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Numerical investigation of co-axial DBD: Influence of relative permittivity of the dielectric barrier, applied voltage amplitude, and frequency

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In this work, a one-dimensional numerical fluid model is developed for co-axial dielectric barrier discharge in pure helium and a parametric study is performed to systematically study the influence of relative permittivity of the dielectric barrier and the applied voltage amplitude and frequency on the discharge performance. Discharge current, gap voltage, and spatially averaged electron density profiles are presented as a function of relative permittivity and voltage parameters. For the geometry under consideration, both the applied voltage parameters are shown to increase the maximum amplitude of the discharge current peak up to a certain threshold value, above which it stabilized or decreased slowly. The spatially averaged electron density profiles follow a similar trend to the discharge current. Relative permittivity of the dielectric barrier is predicted to have a positive influence on the discharge current. At lower frequency, it is also shown to lead to a transition from Townsend to glow discharge mode. Spatially and time averaged power density is also calculated and is shown to increase with increasing relative permittivity, applied voltage amplitude, and frequency. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

I. INTRODUCTION

In the last two decades, there has been a growing interest in using atmospheric non-thermal plasma in dielectric barrier discharge (DBD) as a chemical reactor for remediation of gaseous pollutants and greenhouse gases, at low temperature.1,2 Typical applications include treatment of nitrogen oxides (NOx) and sulphur oxides (SOx) in flue gases and decomposition of CO2, CH4, volatile organic compounds (VOCs), chlorofluorocarbons (CFCs), and other hazardous air pollutants.3–6 Operation of DBD, by application of an electric field between two electrodes separated by at least one dielectric layer, creates highly energetic electrons while maintaining the gas stream at close to room temperature. The electrons due to their high energy may collide with the gaseous pollutants and start disintegrating them into smaller molecules, while simultaneously colliding with the background gases to generate a large number of highly reactive free radicals such as H, O, and OH.7 These free radicals initiate a number of additional reactions with the pollutants and intermediates, thereby speeding up the decomposition.8 The non-equilibrium nature of such plasma discharge provides major advantage, by allowing operation at atmospheric pressure and ambient conditions. Additional features such as easy operation, moderate capital cost, and simple scalability have led to extensive research on DBD for gas cleaning applications.4

Currently, most of the optimization of DBD reactors is being performed by experimental trial and error, which is expensive in terms of both time and resources.8–12 While such diagnostic studies are indispensable, we believe that computational modelling can be used as a complementary tool to optimize the system in a directed way, providing more quantitative process-parameter relationships.

There have been several numerical studies to investigate the influence of applied voltage parameters, gap width, electrode parameters, materials, and width of the dielectric layer, on discharge performance and energy efficiency of the DBDs.13–16 However, most of these studies have been performed on DBDs between parallel-plate electrodes, whereas diagnostics on DBDs with co-axial electrode configuration are comparatively less.17–19 Most of the applications of non-thermal plasma used for decomposing gaseous pollutants are performed in co-axial DBD reactors.8,11,20–24 Thus, there is a need to expand on the preliminary parametric studies on co-axial electrode DBD and study the influence of process parameters on a broader range to get a complete understanding of the process. In this work, we have studied the influence of applied voltage amplitude and frequency over a wide range, along with the influence of relative permittivity of the dielectric barrier on the overall discharge performance in a co-axial DBD.

Although the typical target molecules in gas cleaning applications in co-axial DBD reactors are NOx, SOx, CH4, CO2, Toluene, Naphthalene, etc., their detailed plasma chemistries frequently involve tens of species and hundreds or even thousands of reactions including the electron impact, electron-ion recombination, neutral-neutral, ion-neutral, and ion-ion reactions.7 In addition to the complexity, the large number of reactions also leads to greater uncertainty in the model predictions as the rate constants used are mostly approximate.21 Solving such complex models for a parametric study even

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with a simple one-dimensional model is computationally very expensive. On the other hand, helium has a relatively simpler plasma chemistry. It has a low breakdown voltage and ionizes easily to form a stable homogeneous glow discharge, which is easier to simulate using a fluid model, as opposed to the filamentary discharge typically observed with molecular gases.22–24 These factors help in reducing the model complexity and the computational cost and thus provide more leverage in performing a parametric study on a broader scale. It should be noted that the difference in discharge performance between helium and molecular gases also limits the applicability of the current model. However, using helium is a good starting point and helps in expanding our understanding of the influence of different parameters, which will be useful in future investigations for more practical applications of co-axial DBDs.

