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Experiments and simulations of an atmospheric pressure lossy dielectric barrier Townsend discharge

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Abstract
A diffuse discharge is produced in atmospheric pressure air between porous alumina dielectric barriers using low-frequency (60 Hz) alternating current. To study its formation mechanism, both the discharge current and voltage are measured while varying the dielectric barrier porosity (0%, 48% or 85%) and composition (99% Al\textsubscript{2}O\textsubscript{3}, 99% SiO\textsubscript{2} or 75% Al\textsubscript{2}O\textsubscript{3} + 16% SiO\textsubscript{2} + 9% other oxides). Time-resolved imaging of the emission is carried out to understand the discharge structure. The results indicate that the ionization is driven by an electron avalanche process. This Townsend discharge is found to persist for quite some time (∼3 ms) when the barriers are alumina with a high porosity (>48%). Micro-streamers are observed for the low porosity alumina barriers as well as for other oxide barriers. This discharge formation with highly porous alumina in air is attributed to a relatively low volume dielectric barrier resistivity (∼10\textsuperscript{5} \textOmega/m). Simulations are carried out, accounting for the surface charge loss due to this porosity, as well as for charge accumulation at the barriers.

Keywords: dielectric barrier discharge, high pressure glow discharge, porous dielectric barrier

(Some figures may appear in colour only in the online journal)

1. Introduction

There has been much interest recently in the generation of relatively diffuse non-thermal discharges at atmospheric pressure because of their possible applications to biological sterilization and surface treatment (Montie \textit{et al} 2000, Scott \textit{et al} 2004, Roth \textit{et al} 2005). The use of atmospheric pressure discharges enables much simpler and economical system designs since they do not require complex vacuum processing systems. It is, however, very challenging to generate diffuse discharges in atmospheric pressure air, i.e. ambient air. At low pressure, diffuse glow discharges are sustained by the Townsend breakdown process. This generates multiple electron avalanches that are spatially evenly distributed, originating from the cathode. At high pressure, a streamer can be induced by a single electron avalanche.

This primary avalanche induces a space charge field that is comparable in strength to the externally applied electric field, spawning additional electron avalanches that eventually result in the formation of a streamer. The formation of uniform diffuse discharges in air at high pressure is further complicated by the presence of oxygen. Oxygen tends to quench metastable states—which prevent such streamer formation. There have been numerous studies aimed at generating uniform high pressure non-thermal discharges that use various types of driving sources (wide range of alternating current (ac) frequency, direct current and nano-pulse), dielectric barriers (alumina, glass, etc) and gases (inert gases and N\textsubscript{2}) (Okazaki \textit{et al} 1993, Massines \textit{et al} 1998, Stark and Schoenbach 1999, Trunec \textit{et al} 2001, Kogelschatz 2002, Mangolini \textit{et al} 2002, Massines \textit{et al} 2003, Moon \textit{et al} 2004). Recently, Garamoon and El-zeer (2009), described the use of porous alumina as a dielectric barrier to generate volumetric non-thermal diffuse discharges in atmospheric air. Their studies employed very low-frequency ac discharges. Here, we investigate
the mechanism behind the production of these unique low-frequency driven air discharges through a combination of experiments and numerical simulations.

2. Experiments

The experimental setup consists of two metal electrodes covered by porous barriers, voltage and current probes, and an intensified charge-coupled device (ICCD) camera, as seen in figure 1. The electrodes are made of copper tape trimmed to a circle of 15 mm diameter and placed to face each other. Different types of 3 mm thick barriers are installed on top of the electrodes. The barriers examined include the following: (i) 48% porosity alumina, (ii) 85% porosity alumina, (iii) non-porous alumina, (iv) 31% porosity SiO$_2$ and (v) 35% porosity 75% Al$_2$O$_3$ + 16% SiO$_2$ + 9% other oxides. The barriers are cut into either a square shape of 30 mm sides or a rectangular shape of 40 mm in width and 50 mm in length. The gap between the porous barriers is 1 mm. The left electrode in figure 1 is powered by a high voltage transformer at 60 Hz frequency and the right electrode is grounded. The discharge plasma is generated in atmospheric pressure ambient air. Applied voltages and discharge currents are recorded using a 1000:1 high voltage probe (Tektronix, P6015A) and a Rogowski coil (Pearson Electronics, Model 8122), respectively, and signals are collected on an oscilloscope (Tektronix, TDS 7104).

