Erratum: Gas-confined barrier discharges: a simplified model for plasma dynamics in flame environments (2013 J. Phys. D: Appl. Phys. 46 345204)

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The following parts were omitted from the caption of figure 2:
(a) composition: N₂–He–N₂ case ($N_c = 2$, $r = 1$, $K = 1$);
(b) temperature effect in helium ($N_c = 1$, $r = 1$, $K = 5.5$).
Gas-confined barrier discharges: a simplified model for plasma dynamics in flame environments

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Abstract

In this paper we evaluate the dynamics of non-thermal plasmas developing in extremely non-homogeneous environments. We present the gas-confined barrier discharge (GBD) concept and justify its importance as a first step to understanding the dynamics of non-thermal plasmas in flame environments. In this concept, cold (in a generalized sense) barriers of gas play the role of the dielectrics, with some major differences in behaviour with respect to solid barriers. We present an analytical evaluation of the discharge appearance modes, new experimental results using helium-nitrogen layers that confirm the possibility of avoiding breakdown in the cold layers and a numerical evaluation that helps interpret the development of streamers once they reach a non-ionizing region.

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

1. Introduction

Non-thermal plasmas participate in the enhancement of combustion processes by introducing new kinetic paths, serving as an injection of radicals [1, 2], excited species [3–5], other reactive species [6], by reforming the reactants [7] and through thermal effects. Several groups have contributed to explaining the chemical kinetics of plasma-combustion interaction by trying to isolate the effect of individual species and proposing kinetic mechanisms for the gas discharge [8, 9]. To simplify this complex problem, in many cases the experiments are carefully planned so that the plasma and the combustion processes are separated either in space or in time [10–12] and hence the coupling between both can be achieved either by boundary or initial conditions. More recently, the fully coupled problem of a plasma directly applied to a flame front has been analysed in which the interaction needs to be included directly through the kinetic rates [13].

As an observation, it can be said that the importance of a particular combustion-enhancement process depends on the positioning of the discharge, the composition of the gas where the plasma is being produced (fuel [14, 15], oxidizer [16], reaction front [13] or a premixed gas [17]) and the combustion mode; and, for example in the case of flames, it seems that to ensure that the highly reactive species reach the flame front before recombining or losing their energy, they must be produced as close to it as possible.

Most of the effort in this field is being devoted to elucidating the kinetics part of the problem (what species are contributing). An unexplored area is still the plasma dynamics under combustion conditions (where the species are being produced and how to tailor their appearance to the region where they are most effective). In the most general situation, two sources of inhomogeneities exist in such a process: the inhomogeneities of the combustion process, both in composition and temperature, and those of the plasma, in many cases developing as streamers. The most fundamental parameters affecting the gas discharge, nd and the E/n, will be determined by the combustion properties and, most likely, there will be a reinforcement of the plasma precisely where the thermal kinetics are active, at the low density regions.

The fundamental problem of modelling streamer development under non-homogeneous conditions is a fairly unexplored one, although there has been recent work in the area of streamer development in the upper atmosphere [18, 19] and atmospheric pressure plasma jets, APPJ [20, 21]. To the best of our knowledge, this problem has not yet been addressed within the application of plasma-assisted combustion.
In this paper we propose the gas-confined barrier discharge concept (GBD) as a first step towards understanding the dynamics of plasma–flame interaction, an analytical evaluation of the appearance of different discharge modes, experimental confirmation and interpretation of the phenomenon using a numerical model.

2. Gas-confined barrier discharge concept (GBD)

Many engineering applications present turbulent non-premixed combustion modes. In such a situation, thin high-temperature layers appear (flamelets) that can be modelled as counterflow diffusion flames in which fuel and oxidizer are separated in space and meet at the so-called flame front. The structure of these flames can be described by a very thin reaction front, in the plane where oxidizer and fuel meet at stoichiometric conditions, and a high-temperature profile whose thickness is determined by a convection-diffusion balance. It is clear then that, for any non-premixed flame, there will be a thin high-temperature region surrounded by colder gas and the composition will be non-uniform (the zone of reactants, which may be diluted by an inert gas, will be cold, whereas products, reacting species and diluant will be hot).

