Characteristics of Nanosecond Pulsed Discharges in Atmospheric Helium Microplasmas∗

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Abstract Microplasmas are very interesting due to their unique properties and achievable regimes maintained at atmospheric pressures. Due to the small scales, numerical modeling could contribute to the understanding of underlying phenomena as it provides access to local parameters — and complements experimental global characteristics. A self-consistent formalism, applied to nanosecond pulsed atmospheric non-equilibrium helium plasmas, reveals that several successive discharges can persist as a result of a combined volume and dielectric surface effects. The valuable insights provided by the spatiotemporal simulation results show the critical importance of coupled gas and plasma dynamics — namely gas heating and electric field reversals.

Keywords: microplasmas, self-consistent simulations, space charge, Joule heating, nanosecond discharges

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

1 Introduction

Microplasmas are extremely interesting due to their unique properties [1] linked to the small scales involved (typically \( d < 1 \text{ mm} \)). Potential applications range from nanotechnology-based processing [2] to electric propulsion of spacecraft [3]. The complexity of the small scale discharge is both space and time related due to relatively short lifetimes of species (added to the possible inter-connections between different species involved). In fact, some effects observed might even be amplified as a result of the reduced scale effects as extensively discussed for key plasma parameters in a review [1]. Concerning the lifetime and maintenance of the discharge, characteristics (such as the magnitude, shape and frequency of the voltage pulse) appear as important parameters — as they can have an influence on the threshold thereby limiting the efficiency. Hence, nanosecond pulsed discharges [4] are of high interest as the specific plasma properties could be beneficial for energy or momentum control of specific regions of the discharge as discussed in the following applications.

These features are relevant for instance in electric propulsion for spacecraft [5] and active flow control by non-equilibrium plasmas, an active area of research in aerodynamics. The plasma actuator aims at stabilizing the Tollmien-Schlichting layer in the transition to turbulence [6] and offers several advantages compared to its counterparts: a very short reaction time; capable of acting on several regimes ranging from flow without separation to separated and turbulent flows. It is also low weight and small size with low power consumption [7]. The configuration can also have a significant influence in the plasma dynamics, in the case of dielectric material used on electrode surfaces, namely the thickness and permittivity properties of the dielectric [8,9]. The experiments also show that both momentum transfer and energy transfer can play a governing role and the modeling and simulation will contribute to a comparison of the relative weights. It should be noted that the sinusoidal are more momentum governed whereas the pulse mode is more energy dominant [7]. The plasma components and parameters are critical as discussed above but the gas can also play a crucial role. The effect of temperature (and pressure) is clearly apparent in dielectric discharges. The temperature effects are also measured and are important in the space propulsion microsystems as well as plasma actuators. In effect, the temperature rise leads to an almost linear rise in body force measured [10]. Decreasing pressure extends the dimensions of the discharge inferring the effectiveness of a plasma actuator at low pressure conditions [11]. Remarkably, a force is apparent on the gas even when the plasma is in the off mode, attributed to viscous effects at the surface and turbulent energy losses [12], hence emphasizing the importance of coupled plasma-gas effects [13].

Due to the small geometrical nature of microplasmas, numerical modeling methods can provide access to

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local plasma parameters, to complement more global properties targeted by experimental methods. It is interesting to note that microplasmas are small (typically \( d \) is in the \( \text{mm} \) to \( \mu\text{m} \) range) but the relevant physical property is \( p \cdot d \) (pressure times distance) as defined by Paschen’s curve. Interestingly, the simulation can provide valuable information on parameterization parameters and also provide a refined design for the experiments. The complementary nature of the simulation results would provide valuable insights on the critical phenomena. The plasma discharge can operate from either a surface or a volume point of view. To gain an enhanced understanding of the direct and derived effects (first order and second order effects) for instance heating of the gas, a self-consistent strategy is adopted in the present work. A multi-component formulation implements the plasma and its potential interaction with the gas in a self-consistent coupled model. The metastable species can also participate in the rapid heating process \([14]\). Heating can in fact delay plasma regime transitions (saturation) and impact the interaction between the plasma and gas. Furthermore, the plasma simulations can predict the impact of the charged species on the gas. The gas temperature rise has also been shown to be important in the global dynamics as measurements of a few hundred degrees have been observed in the plasma layer. The understanding of the inter-connected phenomena could lead to opportunities for flux control \([15]\) and significant memory effects may be expected \([16]\).

