3. Density of high-pressure plasmas

Plasma properties inside the discharge region can be described by numerically solving the Boltzman, moment, and Poisson equations for electron and ion species. This numerical calculation is very complicated because of the many coupled differential equations involved. High-order moment equations include terms proportional to the ponderomotive force originating from the square of the electric field. However, we shall obtain a simple analytical expression for the plasma density and its generation by making use of the electron density equation. We therefore assume quasineutrality, where the electron density is the same as the positive ion density in the plasma region. The plasma is generated by electron impact ionization, where high-energy electrons collide with and ionize neutrals, creating secondary electrons and ions. Ionization produces additional electrons. Therefore the electron density plays a pivotal role in the plasma behaviour.

The analytical description is based on the electron moment equation

$$\frac{\partial n_e}{\partial t}+\frac{\partial}{\partial z}(v_d\, n_e) = v_e\, \alpha n_e - \frac{D}{\Lambda^2} - \alpha_r\, n_e^2, \tag{16}$$

where n_e is the electron density, v_d is the velocity of the electron fluid component, v_e is the electron thermal velocity, and α is the ionization rate of neutrals by electrons. In (16), the term proportional to D is the loss of electrons due to diffusion, where Λ is the plasma size, and the term proportional to α_r is the loss of electrons due to recombination. The characteristic ionization time from the first-term in the right-hand side of (16) is $1/\alpha v_d$. The ionization time for an argon plasma at 1 atm pressure is 1 ns for an electron temperature of 2.5 eV. Therefore the discharge occurs within a few tens of nanoseconds. On the other hand, the characteristic recombination time is of the order of milliseconds. The typical plasma size in most applications is of the order of a few centimetres or larger; thus there is negligibly small diffusion loss during this discharge time. In this context, we may neglect the electron loss due to diffusion and recombination. There may not be enough time for a substantial diffusion loss, even for a plasma size Λ in a PDP cell of less than 1 mm.

The subsequent analysis concentrates on the PDP application, although the analysis in this section can be used for other applications where the electron attachment process is negligible in comparison with the ionization process. We neglect the electron attachment process in (16) because most of the gases in a PDP cell are noble gases without attachment. Note that (16) is also very useful to determine the plasma density in a coronal discharge (Uhm and Lee 1997a,b), where a plasma is generated in room-temperature air at 1 atm pressure. The ionization rate α of neutrals by plasma electrons is expressed by (2), which is a good approximation for neutrals ionized by plasma electrons with a temperature less than the ionization energy ϵ_i.

The electrons accelerated by the electric field may not necessarily have a Maxwellian energy distribution. However, a previous experiment (Crompton et al. 1953) showed that a Maxwellian distribution represents the electron energy state better than any other distribution. Even for a small system such as a PDP cell, electrons collide with neutrals far more than 100 times before they reach the anode. As will be seen later, the electron fluid velocity v_d in (16) is related to the thermal velocity, which is almost constant along the axial (z) direction. Therefore (16) can be expressed as

$$\frac{\partial n_e}{\partial t}+v_d\frac{\partial n_e}{\partial z}=\frac{d}{dt}n_e(z,t)=5\times10^{19}\frac{qp\epsilon_i}{\sqrt{\pi}}v_e\exp\left(-\frac{\epsilon_i}{T}\right), \tag{17}$$

where use has been made of (2) with a neutral density of $n_n=2.5\times10^{19}\ p$ particles cm^{-3} and the property of the electron temperature $T \ll \epsilon_i$. Here the chamber pressure p is in units of atm. In obtaining (17), we have neglected the term proportional to $n_e\,\partial v_d/\partial z$ because of rapid thermalization of electrons at high pressure.