The paper is structured as follows: the mathematical model used in the analysis, including the respective governing equations and boundary conditions, is presented in Section II. The results obtained from the analysis, including the discharge current, average electron density, and spatial distribution profiles of electrons, ions, and electric field, are presented and discussed in Section III. Section IV summarizes the final conclusion of this study.

II. MODEL DESCRIPTION

In this work, the co-axial DBD plasma reactor is modelled using a 1-D axisymmetric fluid model in COMSOL Multiphysics v5.2. The model is applied to a cylindrical DBD reactor with two co-axial metal cylinders as electrodes. The 1-D axisymmetric model allows us to account for the radial component of the rotationally symmetric co-axial DBD and also makes it distinct from the conventional 1D models typically used for representing planar DBDs.

Also, DBDs with parallel plate (planar) and co-axial configurations have been shown to have some similar characteristics.17–19 However, the cylindrical configurations of co-axial systems adds an asymmetry due to the difference in surface areas of the electrodes and this has been shown to affect the discharge characteristics. The discharge behaviour is also modified when the dielectric barrier layer is covering just one of the electrodes.19,25 These characteristics are correctly accounted using the 1D-asymmetric geometry used in the model.

The diameters of the internal and external cylinders of the DBD reactor are 16 mm and 23 mm, respectively. The outer electrode is covered (on the inside) with a dielectric barrier layer of 1.5 mm. The discharge is sustained in the 2 mm co-axial gap between the inner electrode and the dielectric barrier. The length of the electrodes is 90 mm. These dimensions represent a generic geometry, based on the wide range of DBD reactors with different discharge gaps, dielectric layer thickness, and electrode lengths that have been used as chemical reactors in several experimental studies.3,6,11 It should be noted that the dimensions of the DBD reactor and dielectric layer have also been shown to influence the discharge.26–28 However in this work, the dimensions are fixed and the effects of relative permittivity of the dielectric barrier and the applied voltage amplitude and frequency are investigated in detail. The inner electrode is grounded and the outer electrode is connected to a high voltage AC power supply.

Governing equations describing the fluid theory originate by solving a set of moments of the Boltzmann equation.24 Typically for most applications, the first three moments are considered, which describe the particle, momentum, and energy conservation. By taking these moments, the Boltzmann equation is reduced to a 3-dimensional, time dependent problem and describes the plasma in terms of averaged quantities such as density, momentum, and mean energy.24,29,30

The zeroth moment of the Boltzmann equation gives the continuity equation describing the rate of change of particles (electrons, ions, or neutral species),

\[
\frac{\partial}{\partial t}(n_p) + \nabla \cdot \vec{I}_p = R_p. \tag{1}
\]

The subscript \( p \) refers to different species such as electrons, ions, or neutral species. \( n \) represents the density of species, \( \vec{I} \) represents the flux vector, and \( R_p \) represents either the source/sink term and accounts for the production or loss of a particular species \( p \) in chemical reactions, ionization events, etc. Losses at the walls are accounted in the boundary conditions and are not explicitly considered in the particle continuity equation.

In the fluid model, the first moment of the Boltzmann equation is not solved explicitly but is replaced by another simplification known as the drift diffusion approximation24,29,31 which is used to derive the flux term in Equation (1).

Flux term for the particles (based on drift-diffusion approximation) consists of a diffusion term and a drift term, given as

\[
\vec{I}_p = \pm n_p \mu_l \vec{E} - D_p \nabla n_p, \tag{2}
\]

where \( \vec{E} \) refers to the electric field, \( \mu \) and \( D \) refer to the mobility and diffusion coefficient of the species, respectively, and their values have been taken from Ref. 32. The first term of Equation (2) is zero for the neutral species.

Source/sink term, \( R_p \), is calculated as

\[
R_p = \sum (c_{pj} r_j), \tag{3}
\]

where \( c_p \) represents the stoichiometric coefficient and \( r_p \) represents the reaction rate of the target species for reaction \( j \).