With such a picture in mind, the simplified model we have chosen to understand the development of a non-thermal plasma under the extremely non-homogeneous conditions of a flame environment is pictured in figure 1. It consists of a sandwich-like structure of two or three layers of gases with very different electrical properties, e.g., a layer of a gas that can be easily broken down (we will refer to this layer as the hot layer) surrounded by two layers of a more insulating gas (the cold layers). We propose that, depending on the selection of the electrical and geometrical parameters, the discharge can be produced in the whole gap or just in the hot layer with the cold layers acting as a pseudo-dielectric (with some main differences that are explored).

2.1. Prediction of the breakdown modes

An analytical evaluation based on differences in the ionization coefficient alone is used to estimate the different breakdown regions using the well-known criteria for Townsend and streamer breakdown [22]. For the Townsend breakdown mechanism, the electron avalanche formed does not distort the applied electric field significantly and emission from the cathode ensures that the phenomenon is self-sustained. The streamer breakdown mechanism is characterized by transient electrical discharges that propagate as thin filament-like weakly conducting structures with very steep ionization fronts.

The model is used to guide the selection of parameters for the experiment to achieve a selective breakdown of the hot layer.

Let us assume there is only variation of the temperature and composition with \( x \), the pressure and the electric field are uniform (figure 1) and that the reduced ionization coefficient for gases \( h \) and \( c \) follows Townsend’s semi-empirical formula (\( i = h, c \)) [22, 23]:

\[
\frac{\alpha_i}{n} = F_i \exp \left( -\frac{G_i}{E/n} \right),
\]

where \( F_i \) and \( G_i \) are constant for each gas.

Let the uniform pressure be \( p_0 \) and the thicknesses of each layer \( d_h \) and \( d_c \), we will call the ratio \( r = d_h/d_c \). The temperature of the hot layer will be \( K \) times the temperature of the cold layer, \( T_0 \). The density in the cold layer will then be \( n_c = p_0/k_B T_0 = n_0 \) and in the hot layer \( n_h = n_0/K \). Also, there can be either one or two cold layers, \( N_c = 1, 2 \), which we will assume have the same thickness and properties.

Since the streamer breakdown mechanism has no direct relation to electrode phenomena [24], it is reasonable to assume that the first electron avalanche will occur in the region where the conditions for ionization are most favourable. For a structure like the one in figure 1, this will be the hot layer. The electric field before the first breakdown will correspond to the externally applied field and, for the geometry considered, is constant throughout the layers:

\[
E = \frac{V}{d_h + N_c d_c}.
\]

Moreover, the propagation of the first electron avalanche across the hot layer alone might be enough to satisfy Meek’s breakdown condition for streamer formation (\( \alpha_0 d_h \approx 20 \)). Thus, combining these two expressions, the minimum applied voltage (in the full gap) to reach Meek’s criterion within the hot layer will be:

\[
V_{\text{crit}}(\text{gases}, N_c, r, K, n_0 d_h) = G_h n_0 d_h \frac{N_c + r}{r K} \ln \left( F_i n_0 d_h / (20 K) \right).
\]

Once a streamer channel has formed, the potential drop along its body will be small (a quasi-neutral plasma is left behind) and so the electric field in the cold layer will increase, at least locally. To confine the discharge to the hot layer we need to ensure that it is still below that needed for breakdown in the cold layer.