Visible discharge emission is imaged in a time-resolved manner using a 1024 by 256 pixel ICCD camera (Princeton Instrument, PI-MAX). The camera is focused onto a centre lens (Nikon micro nikkor) with extension tubes. Unless otherwise stated, the imaging covers a 1 mm width and 5 mm height aligned to the discharge centre, with a spatial resolution of 14 µm pixel$^{-1}$. This imaging region (see figure 1) is smaller than the discharge size to minimize the effect of the electrode edges on emission. The image acquisition is triggered using the voltage signal with a variable time delay using a pulse delay generator (SRS, DG 535). This allows us to take time-synchronized images at different phases in the ac cycle. The images have an integration time of 150 µs.

3. Simulations

Simulations are carried out for the same experimental configuration. Details of the simulation are described in figure 2. Since the plasma is spatially uniform along the radial direction when in the diffuse discharge mode, the simulation is one-dimensional (1D) across the electrode gap. The applied voltage is sinusoidal at 60 Hz with a peak-to-peak voltage of 14 kV, as illustrated in the inset of figure 2. The simulations are carried out for the specific properties of 3 mm thick 48% porosity alumina barriers. In accordance with the provided material properties, we adopt a barrier volume resistivity, $\rho$, of $5 \times 10^5$ Ω m. The relative permittivity of non-porous alumina, $\varepsilon_r$, is typically 10.1 (American Ceramic Society 1985), therefore, the effective relative permittivity of the barrier, $\varepsilon_r$, is estimated to be 5.732 based on a volume-weighted scaling:

$$\varepsilon_r = \varepsilon_{r, \text{alumina}} (1 - \alpha) + \alpha.$$  (1)

Here, $\alpha$ is the barrier porosity.

In the simulations, we account for both surface charge loss due to the barrier porosity and charge accumulation at the barrier–plasma interface due to the migration of charged particles to the dielectric surfaces. The simulations are performed on a uniform grid with a grid cell size of 10 µm. A grid refinement, carried out by reducing the grid size to 2 µm, reproduced similar results in the simulations. The electron and ion number densities and electric potential (voltage) are computed at the cell centre whereas the electric field is computed at the cell boundaries.

The species conservation equations for the number densities of the electrons, positive ions (N$^+$) and O$^+$), negative ions (O$_2^-$), and the excited electronic states (N$_2$(C)) are:

$$\frac{\partial n_e}{\partial t} + \frac{\partial \Gamma_e}{\partial x} = \begin{bmatrix} k_{\text{ioniz}, N_2} n_e N_2 + k_{\text{ioniz}, O_2} n_e O_2 + k_{\text{detach}, O_2} n_{O_2} \varepsilon_{\text{total}} \\ -k_{\text{attach}, n_e O_2} - k_{\text{attach}, n_e O_2} n_{total} \\ -k_{\text{recomb}, n_{O_2} n_e} - k_{\text{recomb}, n_{O_2} n_e} \end{bmatrix}$$

(2)

$$\frac{\partial n_{N_2}}{\partial t} + \frac{\partial \Gamma_{N_2}}{\partial x} = \begin{bmatrix} k_{\text{ioniz}, N_2} n_e N_2 - k_{\text{recomb}, n_{N_2} n_e} \\ -k_{\text{recomb}, ions n_{N_2}} n_{N_2} - k_{\text{conv, ions}} n_{N_2} n_{O_2} \\ -k_{\text{recomb}, ions n_{O_2}} n_{O_2} + k_{\text{conv, ions}} n_{N_2} n_{O_2} \end{bmatrix}$$

(3)

$$\frac{\partial n_{O_2}}{\partial t} + \frac{\partial \Gamma_{O_2}}{\partial x} = \begin{bmatrix} k_{\text{ioniz}, O_2} n_e O_2 - k_{\text{recomb}, n_{O_2} n_e} \\ -k_{\text{recomb}, ions n_{O_2}} n_{O_2} + k_{\text{conv, ions}} n_{N_2} n_{O_2} \end{bmatrix}$$