The second moment of the Boltzmann equation is used to derive the energy conservation equation. The final expression for rate of change of electron energy density including the drift diffusion approximation is described as

\[
\frac{\partial}{\partial t} (n_e) + \nabla \cdot \vec{I}_e + \vec{E} \cdot \vec{\nabla} n_e = R_e, \tag{4}
\]

where \( n_e \) is the electron energy density and \( R_e \) is the energy loss/gain due to inelastic collisions. The flux vector for electron energy \( \vec{I}_e \), is given as

\[
\vec{I}_e = -\frac{5}{3} \left( \mu_e \cdot \vec{E} \right) n_e - \frac{5}{3} \nabla D_e n_e. \tag{5}
\]
A self-consistent electric field distribution is calculated by solving the Poisson’s equation (Equation (6)) in the plasma region and the Laplace’s equation (Equation (7)) in the dielectric material:

$$-\nabla \cdot e_0 \epsilon_0 \nabla V = \rho,$$  
$$-\nabla^2 V = 0,$$  
$$E = -\nabla V,$$

where $\rho$ is the space charge density (C/m$^3$).

Surface charge accumulation on the dielectric layer due to the difference in fluxes between the electrons and ions is taken into account using the following boundary conditions:

$$-n \cdot (\vec{D}_1 - \vec{D}_2) = \rho_s,$$  
$$\frac{d\rho_s}{dt} = n \cdot \vec{J}_i + n \cdot \vec{J}_e,$$

where $n$ is the unit normal, $\rho_s$ is the surface charge density, $\vec{D}_1$ and $\vec{D}_2$ are the electric displacement fields on both sides of the boundary, and $\vec{J}_i$ and $\vec{J}_e$ are the total ion and electron current densities at the wall.

A set of 23 reactions involving helium atoms (He), ions (He$^+$ and He$^{++}$), metastables (He* and He$^{3+}$), and electrons is used in the model. Discharge is driven by applying a sinusoidal electric potential to the outer cylinder with different values of applied voltage amplitude and frequencies. Initial densities of electron and ions are assumed as spatially uniform and set as $10^{14}$ m$^{-3}$. The gas temperature is assumed to be constant at 300 K. In real systems however, the gas temperature in the discharge volume, particularly near the boundaries of the barriers or the electrodes may increase as some part of input power is inefficiently converted to heat or due to high power dissipation in the microdischarges (particularly in the case of molecular gases). Changes to gas temperature have been shown to influence the discharge characteristics in DBD as the reactions between the various plasma species typically have temperature dependant reaction rates. Thus for high frequency/high power applications, liquid cooling of electrodes is regularly used to maintain a constant gas temperature. The results described in this work are applicable only under such strict constant gas temperature conditions.

III. RESULTS AND DISCUSSION

In this work, we have studied the influence of relative permittivity of the dielectric barrier and applied voltage parameters using a numerical analysis. Relative permittivity values of 5, 10, and 15 have been studied, as this covers the range of common dielectric materials used in DBD setup such as quartz, pyrex, alumina, and ceramics. Voltage potential and frequency have been varied in the ranges of 2 kV–40 kV and 1 kHz–50 kHz, respectively. These values cover the typical applied voltage parameters used in experiments. The results of the numerical analysis are presented below.

A. Effect of applied voltage amplitude and frequency

Figures 1–3 show the calculated discharge current and gap voltage profiles at six applied voltage frequencies (1 kHz, 5 kHz, 10 kHz, 20 kHz, 30 kHz, and 50 kHz) during 1 V cycle in an atmospheric DBD in pure helium for peak-to-peak voltage amplitudes of 2 kV, 10 kV, and 40 kV, respectively. By comparing Figures 1–3, the effect of both applied potential and frequency can be studied.

It can be seen that some discharge current profiles exhibit a distinct single peak while some show multiple peaks in the voltage half cycle. The number of peaks in the discharge current profiles increases with the increase in the applied potential but decrease with the increase in frequency.
This trend is in agreement with previously reported studies.\textsuperscript{19,22,34} As can be seen in Figure 1, at an applied potential of 2 kV, the transition from multiple peaks (3 peaks at 1 kHz, Figure 1(a)) to a single distinct peak in the current profile occurs at 5 kHz (Figure 1(b)). The number of peaks at higher voltage, i.e., 10 kV (Figure 2) and 40 kV (Figure 3), for the same corresponding frequencies is higher and the transition from multiple peaks to a single peak occurs at a higher frequency value of 20 kHz.