For the case of a single cold layer (\( N_c = 1 \)), and for perfect conduction by the plasma after breakdown of the hot layer, the full potential drop will occur in the cold layer. If the shorting of the hot layer is not complete, then the electric field in the cold layer will be lower and the avoidance of breakdown of the cold layer will be facilitated.
For the case of a hot layer sandwiched between two cold layers \((N_c = 2)\) there will be an asymmetry in the electric field and the potential drop in one of the cold layers (at the cathode-side) will most likely be greater than in the other; i.e. there will be a non-symmetrical accumulation of charge that will modify the electric field on each side: on the anode-side the electrons are free to move towards the anode, whereas the ions will start piling up in the cathode-side mixing layer due to their slower motion (this will be later justified with the numerical simulation). The worst-case scenario (highest electric field in one of the cold layers) would then be that the full potential drop occurs in the cathode-side layer alone. This is an under-prediction of the region of confinement of the discharge to the hot layer and in reality a higher applied voltage is possible as there can be some potential drop both in the anode-side cold layer and in the hot layer itself.

For the most restrictive situation in which the full potential drop occurs in the cathode-side cold layer, the electric field in it will be:

\[
E = \frac{V}{d_c},
\]

and the breakdown can be assumed to be of Townsend type.

The onset of breakdown of the cathode-side cold layer will be given by \(d_c = \ln(1/\gamma + 1)\) \([22]\), with \(\gamma\) the secondary emission coefficient. Combining, the total voltage to avoid breakdown of the cathode-side cold layer, needs to be lower than:

\[
V_{\text{Paschen,c}}(\text{gases}, N_c, r, K, n_0d_h) = \frac{n_0d_hG_c/r}{C_c + \ln (n_0d_h/r)},
\]

with

\[
C_c = \ln (F_c/\ln (1/\gamma + 1)).
\]

This region is labelled in figure 2 as ‘Confined to hot layer (asymmetry)’. Note that, if the potential drop is equally shared between both cold layers, the applied voltage can be doubled before breakdown of the cold layer occurs (labelled in figure 2 as ‘confined to hot layer (symmetry)’). In reality, an intermediate situation will be more likely.

Equation (3) has a vertical asymptote at \(n_0d_h = 20K/F_h\) and equation (5) at \(n_0d_h = r \ln (1/\gamma + 1)/F_c\).

The point for which equations (3) and (5) are equal gives the envelope for the minimum voltage and \(n_0d_h\) for any geometry for which confinement of the discharge at the hot layer is assured (for streamer breakdown condition of hot layer) (in dot-dash line in figure 2):

\[
V_{\text{env}}(\text{gases}, N_c, r, K) = r \exp \left(\frac{G_c/G_h \ln (F_h/20K)}{N_c + r/K - G_c/G_h} - \frac{N_c + r}{K} - \frac{G_c/G_h}{N_c + r} + \frac{1}{N_c + r} - C_c\right).
\]

Finally, at the left branch of the curve in equation (3), the contribution of the cold layers may enable the streamer criterion to be met when the ionization in the hot layer alone does not suffice. In this case, the first breakdown will occur in the full gap if the Meek condition is reached:

\[
N_c\alpha_c d_c + \alpha_0 d_h \simeq 20,
\]

with,

\[
E = \frac{V}{d_h + N_c d_c}.
\]

Introducing the values for the ionization coefficients, for voltages over \(V_{\text{str,h\text{rec}}}\) there will be breakdown in the full gap:

\[
V_{\text{str,h\text{rec}}}(\text{gases}, N_c, r, K, n_0d_h) = \frac{1}{K} \frac{G_hn_0d_h(N_c + r)}{\ln (1/\beta)} - \frac{1}{K} \frac{F_h}{\ln (1/\beta)},
\]

with \(\beta\) being the solution to equation (11):

\[
\beta + N_c \frac{K F_h}{r} \beta K G_c/G_h = \frac{20K}{F_h n_0 d_h}.
\]

For large \(n_0d_h\), \(V_{\text{str,h\text{rec}}} \to V_{\text{str,h}}\) and the contribution of the cold layer is not needed.
Figure 3. Three parallel jets to study the development of the plasma across a steep composition gradient. The dashed line is the plane of study which would correspond to figure 1.