The electric field E in the discharge chamber is an increasing function of time t until it reaches the breakdown value E_b. The electron temperature T increases with the electric field. Therefore the electron temperature $T(t)$ increases from zero to the temperature T_b at breakdown, as time goes by. Denoting the electrical breakdown time by τ_b, the electron temperature T is related to time t by

$$\frac{t}{\tau_b}=\left(\frac{T}{T_b}\right)^{\eta}, \tag{18}$$

where the index η determines the rise time of the electrical pulse in the system. The pulse rises more quickly as the value of η increases. In other words, the value of the parameter η increases as the electrical pulse rise time decreases. Integrating (17) over time from zero to the breakdown time and changing the integration variable from time t to temperature T, we obtain

$$\ln\left[\frac{n_e}{n_0(z)}\right]=2.1\times10^{27}\frac{q}{\sqrt{\pi}}p\epsilon_i^{3/2}\tau_b f\left(\frac{T_b}{\epsilon_i}\right), \tag{19}$$

where the integral function $f(T_b/\epsilon_i)$ is defined by

$$f\left(\frac{T_b}{\epsilon_i}\right)=\eta\left(\frac{\epsilon_i}{T_b}\right)^{\eta}\int_0^{T_b/\epsilon_i}x^{\eta-1/2}\exp\left(-\frac{1}{x}\right)dx. \tag{20}$$

In (19), the initial electron density $n_0(z)$ is, in general, assumed to be a function of position z. Equations (19) and (20) can be used to determine the plasma density at electrical breakdown for a broad range of system parameters, including the gas ionization cross-section rate of increase q, ionization energy ϵ_i, gas pressure p, discharge time τ_b, and the integral function $f(T_b/\epsilon_i)$. The integral function $f(T_b/\epsilon_i)$ is described in terms of the electron temperature at breakdown and the parameter η related to the electrical pulse rise time.

The logarithm of the electron density n_e in (19) at electrical breakdown is proportional to the breakdown time τ_b and to the value of $f(T_b/\epsilon_i)$. The breakdown electron temperature T_b is usually much less than the ionization energy ϵ_i. The value of $f(T_b/\epsilon_i)$ has been calculated numerically. The numerical data indicate that $f(T_b/\epsilon_i)$ increases significantly as the electron temperature at breakdown increases. These data also indicate that this increase is almost exponential for a low value of the electron temperature such that $T_b/\epsilon_i \ll 1$. We also note from the numerical data that $f(T_b/\epsilon_i)$ increases significantly as the parameter η increases. For low values of the electron temperature satisfying $T_b/\epsilon_i \ll 1$, the integral function $f(T_b/\epsilon_i)$ is almost proportional to η. For example, we note from the data that the integral function at an electron temperature of $T_b/\epsilon_i = 0.15$ is given by $f = 2.9\times10^{-5}$ for $\eta = \frac{1}{2}$, $f = 5.5\times10^{-5}$ for $\eta = 1$, and $f = 1\times10^{-4}$ for $\eta = 2$. This demonstrates clearly that, for a fixed discharge time, the plasma density at breakdown increases substantially as the pulse rise time decreases.

As an example, we consider an argon PDP cell with a typical discharge time $\tau_b = 200$ ns. The rate of increase of the argon ionization cross-section q and the ionization energy ϵ_i are by $q = 1.3\times10^{-17}$ cm^2 eV^{-1} and $\epsilon_i = 15.76$ eV from data in Rapp and Englander-Golden (1965). The value $q = 1.3\times10^{-17}$ cm^2 eV^{-1} has been calculated from data in the range of electron energy ϵ satisfying $\epsilon_i < \epsilon < \epsilon_i + 5$ eV. In other words, the increase rate q is determined from the data in the first 5 eV energy range from the ionization energy. Assuming an electron temperature $T = 2.36$ eV, corresponding to $T_b/\epsilon_i = 0.15$, the plasma density in (19) is calculated to be $n_e(z)/n_0 = 4.1\times10^4$ for $\eta = 1$ and $n_e(z)/n_0 = 2.3\times10^8$ for $\eta = 2$. Obviously, we can see a tremendous increase in plasma density by shortening the pulse rise time. We remind the reader that the plasma density in (19) is expressed as a logarithmic function. Therefore increasing the value of the right-hand side in (19) by quite a small factor can increase the plasma density by several orders of magnitude.