The red lines in Figures 1–3 represent the voltage in the co-axial gap between the inner electrode and the dielectric barrier. The discharge ignites once the gap voltage reaches the breakdown voltage and extinguishes once the gap voltage falls below the breakdown voltage. The multiple peaks occur due to multiple breakdown in a single voltage cycle.\textsuperscript{22,34} This can happen if the gap voltage crosses the breakdown voltage more than once in one cycle, which is more probable at lower frequencies and higher voltages. Thus, we observe a multipeak behaviour at 1 kHz even at a small applied potential of 2 kV. As the voltage is increased, the memory voltage in each cycle increases due to the higher accumulation of charges on the dielectric barrier. This enhances the gap voltage and makes multiple breakdown possible in one cycle.\textsuperscript{35} However, the time interval of the voltage cycle also plays a significant role. At higher frequencies when sufficient time is not there in between the voltage cycles, the discharge does not undergo multiple breakdowns.\textsuperscript{22} Thus, we have seen that both the applied voltage amplitude and frequency contribute.
to the shift from multipeak to single peak current profiles. The reason for the early transition for a voltage potential of 2 kV at 5 kHz is insufficient external voltage, while for voltage potentials of 10 kV and 40 kV the insufficient time between cycles at higher frequencies (above 10 kHz) is the main reason for transition. At higher voltage (40 kV) and higher frequencies (>10 kHz), i.e., for Figures 3(d)–3(f), both voltage and frequency effects are dominant. A similar effect of applied voltage and frequency on the discharge current profiles has been reported previously.\textsuperscript{19,22,34–39} Radu et al.\textsuperscript{34} studied the frequency and voltage dependence of glow and pseudoglow discharges in helium under atmospheric pressure and observed a similar transition from multiple peaks to single peaks at frequencies higher than 10 kHz. This is in agreement with our results obtained for applied potentials of 10 kV and 40 kV (peak-to-peak).

At higher voltage, there is large accumulation of charges which increases the external voltage significantly, making multiple breakdown feasible. However at high frequencies, there is not enough time for second breakdown in the same voltage cycle. Under such conditions, we can see that after the first major peak, the current decreases but does not relax fully and begins to smooth out. At higher frequencies of 30 kHz and 50 kHz and a high voltage of 40 kV (Figures 3(e) and 3(f)), the competing effects of frequency and voltage lead to a nearly sinusoidal waveform. Petrović et al.\textsuperscript{19} also observed similar sinusoidal waveforms for current density profiles at higher frequencies in a co-axial DBD setup.

For all the three voltage values studied in this work, it can be seen that the maximum amplitude of the discharge current peak increases with the increase in applied voltage frequency up to a certain maximum value (which depends on the voltage amplitude). Once this threshold frequency value is reached, the discharge current remains more or less constant or decreases slightly. For applied potentials of 2 kV and 10 kV, current increases as the frequency is increased from 1 kHz to 20 kHz. At higher frequencies (30 kHz and 50 kHz), the peak value of current begins to slowly decrease. This threshold value of frequency for an applied potential of 40 kV is slightly lower, i.e., 10 kHz, after which a further increase in frequency results in the decrease in the peak value current. Thus, the extent to which frequency can increase discharge current in a DBD is limited by the applied potential. For the range of voltage values (600–3000 V) studied by Petrović et al.\textsuperscript{39} in an atmospheric DBD in a cylindrical geometry, they observed similar stabilization of the maximum amplitude of the current peak as the voltage amplitude increased.

Also the maximum amplitude of discharge current increases with the increase in applied potential. This increase, however, slows down with the increase in frequency. For example, the difference in the maximum peak current with increasing voltage is more at a frequency of 1 kHz compared to 5 kHz. This counter effect of frequency on the amplitude of current peak becomes more prominent at higher frequency values (≥20 kHz) and the current peak amplitude for a voltage potential of 40 kV slightly decreases compared to that of 10 kV. It can also be seen from Figures 1–3, at any given frequency as the applied potential increases, the gap voltage reaches the breakdown voltage faster and this results in an early onset of the peak in the discharge current profiles. This trend is also in accordance with the previously reported literature in a co-axial electrode configuration.\textsuperscript{2,17}

A higher current corresponds to a stronger discharge, which would translate in better decomposition efficiency of pollutants. The trends obtained for discharge current as a function of applied voltage magnitude and frequency are consistent with the experimental results of Du et al.,\textsuperscript{40} who studied the NOx removal from diesel exhaust using co-axial DBD and observed that the removal rate of NOx first increased and then decreased with increasing the magnitude and frequency of the voltage.