(4)

$$\frac{\partial n_{N_2^*}}{\partial t} + \frac{\partial \Gamma_{N_2^*}}{\partial x} = \begin{bmatrix} k_{\text{attach}, n_e N_2} + k_{\text{attach}, n_e N_2} n_{total} \\ -k_{\text{detach}, n_{O_2}} n_{total} - k_{\text{recomb}, ions} (n_{O_2} + n_{N_2^*}) n_{O_2} \end{bmatrix}$$

(5)

$$\frac{\partial n_{O_2^*}}{\partial t} + \frac{\partial \Gamma_{O_2^*}}{\partial x} = \begin{bmatrix} k_{\text{excit}, n_e N_2} - k_{\text{quench}} n_{O_2^*} n_{total} - k_{\text{quench}} n_{O_2^*} \end{bmatrix}.$$  (6)

![Figure 1. Experimental setup of discharges produced between porous dielectric barriers at atmospheric pressure in ambient air.](Image)
These are solved together with the conservation equations for the surface charge densities, $\sigma$, at the barrier surfaces (separated by the spacing, $L$):

\[
\frac{d\sigma_{\text{ground-side}}}{dt} = e \left( -\Gamma_{N_2^+}(0) - \Gamma_{O_2^-}(0) + \Gamma_e(0) + \Gamma_{O^+}(0) \right)
+ \frac{\sigma_{\text{ground-side}} \rho(\varepsilon_r \varepsilon_0)}{\varepsilon_0} .
\] (7)

\[
\frac{d\sigma_{\text{driven-side}}}{dt} = e \left( \Gamma_{N_2^+}(L) + \Gamma_{O_2^-}(L) - \Gamma_e(L) - \Gamma_{O^+}(L) \right)
+ \frac{\sigma_{\text{driven-side}} \rho(\varepsilon_r \varepsilon_0)}{\varepsilon_0} .
\] (8)

Here, the first term on the right-hand side accounts for the charge accumulation as a result of the charge transport from the plasma and the second term on the right-hand side accounts for the charge loss due to the low barrier electrical resistivity.

The conservation equations are coupled to the momentum equations. We use a drift–diffusion approximation for the electrons and ions:

\[
\Gamma_e = -D_e \frac{\partial n_e}{\partial x} - \mu_e n_e E
\] (9)

\[
\Gamma_{N_2^+} = -D_{N_2^+} \frac{\partial n_{N_2^+}}{\partial x} + \mu_{N_2^+} n_{N_2^+} E
\] (10)

\[
\Gamma_{O_2^-} = -D_{O_2^-} \frac{\partial n_{O_2^-}}{\partial x} + \mu_{O_2^-} n_{O_2^-} E
\] (11)

\[
\Gamma_{O^+} = -D_{O^+} \frac{\partial n_{O^+}}{\partial x} - \mu_{O^+} n_{O^+} E
\] (12)

\[
\Gamma_* = -D_* \frac{\partial n_*}{\partial x} .
\] (13)

In the above equations, $n_j$ is the number density of species $j$, $\Gamma_j$ is the corresponding particle flux, $E$ is the electric field, $D_j$ is the diffusion coefficient, and $\mu_j$ is the species mobility. For ions, the diffusion coefficient is related to the mobility through the Einstein relation,

\[
D_j = \frac{\mu_j kT_j}{e} .
\] (14)

Here, the ion temperature is assumed to be equal to the neutral species temperature. The mobility of positive and negative ions is taken from Basurto et al (2000).

The kinetic mechanism and corresponding reaction rate coefficients, $k_j$, used in the above equations are summarized in Table 1. In this table, $k_{\text{ioniz},N_2}$ and $k_{\text{ioniz},O_2}$ are the electron-impact ionization rate coefficients of $N_2$ and $O_2$, respectively. The electron detachment, binary, and three-body electron attachment rate coefficients are $k_{\text{detach}}$, $k_{\text{attach}}$ and $k_{\text{attach,3}}$, respectively. The rate coefficients for recombination between either the electrons and ions, or positive and negative ions are $k_{\text{recomb}}$ and $k_{\text{recomb,ions}}$. The ion conversion rate coefficient resulting from collisions between $N_2^+$ and $O_2$ is $k_{\text{conv,ions}}$, the electron-impact excitation rate coefficient of the $N_2(C)$ state is $k_{\text{excit}}$, and $k_{\text{quen}}$ and $\nu_{\text{quen}}$ are the collisional and radiation quenching rate coefficients of $N_2(C)$. Calculations of $D_e, \mu_e$, and the reaction rate coefficients involving electrons are facilitated using the commercially available Bolsig$^*$ software package (Hagelaar and Pitchford 2005). In carrying out the simulations, the reaction rate coefficients, and $D_e$ and $\mu_e$ are pre-tabulated as a function of reduced electric field (Td).