2 Governing equations: self-consistent approach

The microplasma regime is an active area of research due to the applications such as plasma-based flow control and electric propulsion. Indeed, as illustrated by phenomena observed within microplasmas, it is deemed useful to consider a fundamental (co-planar parallel-plate) configuration: to understand the contribution of coupled effects among several governing and interconnected effects. The inter-related effects can have several sources as illustrated in Fig. 1. Interestingly, these effects observable in classical discharges can be amplified due to effects of smaller scales, as discussed in the next sections.

For instance, the plasma-induced fluid dynamics, heating and depletion can be captured in microplasmas \([17]\). The effect of temperature has also been experimentally demonstrated to have some control on transition effects \([11]\) and the present model also includes coupled gas effects. Hence, a self-consistent modeling of the electrons, ions, metastables and the electric field is therefore important and challenging due to the disparate time scales involved. The importance of metastables \([18]\) and Penning ionization in helium has also been highlighted. This self-consistent formalism has been detailed in previous work and is also used in the present simulations. Thus, the self-consistent formalism can be schematically summarized in Fig. 1. The self-consistent directly coupled plasma/gas/metastable governing equations have been detailed and validated previously \([17]\)—the key plasma and gas equations are summarized below.

![Fig. 1 Self-consistent effects are highlighted and amplified in microplasmas (MP)](image)

Eq. (1) shows the conservation equation for charged species (\( s \)) shows electrons and ions respectively, for the plus and minus signs in the second right hand side term). For ions, the drift-diffusion formulation was also compared to the ion momentum equation in our simulations and results were found to be very similar. Eq. (2) depicts the Poisson equation describing the potential \( V \) and the corresponding electric field \( E \), including space charge effects:

\[
\frac{\partial n_s}{\partial t} + \nabla \cdot [n_s \mu_s \vec{E}] = D \nabla^2 n_s = S_s, \tag{1}
\]

\[
\Delta V = -\frac{\rho}{\varepsilon_0} = -\frac{e(n_e - n_i)}{\varepsilon_0} \text{ with } \vec{E} = -\nabla V. \tag{2}
\]

The subscript \( s \) refers to the particle considered, \( n_s \) is the density \( n_e \) and \( n_i \) are electron and positive ion densities, \( \vec{v}_s \) the mean velocity, \( S_s \) the source term, \( D \) the diffusion coefficient, \( \mu_s \) the mobility and \( e \) the electron charge. The electric field close to the anode is derived by Gauss’ law \([17]\) and given by Eq. (3).

\[
\varepsilon_\text{d} E_{z,\text{d}} n_e - \varepsilon E_z n_n = \sigma, \tag{3}
\]

where \( \varepsilon_\text{d} \) is the dielectric constant and \( E_{z,\text{d}} \) and \( E_z \) are the longitudinal electric field in the plasma (near the solid/gas interface) and the dielectric respectively, \( \sigma \) is the surface charge density and \( n_n \) the normal unit vector at the surface. The dielectric anode is considered to have a surface charge. The surface charge on the dielectric is updated after each time-step from the plasma current densities and knowledge of the electric field close to the solid-gas interface.

The neutral dynamics is governed by the macroscopic hydrodynamic equations of a compressible and viscous fluid comprising conservation equations of densities
of mass $m_N N(\vec{r}, t)$, momentum $m_N N(\vec{r}, t)\vec{v}_N(\vec{r}, t)$ and total energy $\varepsilon(\vec{r}, t)$ respectively:

$$\frac{\partial m_N N(\vec{r}, t)}{\partial t} + \nabla \cdot [m_N N(\vec{r}, t)\vec{v}_N(\vec{r}, t)] = 0, \quad (4)$$

$$\frac{\partial m_N N(\vec{r}, t)\vec{v}_N(\vec{r}, t)}{\partial t} + \nabla \cdot [m_N N(\vec{r}, t)\vec{v}_N(\vec{r}, t)\vec{v}_N(\vec{r}, t)] = n_e \frac{m_N m_s}{(m_N + m_s)} \nu_{en}(\vec{v}_s - \vec{v}_N) - \nabla \cdot \vec{J} - \nabla \cdot \vec{v}_N, \quad (5)$$

$$\frac{\partial \varepsilon(\vec{r}, t)}{\partial t} + \nabla \cdot [\varepsilon(\vec{r}, t)\vec{v}_N(\vec{r}, t)] = -\nabla \cdot \vec{J} - \nabla \cdot [\vec{v}_N \cdot (p \vec{v}_N + \vec{\tau})] + f_t \vec{J} \cdot \vec{E}, \quad (6)$$