As can be seen, the observations described in this work in reference to the effect of applied voltage amplitude and frequency are in good agreement with the previously reported literature for both parallel-plate and cylindrical DBD geometries. The ample broad range of values for both the voltage parameters studied in this work allows us to investigate the complex interdependence of the voltage parameters and their influence on the discharge performance. It also helped in identifying the limiting threshold potential and frequency values, along with the transition values from multipeak to single current profiles.

Figures 4–6 show the calculated spatially averaged electron density profiles at different applied voltage frequencies during 1 V cycle in an atmospheric DBD in helium for peak-to-peak voltage amplitudes of 2 kV, 10 kV, and 40 kV, respectively. As can seen from these figures, electron density profiles follow the same trend as the corresponding discharge current profiles shown in Figures 1–3. The single peak or multiple peaks as observed in discharge current profiles above are duplicated in the electron density profiles as well. It can also be seen from Figures 4–6 that the maximum value of electron density increases with the increase in voltage at lower frequencies (≤10 kHz). For higher frequencies, i.e., 20 kHz, 30 kHz, and 50 kHz, there is very little difference in maximum electron density as the voltage is increased. Also, at any given applied potential, the peak value of average electron density increases with increases in frequency up to a certain threshold frequency (which depends on the voltage potential) and then begins to decrease slowly.

It should also be pointed out that except for the electron density profile for 1 kHz at 2 kV applied potential (Figure 4(a)), where maximum electron density is in the order of 10\textsuperscript{7} cm\textsuperscript{-3}, all other frequency and voltage conditions lead to maximum electron density in the order of 10\textsuperscript{9} cm\textsuperscript{-3}. Another important point to be noted is that at frequency values ≤20 kHz, the electron density decreases to the base value of ≈200 cm\textsuperscript{-3} at the transition point between the positive and negative voltage half cycles. However at higher frequencies, 30 kHz and 50 kHz, the electron density relaxes at a much higher value. Fox example, at an applied potential of 2 kV, the minimum electron density for 30 kHz and 50 kHz frequencies is in the order of 10\textsuperscript{9} and 10\textsuperscript{8}, respectively. The same at the applied potential of 40 kV is in the order of 10\textsuperscript{9} and 10\textsuperscript{8}. The only exception to this rule is the electron density profile obtained for the applied potential of 10 kV with a frequency
of 30 kHz. The reason for this outlier is however not exactly clear at this point.

B. Mode of discharge

The atmospheric pressure DBD typically operates in the filamentary mode, characterised by numerous discharge channels or filaments separated from each other which usually last about 10 ns. Under some operating conditions or for some gases which have low dielectric breakdown voltage such as helium, DBD can operate in a homogeneous mode in which a spatially homogeneous discharge in the direction parallel to the electrodes is obtained. The homogeneous mode can be classified as either atmospheric pressure Townsend discharge (APTD) or atmospheric pressure glow discharge (APGD). Current profiles in the homogeneous mode generally show a single current peak per half-cycle of the voltage; however, under some conditions multiple peaks can also occur, and in this scenario, it is said to be operating as pseudo-glow discharge. Homogeneous discharge at atmospheric pressure (APTD or APGD) is typically observed when the Meek criterion for avalanche-to-streamer transition is not satisfied. Many researchers have investigated homogeneous discharge in noble gases such as helium, neon, and argon; however, the exact mechanism behind homogeneity of discharge at atmospheric pressure is still under debate. Many factors such as high pre-ionization levels, higher threshold energy of metastables, streamer coupling, penning ionization (with

![FIG. 4. Calculated spatially averaged electron density profiles in an atmospheric DBD in helium at an applied voltage of 2 kV for different applied frequencies ranging from 1 kHz to 50 kHz.](image)

![FIG. 5. Calculated spatially averaged electron density profiles in an atmospheric DBD in helium at an applied voltage of 10 kV for different applied frequencies ranging from 1 kHz to 50 kHz.](image)
added impurities), etc., have been suggested to be responsible for uniformity of the discharge.44,45,47,48 Two specific properties of helium, namely, the high ionization energy and the small molecular size which leads to higher mean free pathway for the free electrons resulting in lower breakdown voltages, together, greatly reduce the ionization in a single electron avalanche. Unable to reach the Meek criterion, the discharge propagates via the Townsend mechanism.45,49 The “memory effect” is also attributed to providing high pre-ionization levels in helium, which helps in increasing avalanche radius avoiding the formation of narrow streamers and results in larger number of initial avalanches which overlap to produce the uniform discharge.47,48 The interaction of avalanches essentially reduces the electric field and prevents the Meek criterion to be reached suppressing the start of filament formations. Also, in helium discharge at high pressures, contraction or other instabilities are prevented due to the fast heat and mass transfer processes, thus helping to sustain the homogeneous discharge.44