Figure 2 shows the analytical prediction of different discharge modes for two different sandwich-like structures, one with uniform temperature but different composition in the layers and the other with uniform composition but two layers at different temperatures. It can be seen how, depending on the temperature ratio of the layers, the gases present, the ratio of thicknesses of the layers and the applied voltage, three different situations can take place: no breakdown, breakdown of the hot layer alone and breakdown of the full gap. Although the model is crude, the trends are expected to hold and the parameters are used to guide the experiments.

Note that other situations are also possible depending on the voltage rise-times, the gases present and which layers are in contact with the cathode.

3. Methods

3.1. Experimental approach

The experimental set-up used for the study of the propagation of the non-thermal plasma across a composition profile is shown in figure 3. It consists on three confined plane parallel jets. All exit slots are 2 mm wide and 35 mm long. The exit velocities of the jets, \( u \approx 5 \text{ m/s} \), are selected to ensure laminar flow, slow growth of the diffusion layers and negligible buoyancy effects where the discharge is produced. The jets are directed vertically.

The electrodes consist on two copper strips of 2 mm width placed at 4 mm of the jet exit. Results using copper wire electrodes of 0.5 mm diameter placed on the same location did not significantly change the appearance of the discharge. A glass microscope slide 1 mm thick was used as a safety dielectric barrier attached to the cathode for some of the experiments, studies without the slide were also performed. No circuit elements were added to better match the transfer of power to the gas.

The plane of study is the plane of the electrodes (orthogonal to the flow) which corresponds to the dashed line in figure 3.

Experiments were performed at atmospheric pressure and ambient temperature. Repetitive pulsed nanosecond duration voltage of positive polarity is used (up to \( \sim 20 \text{kV} \) amplitude in open circuit, 20 ns duration and 3 kHz repetition frequency) from a FPG 10-30NKS10 high-voltage pulse generator (FID GmbH). Further confirmation of the phenomena is achieved using ac voltage (6–9 kV peak-to-peak, \( \sim 60 \text{kHz} \)). Diagnostics include photography, exploratory spectra using optical emission spectroscopy and current and voltage waveforms.

3.2. Numerical approach

A numerical model is used to help explain the experimental observations.

Although the phenomena at hand are clearly three dimensional and the role of the bulk transport processes (specially convection) is essential to describe the repetitiveness and periodicity of the process, at the timescale of a single discharge pulse, the bulk flow properties can be assumed frozen.

With this assumption, the development of a streamer across a composition profile (such as that shown in figure 1) has been studied numerically using 1D and 2D models. The governing equations are the ion and electron continuity equations in the drift–diffusion approximation coupled to Poisson’s equation [25]. The mobility of the electrons as well as the electron impact ionization coefficient are evaluated in the local field approximation [22, 26]. The mobility of the ions is assumed to be a function of density and is taken from the literature [27] and the diffusion coefficients are obtained from the Einstein relation.

To simplify the problem as much as possible, the minimal streamer model is considered [28] and the effect of photoionization for a mixture with nitrogen and pre-ionization from previous pulses is substituted by a minimum background plasma density [29]. For some mixtures, ionization due to electron impact alone is not realistic, e.g. when using a helium-nitrogen mixture Penning ionization will surely play an important role. However, since our aim is to clarify whether or not a streamer plasma can be blocked or deflected by an adverse ionization region (lower density or higher \( G \) in equation (1)), we will use the simplest model available using the insight given by [30] for plasma bullets in helium–air mixing layers.

The presence of a layered gas (figure 1) is included in the model for the mobilities, diffusion and ionization coefficients which are not only a function of the local reduced electric field but also of the composition of the gas at that point [20]. That is,

\[
\mu, n, D_n, \mu, n, D_i, n, \alpha/n = f \left( \frac{E(x, y, t)}{n(x)} \text{composition}(x) \right) \tag{12}
\]

A smooth curve for the composition profile is used and a simplified model for the mixing zone is assumed for all the coefficients (Wieland approximation for the ionization coefficient [31] and Blanc’s law for the transport coefficients [32]).