In Table 1, $E/n$ is the reduced electric field, and $T$ and $T_e$ are the gas and electron temperatures, respectively. The units of $E/n$ in the formula are Td, and those of $T$ and $T_e$ are K.

The electric field at the cell boundaries are updated after each time step by solving Poisson’s equation with boundary
conditions imposed by charges on the barrier surfaces:

\[
\frac{\partial}{\partial x}(\sigma_0 E) = (n_{N_2} + n_{O_2} - n_e - n_{O_2}^-)
+ \sigma_{\text{ground-side}} \delta(x) + \sigma_{\text{driven-side}} \delta(x - L) \\
- (\varepsilon \varepsilon_0) E_{\text{ground-side barrier}} + \varepsilon_0 E_{\text{ground-side gas}}
\]

\[
= \sigma_{\text{ground-side}}
- \varepsilon_0 E_{\text{driven-side barrier}} + (\varepsilon \varepsilon_0) E_{\text{driven-side barrier}}
= \sigma_{\text{driven-side}}
\]

\[
V_{\text{app}}(t) = -E_{\text{ground-side barrier}} d
- \int_0^L E \, dx - E_{\text{driven-side barrier}} d
\]

In equations (15–17), \( \varepsilon_0 \) is the vacuum permittivity, \( L \) is the distance between the barriers, \( \delta(x) \) and \( \delta(x - L) \) are the Dirac-delta functions centred on \( x = 0 \) and \( x = L \), respectively, \( V_{\text{app}} \) is the applied voltage, and \( d \) is the porous barrier thickness. \( E_{\text{ground-side barrier}} \) and \( E_{\text{driven-side barrier}} \) are the electric fields inside the ground-side and driven-side porous barriers whereas \( E_{\text{ground-side gas}} \) and \( E_{\text{driven-side gas}} \) are the electric fields at the porous barrier surfaces of the ground and driven electrodes.

Secondary electron emission induced by positive ion bombardment at the porous barrier surface provides a boundary condition on the electron flux:

\[
\Gamma_e = -\gamma \Gamma_.
\]

The secondary electron emission coefficient, \( \gamma \), is determined to be 0.8 by matching the simulated peak current to the measured. The general discharge behaviour was not a strong function of the secondary emission coefficient used while the peak current increases with increasing the coefficient. This value for \( \gamma \) is higher than what is often used in discharge simulations. We attribute the need to use a higher value to account for the increased effective surface area associated with the high porosity of the barriers.

For initial conditions, the gas pressure and temperature are fixed at 1 atm and 300 K. The radical and ion species number densities are initially set to a very low value of \( 10^{-3} \) cm\(^{-3}\). The simulation runs for many ac cycles and are found to reach a quasi-steady behaviour within five or more cycles. The properties of the discharge after several cycles are found to be rather insensitive to the assumed initial species densities.

The equations are discretized according to the Scharfetter–Gummel scheme (Scharfetter and Gummel 1969), which affords improved numerical stability when solving drift–diffusion problems. The system of equations (less Poisson’s equation) is solved iteratively with an adaptive time step using the Sundial package (Hindmarsh et al 2005). Poisson’s equation is solved by the method of lower-upper (LU) triangular matrix decomposition using the linear algebra package (LAPACK) (www.netlib.org/lapack/).

4. Results

Voltage and current waveforms for discharges incorporating 3 mm thick 48% porosity alumina barriers over a 30 mm × 30 mm square area are shown in figures 3(a)–(d) for peak-to-peak applied voltages of 11 kV, 12 kV, 14 kV and 15 kV, respectively. For the 11 kV condition, there is no visible plasma emission to the eye and the current probe detects only displacement current (see figure 3(a)). As the peak-to-peak voltage is increased to 12 and 14 kV, a spatially homogeneous emission (along the radial direction) is observed, lasting for about 3 ms. This emission coincided with the positive and negative peak in the discharge voltage and appears as an additional conduction current contribution to the total discharge current recorded (see figures 3(b) and (c), respectively). A false-colour image of this diffuse discharge taken by a digital camera with a 0.62 s exposure time is presented in figure 4(a). This volume-filling discharge is quite distinct from a typical emission pattern seen in dielectric barrier discharges which, in air, consist of micro-streamers usually lasting less than 100 ns. As a result, the current waveform is rather continuous in time while that of typical dielectric barrier discharges has current spikes near the breakdown voltage. An interesting feature in figure 3, particularly apparent at the higher voltages, is that the current and voltage waveforms are almost in phase, indicating that the contribution to the total