The two homogeneous discharge modes (ATGD and APTD) show distinct spatial profiles for charged particles and electric field at the point of breakdown or at the point of maximum discharge current. Two most important differences are level of ionisation which is significantly lower in APTD compared to APGD and formation of cathode fall and a positive column region in APGD which are absent in APTD. Magnitude of electric field typically decreases linearly from the cathode to the anode, electron density of the order of $10^7 \text{ cm}^{-3}$, and absence of a positive column region. On the other hand, profiles in Figures 7(b) and 7(c) show the typical characteristics of the glow discharge mode, such as the presence of a clear cathode fall and positive column region and electron and ion number densities in the order of $10^{11}$. These spatial profiles for the Townsend and glow discharge modes are in accordance with the previously reported literature.10,34,50 It should be noted that though both Figures 7(b) and 7(c) exhibit characteristics of the glow mode, the maximum electron and ion densities in Figure 7(c) are slightly less than those in Figure 7(b). This suggests a slightly weaker discharge in the reactor at high values of frequency and voltage (50 kHz and 40 kV) compared to median values (10 kHz and 10 kV).

C. Effect of relative permittivity

Figures 8 and 9 show the effect of relative permittivity of the dielectric barrier on the co-axial DBD performance for
two applied voltage frequencies, 1 kHz and 5 kHz, at the voltage potential of 2 kV. As can be seen from Figure 8, the amplitude of the current peak increases with the increase in \( \epsilon_r \) of the dielectric barrier. The increase in current amplitudes is exponential. Maximum current amplitude for \( \epsilon_r = 10 \) is about 5 times higher than that for \( \epsilon_r = 5 \) and maximum current amplitude for \( \epsilon_r = 15 \) is about 20 times that of \( \epsilon_r = 10 \). It should also be noted that the discharge for \( \epsilon_r = 5 \) and \( \epsilon_r = 10 \) at an applied voltage frequency of 1 kHz and an amplitude of 2 kV is in the Townsend mode (Figures 8(aii) and 8(bii) and undergoes a transition to the glow mode (Figure 8(cii)) as the \( \epsilon_r \) is increased to 15. This explains the dramatic increase in discharge current amplitude and electron density for \( \epsilon_r = 15 \) as compared to \( \epsilon_r = 5 \) and 10 in Figure 8. Wang et al.\textsuperscript{53} have also observed a similar transition of discharge mode by increasing the relative permittivity of the dielectric barriers for a pulsed DBD discharge between two parallel plates. Golubovskii et al.\textsuperscript{54} observed that increasing the relative permittivity of the dielectric barrier reduces the stability of the homogeneous discharge modes in a planar DBD in nitrogen.

Figure 9 shows the effect of relative permittivity at a higher applied frequency of 5 kHz. Similar to what is observed in Figure 8 for 1 kHz, discharge current amplitude increases with the increase in the value of \( \epsilon_r \) even for 5 kHz; however, the increase this time is more linear. Spatially averaged electron density also increases with the increase in relative permittivity. Chen et al.\textsuperscript{13} also observed an increase in the peak value of electron density with the increase in \( \epsilon_r \) for a pulse discharge in atmospheric-pressure pure helium between two parallel-plate electrodes. Discharge for all three conditions described in Figure 9 operates in the glow mode, and thus, the spatial number density profiles of electron and ion densities and spatial electric field distribution are roughly of similar magnitudes to that described in Figure 8(cii).

It should also be noted from Figures 8 and 9 that an increase in relative permittivity of the dielectric layer results in early ignition of the discharge, and accordingly the first peak in discharge current and electron density appears early with the increase in relative permittivity signifying a faster breakdown. This behaviour is consistent with previously reported studies on DBDs with planar configuration and has been explained as follows. Increasing the relative permittivity of the dielectric barrier leads to an increase in the capacitance of the DBD, which leads to an increase in gap voltage as the voltage across the dielectric is decreased.\textsuperscript{51,52} Peak in discharge current is observed when the gap voltage reaches the breakdown voltage. Thus, a faster breakdown is observed for DBD with higher relative permittivity. An increase in gap voltage also leads to an increase in ionisation, which can explain the dramatic increase in discharge current for \( \epsilon_r = 15 \) at 1 kHz and 2 kV, leading to the transition of discharge modes.