The model assumes additional dielectrics attached to the electrodes, which would be placed in the experiment as safety barriers in case of perforation of the cold gas.

For the numerical method used, the continuity equations have been discretized using a finite element approach and
the Poisson equation using finite differences. The particle fluxes are modelled using a Scharfetter–Gummel exponential representation [33]. The procedure for solving the system is to alternate the solutions of the continuity and Poisson equations using a semi-implicit scheme as explained in [34].

4. Experimental results: non-homogeneous composition

The following test case is considered for the results presented in this paper: a discharge in He/air (or N₂) at atmospheric pressure and ambient temperature. Helium and air (or nitrogen) were selected because, from the readily available gases, they have the most different coefficients in the Townsend formula: for He, \( F = 9.32 \times 10^{-21} \text{ m}^2 \), \( G = 105 \text{Td} \) and for air, \( F = 4.66 \times 10^{-20} \text{ m}^2 \), \( G = 1130 \text{Td} \) [22].

For a voltage within the predicted region of the GBD (figure 2), and using pulsed voltage of \( \sim 20 \text{ ns} \) duration, the discharge was indeed shown to be confined to the helium layer as shown in figure 4.

The photographs shown in figures 4, 6 and 8 correspond to the plane of the electrodes, that is looking from downstream of the flow to the jets, see dashed line in figure 3. As the electrodes are 2 mm wide, this is a short region streamwise of the flow so that, where the discharge develops, there should be little variation of the composition profile in the streamwise direction. However, the centre jet cannot be considered pure helium (as seen by the nitrogen emission) but still the confinement to the helium jet is achieved as the ionization properties of each layer are dominated by the species in greater abundance (for relatively low mixing fractions, see figure 7(a)).

In all cases, the discharge had a filamentary appearance, with filaments travelling along \( x \) or streamwise of the bulk flow, and the filaments were clearly seen to change direction as much as 90° to \( y \)-directed or streamwise of the bulk flow, when they reached the He–N₂ mixing layer. Filaments travelling upstream of the bulk flow were more common since the composition profile is sharper and there is a higher concentration of helium (downstream of the bulk flow mixing is enhanced and the composition profile is more diffusive).

Even though the discharge developed in the helium layer alone, the filamentary structure can be explained by trace amounts of nitrogen; [24] cites how if 1% of air is added to helium, the discharge transitions from uniform to filamentary. Representative voltage and current waveforms of these experiments are shown in figure 5.

To further confirm the effect of the cold gas barrier, the same experiments were repeated without the glass slide and with the electrodes directly exposed to the gas. Figure 6 confirms that it is the nitrogen layers that stop the filamentary discharges, and indeed behave like a barrier to the discharge. However, there are some main differences with the use of solid dielectrics (repetitive unipolar nanosecond-pulse DBD has been studied for traditional DBD, using solid dielectrics, for example by [35, 36]) as these gaseous layers not only present a capacitance but also a resistive component.

First, there is an asymmetry in the behaviour of the cold layers as compared to solid dielectrics which can be appreciated when the He is directly in contact with the electrodes: the discharge is more luminous when the nitrogen is in contact with the cathode as positive charge can be accumulated in the He/N₂ mixing layer, whereas when the nitrogen layer is in contact with the anode, the electrons will drift away at a shorter time scale.
Second, when using gaseous dielectrics, bulk transport of the flow (convection) and charge transport (drift and diffusion across the cold layers) contribute to the depolarization before the next pulse is applied. For the experiments here performed, the flow residence time in the discharge cell is of the same order as the pulse repetition frequency.