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Rate coefficient</th>
<th>Ref</th>
</tr>
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<tbody>
<tr>
<td>( N_2 + e \rightarrow N_2^+ + 2e )</td>
<td>( k_{\text{ionize, } N_2} )</td>
<td>Phelps and Pitchford (2013)</td>
</tr>
<tr>
<td>( O_2 + e \rightarrow O_2^- + 2e )</td>
<td>( k_{\text{ionize, } O_2} )</td>
<td>Phelps (2013)</td>
</tr>
<tr>
<td>( O_2 + M \rightarrow O_2^- + M + e )</td>
<td>( k_{\text{detach}} = 1.24 \times 10^{-17} \exp(-179/(8.8 + E/n))^2 ) m(^3) s(^{-1})</td>
<td>Pancheshnyi (2013)</td>
</tr>
<tr>
<td>( e + O_2 + M \rightarrow O_2^- + M )</td>
<td>( k_{\text{attach, } 1} = 1.07 \times 10^{-24}(300/T)^2 \exp(-70/T) \times 1500 \times (T_0 - T)/T_0 ) m(^3) s(^{-1}) if ( M = N_2 )</td>
<td>Kossyi et al (1992)</td>
</tr>
<tr>
<td>( e + M^+ \rightarrow M )</td>
<td>( k_{\text{recomb}} = 2.0 \times 10^{-13}(300/T_0)^{0.5} ) m(^3) s(^{-1})</td>
<td>Kossyi et al (1992)</td>
</tr>
<tr>
<td>( M^+ + O_2 \rightarrow M + O_2 )</td>
<td>( k_{\text{recomb, ions}} = 2.0 \times 10^{-13}(300/T_0)^{0.5} ) m(^3) s(^{-1})</td>
<td>Kossyi et al (1992)</td>
</tr>
<tr>
<td>( M + N_2, O_2 )</td>
<td>( k_{\text{comb, } n} = 6.0 \times 10^{-17}/300/T_0 ) m(^3) s(^{-1})</td>
<td>Capitelli et al (2000)</td>
</tr>
<tr>
<td>( n + N_2(X) \rightarrow n + N_2^-(C) )</td>
<td>( k_{\text{excit}} = 10^{-17} ) m(^3) s(^{-1}) if ( M = N_2 )</td>
<td>Phelps and Pitchford (2013)</td>
</tr>
<tr>
<td>( n + O_2(X) \rightarrow n + O_2(C) )</td>
<td>( k_{\text{quench}} = 3 \times 10^{-16} ) m(^3) s(^{-1}) if ( M = O_2 )</td>
<td>Capitelli et al (2000)</td>
</tr>
<tr>
<td>( N_2(C) + M \rightarrow N_2(X) + M )</td>
<td>( k_{\text{quench}} = 3 \times 10^{-7} ) s(^{-1})</td>
<td>Capitelli et al (2000)</td>
</tr>
</tbody>
</table>
current by the displacement current across the dielectric is small. Since the micro-discharges are terminated as a result of the decrease in a net applied potential while the charge accumulates on the barrier surfaces, the loss in the surface charge densities is necessary to sustain a diffuse discharge over a long duration by maintaining the net applied potential into a certain level. The porous barriers seem to leak the charges to the electrodes, providing a regime that the transition to sparking is prevented but the electric field is high enough to sustain the plasma. The formation of a spark connecting the gap between the barriers is observed when a 15 kV $p-p$ voltage is applied, as seen in figure 4(b).