Wang et al.\textsuperscript{2} studied nitric oxide (NO) removal in a coaxial DBD reactor and found that NO removal efficiency increased when corundum (\( \epsilon_r = 9.8 \)) was used as the dielectric material, compared to ceramic (\( \epsilon_r = 5.8 \)) or quartz (\( \epsilon_r = 3.75 \)). The higher conversion obtained with corundum was attributed to the higher capacitance (due to higher \( \epsilon_r \) of corundum), reduced impedance and increased power in the DBD. Ozkan et al.\textsuperscript{27} also studied the effect of relative permittivity on the discharge mode and CO\textsubscript{2} conversion in a tubular flowing DBD. They however did not observe any linear trend of increased conversion with increasing relative permittivity of the dielectric materials. This anomaly was attributed to the other parameters such as surface roughness and thermal conductivity, which were different for the various dielectric materials investigated in their work. Thus, it should be noted that while relative permittivity (electrical property) has a significant influence, the thermal and surface properties of the dielectric materials should also be accounted (unless they are similar), to understand the influence of different dielectric materials on the overall discharge performance.
FIG. 8. Calculated discharge current profile (black solid line) and gap voltage (red solid lines) in an atmospheric DBD in helium at an applied voltage frequency of 1 kHz and a voltage amplitude of 2 kV (blue dashed lines) for three different relative permittivities of the dielectric barrier, (a) $\varepsilon_r = 5$, (b) $\varepsilon_r = 10$, and (c) $\varepsilon_r = 15$. (ai), (bi), and (ci) represent the spatially averaged electron density profiles, while (a(ii), (b(ii), and (c(ii) represent the spatial number density profiles of electron and ion densities and spatial electric field distribution in the radial direction at the moment of maximum discharge current, for the corresponding three different relative permittivities.

FIG. 9. Calculated discharge current profile in an atmospheric DBD in helium at an applied voltage frequency of 5 kHz and a voltage amplitude of 2 kV for three different relative permittivities of the dielectric barrier, (a) 5, (b) 10, and (c) 15. (ai), (bi), and (ci) represent the corresponding calculated average electron density profiles.
TABLE I. Spatially and time averaged dissipated power density (W cm⁻³) for 1 V cycle at different applied voltage amplitudes and frequencies.

| Voltage (kV) | Frequency (kHz) | 1  | 5  | 10 | 20 | 30 | 50 |
|-------------|----------------|----|----|----|----|----|----|
| 2           | 0.002          | 0.02 | 0.05 | 0.12 | 0.17 | 0.28 |
| 10          | 0.04           | 0.18 | 0.36 | 0.72 | 1.09 | 1.92 |
| 40          | 0.16           | 0.88 | 1.78 | 3.64 | 5.41 | 10.03 |

D. Spatially and temporally averaged performance indicators

Along with electron density, power consumption of the discharge is also an important indicator of the performance and energy efficiency of the DBD reactor. The average power density over a period T is obtained by integrating the instantaneous power dissipated in the system, as follows:

\[ \bar{P} = \frac{1}{T} \int_0^T V_{\text{gap}}(t)I_{\text{cond}}(t)dt, \]

(11)

where \( V_{\text{gap}} \) and \( I_{\text{cond}} \) represent the gap voltage and conduction current, respectively.

Tables I and II show the spatially and time averaged dissipated power density and electron density for 1 V cycle, in the entire range of applied voltage amplitudes and frequencies discussed in Figures 1–3.

As can be seen from Table I, power density of the DBD increases with the increase in both applied voltage amplitude and frequency. Similar trends for power density have been observed previously for parallel-plate DBD and co-axial DBD. For parameter values studied in this work, the lowest power density of 0.002 W/cm³ is obtained at an applied frequency of 1 kHz and a voltage of 2 kV, while the highest power density of 10.03 W/cm³ is obtained at an applied frequency of 50 kHz and a voltage of 40 kV.