$m_N, N(\vec{r}, t), v_N(\vec{r}, t), p$ and $T$ are the mass, density, velocity, pressure and temperature of the gas respectively, $\vec{r}$ and $t$ represent the vector position and time. The collision terms of Eq. (5) (subscript $s$ corresponding either to electrons or ions in collision with atoms) can be simplified by using the following approximation for the collision frequency $\nu_{en}$ between charged and neutral particles: $m_e \nu_{en} = k_B T_e/D_e$. The total energy $\varepsilon$ is the sum of the kinetic and thermal energy; $k_B$ is the Boltzmann constant and $\vec{E}$ is the identity tensor. The system of transport Eqs. (1) to (3) is closed by the equation of state of an ideal gas ($p = k_B N T$) and by Fourier’s law for the heat flux $Q$ and the Newtonian approximation for the viscous tensor $\vec{\tau}$.

Note that the three equations describing the neutral dynamics are not only strongly coupled but are moreover dependent on the charged particles dynamics via the terms $n_e \frac{m_N m_s}{(m_N + m_s)} \nu_{en}(\vec{v}_s - \vec{v}_N)$ and $f_t \vec{J} \cdot \vec{E}$. Indeed, these terms represent respectively the action of the plasma on the neutral gas by two modes of transfer namely momentum (due to convection) and energy transfer (due to Joule heating). This implies that the neutral dynamics is also conditioned by the charged particle dynamics.

The influence of secondary emission can also include other components such as photoemission and field emission as parameterized and compared in Ref. [19]. For the configuration considered in the current work, the secondary emission is mainly due to ion impact on the electrode. It is interesting to note that for certain configurations, field emission can become more significant and has to be included as a phenomenon [20].

Interestingly, the validity of the continuum model has been demonstrated by comparing the distribution functions predicted by a particle Monte Carlo method as well as characteristic plasma parameters. It is important to note that null-collision Monte Carlo formalism and results have been discussed in previous publications [18,21] which validated the use of a fluid based formalism even for small gap discharges. The focus of the present paper is on the fluid-based model and results. Fig. 2 illustrates the competition between microscopic phenomena and global effects (i.e. loss due to collisions and gain due to electric field). The distribution functions were also investigated for short-gap discharges [21]. It was concluded from the particle method results that the hypothesis of a continuum fluid model remains valid for a short-gap discharge. The present fluid-based simulations provide complementary and interesting information on the bulk properties such as space charge and neutral gas heating. It should be noted that particle based methods, such as Direct Simulation Monte Carlo (DSMC) or PIC-MC, have also been applied to small scale devices [22].

Moreover, it is interesting to note that the properties of the applied voltage have a crucial importance as it can further enhance heating in certain cases. For instance, the nanosecond pulse can input more energy compared to a sinusoidal alternating current discharge and increase the gas temperature by several hundreds of Kelvins [23]. The voltage applied in the present study is a nanosecond unipolar pulse with a trapezoidal shape: rise time of 10 ns, and plateau of 625 V for a pulse width of 10 ns. It is important to note that even though the applied voltage is relatively small, the corresponding electric field is relatively high as the distance between the electrodes is small in microplasmas, leading to high $E/N$ values.

### 3 Results: plasma and gas dynamics

The results are obtained by the multi-species self-consistent scheme discussed in the modeling formalism in the previous section. The distance between the electrodes is 200 $\mu$m and the electrodes are covered with a dielectric material with a relative dielectric constant of 5. The helium gas is at atmospheric pressure and is quiescent. It is interesting to note that in microplasmas the small scale leads to specific and enhanced physical behaviors. Hence, the initial evolution of the small scale discharge is significantly different from a classical discharge mainly due to the closeness of the electrodes.
The electrodes in the cases shown are dielectric but a discharge can be achieved with or without a dielectric barrier [24].