The voltage and current waveforms for barriers of the same properties as figure 3(c) but for a larger surface area (40 mm by 50 mm) are shown in figure 5. This case also produces a diffuse discharge and while the peak current is proportionally higher (as expected) the excursions in this current due to filamentary structure seems to be significantly less. Imaging of visible emission from the discharges is performed for the case of figure 5, to study the discharge behaviour and structure in more detail. Two points within the current cycle, P1 and P2, were chosen as starting points for time-synchronized recordings captured with the ICCD. These points, illustrated in figure 6, are where the current starts to increase at both the positive (P1) and negative (P2) cycles of the driving voltage. Because of the change in polarity, the driven and grounded electrodes act as an anode at time markers P1 and P2, respectively. Images recorded with 100 $\mu$s separation during 400 $\mu$s after P1 and P2 reference phases are illustrated in figures 7(a) and (b), respectively. The emission appears to be relatively uniform along the direction parallel to the electrode surface for both the positive and negative
Figure 5. The voltage and current waveforms at 14 kV applied voltage with 3 mm thick alumina plate of 48% porosity and larger surface area.

Figure 6. The voltage and current waveforms marked with reference phases, P1 and P2 when current starts flow at positive and negative half cycle.

cycles. Interestingly, the brightest emission is observed near the anode for both cycles. This suggests that the sheath development near the cathode region is relatively weak and that the ionization is mostly by an electron avalanche process or Townsend discharge, which is thought to be difficult to produce in a standard ambient air. A sequence of images taken with a 500 µs separation in time is shown in figures 8(a) and (b) for both the positive and negative cycles, respectively. We see that this Townsend discharge is sustained over a relatively long duration of 3 ms.

We attribute the formation of these uniform (non-filamentary) discharges to the relative low electrical resistivity of the barrier (of order $10^5$ Ω m) that is attributable to the barrier porosity and its associated surface leakage currents. To support this conjecture, barriers with different porosities and different material compositions were also tested. The voltage and current waveforms of the discharges produced between 3 mm thickness alumina barriers of 85% and 0% porosity are plotted in figures 9(a) and (b), respectively. The alumina barriers of 85% and 0% porosity have lower and higher electrical resistivity than that of the 48% porosity case. According to material specifications, the non-porous alumina barrier has a
resistivity of about $10^{12} \, \Omega \cdot m$. At a 14 kV peak-to-peak voltage, the 85% porosity barrier provides a higher current than that for the 48% porosity case. However, a higher applied voltage is required to produce visible discharges for the non-porous alumina barrier and the current waveform resembles that of a more conventional filamentary air dielectric barrier discharge.

Two different material compositions, a 3 mm thick SiO$_2$ plate at 31% porosity and a 3 mm thick 75% Al$_2$O$_3$ + 16% SiO$_2$ (+9% other oxides) plate at 35% porosity, are also tested as barriers. Their electrical resistivities are $10^{14} \, \Omega \cdot m$ and $10^9 \, \Omega \cdot m$, respectively. These resistivities are much higher than that of the 3 mm thick alumina plate of 48% porosity. The voltage and current waveforms of the discharges produced between these barriers are shown in figures 10(a) and (b). Both are found to form typical filamentary discharges. However, it is noteworthy that many more filamentary micro-discharges are produced for the 75% Al$_2$O$_3$, 35% porosity case. The discharge duration also appears to be much longer than that of the 31% SiO$_2$ porosity case. This indicates that the barrier material as well as its porosity also affects the discharge dynamics.

The simulations corresponding to the experiment are conducted for discharge conditions that the barriers are 3 mm thick porous alumina and the peak voltage is 14 kV. The spatial and temporal evolution in the computed electric field and electron number density are shown in figures 11(a) and (b), respectively. The electric field is found to be almost constant across the domain since net charge density in this discharge is not high enough to shield the applied potential. The electrons are first produced in a region close to the driven electrode when it is positively biased (anode) where the number density is highest, peaking at a value of about $1.5 \times 10^7 \, \text{cm}^{-3}$. This spatial distribution indicates that the plasma is generated as a result of electron avalanche ionization as electrons drift across the gap. As the discharge voltage reverses in time when the driven electrode is now negatively biased (cathode), so does avalanche ionization process, with the plasma now formed near the ground electrode (anode) of nearly equal peak in the plasma density.