Electron number density which depends largely on the power consumption in the DBD also shows a similar trend with increasing applied voltage frequency and voltage amplitude values, as can be seen in Table II. Spatially and time averaged electron density over 1 V cycle increases consistently with increasing applied voltage amplitude and frequency values. This trend is consistent with that reported by Valdivia-Barrientos et al. based on electrical modelling of a co-axial DBD. Naz et al. also observed a linear increase in electron density with increasing applied potential.

It should be pointed out that the increase in average electron density is more prominent at lower frequency (<10 kHz) and lower voltage amplitude (<10 kV) values where we see an order of magnitude increase. At higher applied voltage frequency and amplitude values (≥20 kHz and >10 kV), the average electron density is stabilised and there is only a modest increase with further increase in frequency or voltage (remains in the same order of magnitude).

Table III shows the effect of relative permittivity on spatially and time averaged dissipated power density and electron density values, for the two set of conditions described in Figures 8 and 9, respectively. As can be seen from Table III, average power density and electron density increase with increase in \( \epsilon_r \). This is expected as increase in \( \epsilon_r \) leads to increase in gap voltage, which is directly proportional to the power dissipated in the system. Also, as electron density is a function of power density in the system, it increases proportionately.

As can be seen in Table III, the percentage increase in both average power density and electron density with increase in \( \epsilon_r \) is substantially higher for lower frequency of 1 kHz (Table III) as compared to 5 kHz (Table III). The transition from Townsend to glow discharge mode, as \( \epsilon_r \) is increased to 15, at a lower frequency of 1 kHz, can explain the dramatic increase in power and electron density values in Table III. At a higher frequency of 5 kHz, as can be seen in Table III, the increase in average power and electron densities with the increase in relative permittivity is linear.

However, it should be noted that, although the wide range of simulation parameters used in this study may cover the avalanche-streamer transition in the DBD, only the ionization mechanism in the avalanche has been used. This assumption is a limitation of the current model and future studies should pursue research efforts to revise the model by including more diverse set of mechanisms valid over a broad range of parameters.

IV. CONCLUSION

In this work, a numerical analysis of co-axial DBD in pure helium has been carried out using 1-D fluid model. The
numerical model has been used to understand the influence of relative permittivity of the dielectric barrier and the applied voltage parameters on the discharge performance of the DBD. The relative permittivity, voltage, and frequency values are varied in the range of 5–15, 2 kV–40 kV, and 1 kHz–50 kHz, respectively.

It has been found that the maximum amplitude of the discharge current peak increases with increase in applied voltage frequency up to a certain threshold value (which is dependent on the applied voltage amplitude). Above the threshold frequency, discharge current stabilises and begins to decrease slowly. This threshold frequency for the applied potential of 2 kV and 10 kV is 20 kHz, and the same for the applied potential of 40 kV is 10 kHz.

The maximum amplitude of the discharge current peak also increases with the increase in applied voltage amplitude; however, the percentage increase decreases with increasing frequency. At any given frequency, increase in applied potential results in a faster onset of the discharge. The number of peaks in the discharge current profiles decreases with increasing frequency of the applied voltage but increases with increasing amplitude of the voltage. The transition from multiple peaks to a single distinct peak for an applied potential of 2 kV occurs at 5 kHz, while the transition for applied potentials of 10 kV and 40 kV occurs at 20 kHz.

Spatially averaged electron density profiles follow the same trend as the discharge current profiles. At the transition point when the voltage polarity changes, the average electron density relaxes to a base value, which is found to be increasing with applied voltage frequency.

Maximum amplitude of the discharge current peak increases with the increase in relative permittivity of the dielectric barrier. At a low frequency of 1 kHz, the increase in current amplitude is found to be exponential, as the discharge undergoes a transition from the Townsend mode at $\epsilon_r = 5$ and 10 to the glow mode at $\epsilon_r = 15$. At an applied voltage frequency of 5 kHz, the increase of discharge current magnitude with increasing $\epsilon_r$ is linear. In has also been found that increasing relative permittivity results in an early onset of discharge.

Spatially and time averaged power and electron density values have also been compared and were found to be increasing with increasing relative permittivity, applied voltage amplitude, and frequency values. However, the percentage increase in average electron density is found to slow down at higher voltage amplitude and frequency (>10 kV and ≥20 kHz).

Simulation results obtained in this study on the generic co-axial DBD geometry have been compared with the relevant experimental or numerical studies. Simultaneously, a comparison has also been drawn to the corresponding process-parameter relationships reported for DBD with planar electrode configuration.

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