Exploratory optical emission spectroscopy indicated that the dominant emission came from the second positive band of molecular nitrogen, as even a small fraction of nitrogen in the helium stream makes this emission dominant. However, the He line at 706.5 nm was also seen, and a more refined observation is planned in order to highlight the He emission.

The Boltzmann equation was solved using BOLSIG+ [26] for the case of 120 Td to explain the dominant emission seen, see figure 7(a). It can be appreciated how most of the energy is spent in the excitation of N\textsubscript{2} even for \(X_{\text{N}_2} \approx 0.05\). Also, note how the fraction of energy that goes to ionization of N\textsubscript{2} is increased when helium is added (and there is a maximum at \(X_{\text{He}} \approx 0.9\)), this might be surprising at first but can be explained through the electron energy distribution function dependency on composition, see figure 7(b). The EEDF in pure He has a higher mean energy than in pure N\textsubscript{2}, hence ionization is maximum for \(X_{\text{He}} = 1\): more electrons at high energy (longer tail) and more targets; whereas ionization of N\textsubscript{2} presents a maximum at some value of \(X_{\text{He}}\): competing effects of number of targets and high energy tail of electrons, the importance of the high energy tail is higher so the maximum takes places at \(X_{\text{He}} \approx 0.9\).

On top of this, there will be Penning ionization, whose rate depends on \(X_{\text{N}_2}\) and the excited helium produced. Since the chemistry of the helium layer is very influenced by the nitrogen that has leaked in, experiments for a uniform composition but gradient temperature are underway to eliminate these effects and have more conclusive results.

Results were very similar when replacing the nitrogen by air.

If the flowing air was replaced by stagnant (ambient) air, the cold layer was perforated. This indicates the essential role of the convecting transport, both of charged species and heat when the repetitive unipolar strategy is used.

As a final test to further confirm that the nitrogen layers are acting as a barrier, ac voltage instead of nanosecond-duration pulses was tested and the confinement to the helium layer was also observed, figure 8. Experiments with and without the glass slide were performed and analogous conclusions were reached.

In these experiments lower applied voltages were used and the discharge appeared to be self-organized (for the case of the nitrogen in contact with the powered electrode) and glow-like. A more detailed investigation of the substitution of pulsed nanosecond discharges by sinusoidal voltage is underway.
5. Interpretation guided by numerical results

The numerical model described in section 3.2 has been used to help explain the experimental observations for a first filament arising and after the pulsed voltage ends. Since our goal is to provide a phenomenological description of the discharge evolution and not to reproduce our experimental results, the dimensions of the discharge cell used are smaller than in the experiments to reduce computational time. For the numerical evaluation, the gas gap is 3 mm long in the \( x \)-direction (along the gradients) with the composition profile as shown in figure 9. The dielectrics are 0.5 mm thick and have a dielectric constant of \( \epsilon_r = 5 \). The dimension of the gap in the \( y \)-direction was taken to be 15 mm although symmetry was considered and only half of the domain was solved for. The secondary emission coefficient from the cathode was taken to be \( \gamma = 0.1 \). The pulse voltage amplitude was set to 3 kV. With these conditions, we should be within the region of confinement to the hot layer of figure 2. Longer pulses than in the experiment (150 ns) were selected to clearly observe the propagation dynamics of the ionization front once it reaches the mixing layer.

The grid is rectangular and for the simulations here shown has 70 \( \times \) 70 elements on the gas grid and 90 \( \times \) 70 elements on the potential solver grid (includes dielectrics). This grid is very coarse and the results here presented suffer from numerical diffusion which produces artificial seeds of electrons locally in front of the streamer head [37] acting as a spurious form of photoionization that is in part responsible for the lateral streamer propagation. In this paper we attempt to provide a first description of the behaviour of gaseous pseudo-dielectrics and the modelling will be more refined in forthcoming publications.