The plasma density at electrical breakdown is calculated by substituting the electron temperature T_b obtained from (14) into (19) and (20). Owing to the complicate integral equation in (20), it is still difficult to find a simple scaling law for the plasma density from (19). However, we recognize the inequality

$$f\left(\frac{T_b}{\epsilon_i}\right) < \frac{1}{2}\eta\left(\frac{T_b}{\epsilon_i}\right)^{1/2}\exp\left(-\frac{\epsilon_i}{T_b}\right) \tag{21}$$

from the integral function in (20). The inequality in (21) shows that $f(T_b/\epsilon_i)$ is proportional to the parameter η, as expected. We also note from (21) that the integral in (20) is an exponential function of the electron temperature. Substituting (14) into (21) and eliminating the exponential function of the electron temperature T_b, the plasma density in (19) satisfies

$$\ln\left(\frac{n_e}{n_0}\right) < 2.1\times10^7\,\eta\,\sqrt{T_b}\,\frac{\tau_b}{d}\ln\left(1+\frac{1}{\gamma}\right), \tag{22}$$

which is a density scaling law for a plasma generated by an electrical discharge in high-pressure gas. Several points are noteworthy from (22). First, the logarithm of the electron density at breakdown is proportional to the discharge time τ_b, and the parameter η is related to the pulse rise time. Increasing the discharge time enhances the plasma density significantly. However, the discharge time τ_b in a PDP cell may be limited by charge accumulation at the surfaces of the dielectric materials. Secondly, the logarithm of the plasma density is inversely proportional to the gap d between the two electrodes. Decreasing the distance between electrodes enhances the plasma density tremendously. Thirdly, the plasma density at breakdown depends slightly on the secondary electron emission coefficient γ at the cathode. In fact, the plasma density decreases slightly as the secondary electron emission coefficient γ increases, although the breakdown field may decrease. Finally, we note from (22) that the plasma density is proportional to the square root of the electron temperature at breakdown. Note from (14) that the electron temperature T_b at breakdown is almost linearly proportional to the ionization energy ϵ_i. We therefore recognize that the plasma density at breakdown is an increasing function of the ionization energy.

Equation (22) qualitatively describes the plasma density at electrical breakdown in high-pressure gas. A correct estimate of the plasma density at breakdown must be obtained numerically from (14), (19), and (20), instead of (22).

4. Conclusions

The properties of plasmas generated from a high-pressure discharge have been investigated in this paper. The electron temperature of a high-pressure plasma was obtained from the Townsend criterion in Sec. 2. Several points are noteworthy from the breakdown electron temperature in (10) and (11). First, the electron temperature at breakdown is uniquely expressed in terms of the ionization properties (ϵ_i and q) of the gas, the second ionization coefficient γ at the cathode, and the gas pressure parameter pd. Secondly, the net ionization rate ξ approaches unity as the gas pressure parameter pd in (10) decreases. Thus we note from (11) that in a low-pressure gas, electron attachment does not have a significant effect on the electron temperature T_b and electric field E_b at breakdown. Thirdly, the attachment process does play a decisive role in the breakdown phenomenon for a high-pressure gas. In other words, the influence of the Townsend's second ionization coefficient γ is negligible in electrical discharges in a high-pressure gas with a non-zero electron attachment coefficient. Finally, we note that the electron temperature at breakdown decreases as the parameter pd associated with gas pressure and system dimension increases.

An analytical expression for the high-pressure plasma density was obtained in Sec. 3 by making use of the electron rate equation and neglecting electron attachment. A simple scaling law (22) for the plasma density shows that the logarithm of the electron density at breakdown is proportional to the discharge time τ_b and the parameter η related to the pulse rise time. An increase in the discharge time enhances the plasma density significantly. The logarithm of the plasma density in the scaling law is inversely proportional to the gap d between the two electrodes. Finally, we also noted from (22) that the plasma density at breakdown is an increasing function of the ionization energy.

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