Simulated voltages on the both the porous barrier and electrode surfaces, as well as simulated discharge current are shown in figures 12(a) and (b), respectively. The current is calculated by multiplying the current density by the discharge area, which is estimated to be about 9 cm$^2$. When the plasma is initiated (at about 3 ms), a slight voltage decrease (and increase) is seen at the anode-side (and cathode-side) surface as a result of the surface charge accumulation despite current leaking through the porous barrier to the electrodes.
Unlike typical dielectric barrier discharges, the discharge conduction current is relatively long-lived and does not depict the usual bursts of nanosecond peaks indicative of streamer formations.

The simulated spatial and temporal evolution of the number densities of $N_2^+$, $O_2^+$, and $O_2^-$ are shown in figures 13(a), (b) and (c), respectively. Since the positively charged particles drift towards the negatively biased electrode, the population of the positive ion number densities is expected to be highest near the cathode. While this is found to be the case for $O_2^+$, it is apparent that $N_2^+$ does not follow this trend. The reason for this unexpected behaviour is because of the fast collision-induced ion conversion between $N_2$ and $O_2$. $N_2^+$ is initially produced at the anode where the ionization is relatively strong and then transfers its charge to $O_2$ before migrating towards the cathode. As expected, $O_2^-$ has the highest number density near the anode where the electron number density is highest.

The spatial and temporal evolution of the excited electronic states of the $N_2(C)$ number density is shown in figure 14(a). The spatial and temporal structure of the $N_2(C)$ state populations is expected to be representative of the observed overall emission, since a significant portion of the discharge emission is from the radiation decay of $N_2(C)$. Consistent with the experimental findings (figure 8), the highest $N_2(C)$ emission is observed near the anode. The direct comparison for the highest spatial intensity is made between the simulated $N_2(C)$ and the measured (visible) emission in figure 14(b). The onset of the emission and its duration are almost same, but in the measured, the intensity is slightly higher at the phase that the plasma is forming. The results of the simulations are in general, found to be in good overall agreement with the experiments. The simulations confirm that the discharge is sustained through an electron avalanche process consistent with the structure of a Townsend discharge. More specifically, the simulations capture the observed behaviour in the discharge current (figure 12(b)).
Figure 13. Spatial and temporal evolution for the number densities (cm$^{-3}$) of charged ions of (a) N$_2^+$, (b) O$_2^+$, and (c) O$_2^-$ for discharge conditions that the barriers are 3 mm thick 48% porous alumina and the applied voltage is 14 kV.

Figure 14. Spatial and temporal evolution of excited electronic state of N$_2$(C) number density (cm$^{-3}$) for discharge conditions that the barriers are 3 mm thick 48% porous alumina and the applied voltage is 14 kV.

5. Summary

A uniform diffuse discharge was produced in standard air between the porous alumina barriers. Time-resolved emission suggests that the discharge is sustained by an electron avalanche mechanism with the strongest ionization occurring adjacent to the anode. The formation of this discharge was attributed to the low electrical resistivity of the porous barriers. The use of non-porous alumina plates and porous plates containing silicon oxides of higher resistivity resulted in the formation of spatially localized streamers. Detailed 1D simulations were carried out, accounting for excited-state kinetics and chemistry, as well as for charge accumulation and loss at the surface of the porous barriers. The simulations were in good agreement with the measurements of both emission and current waveforms, confirming that the strongest emission, due primarily to the radiation decay of electronically excited nitrogen, was adjacent to the anode. The electron density was also highest in the vicinity of the anode and the electric field was almost constant across the electrodes, also indicative of a Townsend discharge regime.

Acknowledgments

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References

American Ceramic Society 1985 Ceramic source (Columbus, OH: The Society)
Basurto E, Urquijo J de, Alvarez I and Cisneros C 2000 Mobility of He⁺, Ne⁺, Ar⁺, N₂⁺, O₂⁺, and CO₂⁺ in their parent gas Phys. Rev. E 61 3


Garamoon A A and El-zeer D M 2009 Atmospheric pressure glow discharge plasma in air at frequency 50 Hz Plasma Sources Sci. Technol. 18 045006


Montie T C, Kelly-Wintenberg K and Roth J R 2000 An overview of research using the one atmosphere uniform glow discharge plasma (OAUGDP) for sterilization of surface and materials IEEE Trans. Plasma Sci. 28 41–50

Moon S Y, Choe W and Kang B K 2004 A uniform glow discharge plasma source at atmospheric pressure Appl. Phys. Lett. 84 188–90