As a matter of fact, the initial cloud of electrons rapidly disappears (due to the short scale), within a few nanoseconds, absorbed by the anode. The primary electron cloud transport to the electrode happens without significant amplification in its wake, as compared to classical larger discharges as depicted in Fig. 3. The microplasma evolution is therefore governed by the secondary plasma, created by cathode surface effects (such as secondary emission), which becomes a critical parameter. The secondary electrons created and transported are subsequently amplified within the small volume, if the phenomenon is sustainable. In the present case investigated, a severe drop of about 2 orders of magnitude in the maximum of the plasma number density is observed when the initial cloud reaches the electrode (around 4 ns). However, the secondary emission coupled to the volume amplification is sufficient to stabilize the plasma density onwards. The Townsend regime is reached at this point, implying a stable amplification of species in the next sequence as shown in Fig. 3.

It is interesting to note that the slow rise of the applied voltage (as compared to a constant applied voltage) due to the pulse regime also contributes to modifying the characteristics of the plasma. In fact, the rise and fall of the voltage pulse can contribute to several discharges within a single pulse [25]. Fig. 4 shows the first discharge which corresponds to the pulse voltage and the inception of a potential second discharge as a result of charge accumulation during the voltage fall time (as evidenced by the rise in the plasma number densities in Fig. 4(b)).

The charging of electrode, namely the charging of dielectric surface with a blanket of electrons is at the source of this dual effect. This in turn leads to a localized electric field inversion. The negatively charged electron species are able to move in both directions, as opposed to a single direction imposed in the initial voltage/electric field distribution. Likewise, the ions are also propagating locally in both directions. The inversion region is relatively small but the combined effects of plasma transport, amplification and accumulation of charges all contribute to the distribution and evolution of discharges. The rapid rise at the late stages of the voltage pulse is correlated with charge accumulation at the anode (Fig. 5). The charge
accumulation is initiated near the electrode surfaces but also tends to propagate in the bulk.

Fig. 5 Distribution of ion density (in \( \text{m}^{-3} \)) (a) and longitudinal electric field (in V/m) (b) in the helium microplasma at 17.7 ns

In turn this charging leads and contributes to gradual electric field inversion. The field inversion has been observed both experimentally and in simulations in the literature \cite{26}. It is interesting to note that drift and amplification lead to alternating positively dominated and negatively dominated space charge in the bulk of the discharge, joined by perfectly matching electron and ion populations. Interestingly, this condition of pseudo neutrality is self-consistently attained in the simulation without pre-imposed conditions. This distribution in turn leads to fluctuating directions of electrons and ions as governed by the space charge, i.e. electrons are moving towards the anode and towards the cathode in certain specific regions. This leads to a second peak which has also been observed in a 1-D particle simulation \cite{27}. The localized space charge in reduced dimensions is interesting as it can help focus momentum transfer \cite{28}. The plasma densities reach high number densities which initiates heating of the gas as depicted in Fig. 6. This also creates a depopulation of the gas which could lead to amplification of the reduced field \((E/N)\) as time evolved (especially for recurring discharges). Heating of the gas has also been observed experimentally and numerically due to Joule heating effects and the larger the number of pulses the higher the gas temperature achieved \cite{29}. In fact, Joule heating could be the governing phenomena as opposed to momentum transfer \cite{30}.

Fig. 6 Gas characteristics \((P: \text{pressure in torr}; \ T: \text{temperature in K}; \ N: \text{neutral gas density in } \text{m}^{-3}\) as a result of interaction with the microplasma at 19 ns

It is interesting to note that based on the evolution of the microplasma it can be inferred that memory effects could participate to subsequent discharges. Interestingly, both the space charge memory effect on the surface—and possibly a gas memory effect \cite{18} in the volume (if depletion persists over the multiple discharges) could both play a significant role. The heating could also be used in a spark type actuator configuration if the effect can be amplified over time in recurring discharges.

4 Concluding remarks

The microplasma discharge can exhibit several coupled effects as the effects are amplified due to the gradients constrained within small space and time evolutions. These self-consistent behaviors are further emphasized if the power cycle is non uniform. In the present simulations, a double discharge is observed and space charge localized effects induce electric field reversals and also trigger neutral gas heating. The surface effects of charging at the dielectric electrodes also permeate into the bulk initiating electric field reversals—which affect both plasma and gas effects. It highlights the importance of a self-consistent model to capture the spatiotemporal evolution of microplasmas. Both plasma and gas memory effects are noted to work concurrently namely charging of the dielectric, electric field reversals and heating: emphasizing the importance of self-consistent modeling in order to capture the evolution of high voltage nanosecond microplasmas. It also demonstrates that both volume effects (electric
field reversals and gas heating) and surface effects (charging and secondary emission at electrodes) are of critical importance in microplasmas.

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