Initial conditions for the simulation of the first filament were taken as a Gaussian spot of plasma placed in the plane of symmetry of the gap and in the He/Air mixing layer at the cathode side at the moment when the voltage pulse is applied. An anode-directed electron avalanche is formed and when it reaches the anode-side mixing layer, the electric field is sufficiently distorted by the space charge that a cathode-directed streamer can start propagating towards the cathode. In theory, an anode-directed streamer could also develop from this mixing layer but the reduced electric field in the air side is insufficient to provide the ionization mechanism.

Within the model, once the cathode-directed streamer reaches the cathode side He/air mixing layer, its propagation can be impeded if the field is not high enough to penetrate the air. Instead, the volume streamer stagnates and for some of the conditions tested, two lateral streamers propagate along the mixing layer (this solution is similar to the behaviour in a standard DBD configuration once the streamer reaches the dielectric barrier [38] or to plasma bullets in APPJ [30]). In all cases, the electrons are free to drift towards the anode but the ions are piling up on the cathode-side mixing-layer (slower drift), creating a positive charge layer on it, and thus confirming the asymmetric behaviour of the anode-side and cathode-side nitrogen layers.

Note that although the stagnation of the first filament at the He/air mixing layer can be explained by differences in ionization coefficient alone, once a conductive channel is formed, the path of highest conduction also has a role in the subsequent aiming to specific regions [39].

After the voltage pulse application, within the assumptions of the model (e.g. the only electron loss mechanism considered is transport to the walls), it was observed that due to the configuration of the potential at this point, the electrons stop escaping towards the anode and start drifting towards the centre of the gap resulting in a positive feedback mechanism for the
concentration of successive discharges in the helium layer if the repetition frequency of the voltage pulses is faster than the flow residence time, see figure 10. The excess ions are escaping by their drift towards both electrodes and the quasi-neutral electron and ion mixture is governed by ambipolar diffusion.

Finally, the model can also be used to explain the behaviour of the conduction current. A short time after the voltage pulse is applied, the electrons start arriving to the anode and keep arriving as long as the streamer is propagating towards the cathode. Once the ionization front reaches the cathode-side He-air mixing layer, two effects limit the current spike (apart from the voltage pulse duration): first, the plasma created by their drift towards both electrodes and the quasi-neutral electron and ion mixture is governed by ambipolar diffusion.

For this second effect to be significant, the charge accumulated in this layer, \( \frac{Q}{A} \approx e(n_i - n_e)\delta x_{\text{mix}} \), needs to be:

\[
\frac{Q}{A} = \frac{e_0 V}{d_h + d_c} \sim 10^{-5} \text{ C m}^{-2},
\]

which is the case for the model within the tested case.

Thus, the current spike duration is of the order of the electron drift time to the anode (~60 ns) as long as there is an applied voltage during that time. Also, note that the voltage pulse duration should be selected shorter than the lifetime of the charge layer which is given by the ion drift/diffusion time \( \sim 1 \mu \text{s} \). After the main current spike, there can be a residual current due to the conductive channel created between this layer and the anode which will be significant if there are lateral streamers propagating along the mixing layer, figure 11.

6. Conclusions

The dynamics of streamer plasma development under combustion conditions has been considered. Through the gas-confined barrier discharge (GBD) concept we have shown that streamer discharges can be confined to regions of easier ionization (in this paper we have shown experiments for favourable composition conditions); this is very promising in the sense that the non-thermal plasma will be strongest, and in the limit confined to the regions where it is most effective in supplying active species to the flame. We have presented novel experiments demonstrating the possibility of confining the discharge to a helium layer in contact with nitrogen layers and have explored several physical explanations using a simple numerical model. In particular, differences in electron impact ionization coefficients can explain the results although other important contributions have been recognized and need to be assessed further. Future efforts will explore the effect of a gradient in temperature (hot-cold layers with uniform composition) to check the applicability of the GBD concept to a temperature difference. The temperature experiments will clarify the results here presented since the He–N\(_2\) composition complicated the interpretation of the results.

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