Jetting axial flow induced by nanosecond repetitively pulsed discharges in quiescent ambient air

Sergey A Shcherbanev∗, Tanguy Krzymuski, Yuan Xiong and Nicolas Noiray

CAPS Laboratory, Department of Mechanical and Process Engineering, ETH Zürich, Zürich 8092, Switzerland

E-mail: shcherbanevs@ethz.ch

Received 13 May 2022, revised 22 June 2022
Accepted for publication 1 July 2022
Published 13 July 2022

Abstract
This study investigates the phenomenon of jetting axial flow induced by nanosecond repetitively pulsed discharges (NRPD) in quiescent ambient air in a pin-to-pin electrode configuration. Axial stratification of discharge parameters (electron number density, temperature, specific energy, etc) influences the hydrodynamic effects leading to directed gas flow from the cathode towards the anode. The experimental results presented in this paper were obtained using schlieren imaging, optical emission spectroscopy (OES), and electrical measurements of the deposited energy. A jetting axial flow was induced for all considered gap distances (0.5–5 mm) and pulse repetition frequencies of ≥10 kHz. The direction of the induced flow is defined by the polarity of the applied high-voltage pulses. It was found that the flow does not arise immediately after the initiation of the first pulse of the applied burst but is induced after a certain number of pulses. Using temporally and spatially resolved OES the electron densities and temperatures were measured in the vicinity of the cathode and anode before and after the generation of the axial flow. A model explaining the generation and maintenance of the axial flow in NRPD and the role of the inhomogeneities of plasma parameters along the plasma channel on hydrodynamic effects is suggested and discussed.

Keywords: nanosecond repetitively pulsed discharges, LTE plasma, hydrodynamic effects, jetting axial flow

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

1. Introduction

Nanosecond discharges initiated within a pin-to-pin arrangement undergo different regimes depending on the duration of the applied waveform, voltage amplitude, pulse repetition frequency (PRF), and inter-electrode gap distance. Previously, it was shown by Pai et al [1] that three different regimes of nanosecond repetitively pulsed discharges (NRPD) can be distinguished: corona, glow, and spark. It was shown that the optical emission of the discharge in air of all three above-mentioned regimes is mostly given by 1st and 2nd positive systems of molecular nitrogen and the regimes differ by electron number density and specific energy deposition. The corona and glow regimes are accompanied by low gas heating and low electron number densities [2]. In the spark mode of the NRPD [3], the current and thus the electron density are significantly higher than in the other two regimes. The heat...
release rate is also much higher in the spark regime, which leads to fast gas heating [4, 5] at a temperature increase rate of \( \sim 30 \, \text{K ns}^{-1} \) at atmospheric pressure.

It was recently found [6–9] that apart from the above-mentioned regimes of nanosecond discharge, another discharge behavior can be observed while decreasing the inter-electrode distance or increasing the applied voltage amplitude and/or duration. Lo et al [6] showed that complete ionization of a gas with an electron number density of \( \sim 10^{19} \, \text{cm}^{-3} \) can be achieved on a nanosecond time scale. Similar plasma parameters were observed in NRP microdischarges [7] confined to a gap distance of 200 \( \mu \text{m} \). The electron number density was measured using Stark broadening and electrical conductivity measurements, and both methods showed that \( n_e \) reached a maximum value of \( 10^{19} \, \text{cm}^{-3} \). Later, Minesi et al [8] studied the effect of gas pressure on the transition to fully ionized plasma in pin-to-pin NRPD. Using optical emission spectroscopy (OES), it was shown that the transition from non-thermal spark to fully ionized thermal spark occurs abruptly on a time scale of approximately 0.5 ns. This transition was accompanied by the emergence of a thin (\( \sim 100 \, \mu \text{m} \)) filament with dominant N\(^+\) and broadband continuum emission. Parkevich et al [9] reported that the fast transition to fully ionized plasma is associated with extremely fast (\( \ll 1 \, \text{ns} \)) explosive formation of micro cathode and anode spots. These spots appeared near the surface of the pin electrode and grew towards the center of the inter-electrode gap at later times. Similar elevated electron number densities in the vicinity of the electrodes were observed by Stancu et al [10] in water vapor using OES measurements. These results demonstrate significant inhomogeneities of \( n_e \) along the discharge axis, even at short gap distances (2–3 \( \mu \text{m} \)).

Due to the fast heat release, the nanosecond spark discharges produce intense hydrodynamic distortions. The hydrodynamic effects of NRPD have been extensively studied in a single-shot regime in a quiescent environment both experimentally [11–17] and numerically [18, 19]. In particular, it was shown in [15] that fast gas heating on a nanosecond time scale leads to the formation of a cylindrical shock wave after discharge initiation. It was shown that the intensity of the shock wave significantly depends on the energy fraction spent on fast gas heating which is dictated by reduced electric field values. In [11, 16, 17] it was shown that a toroidal recirculation pattern is formed within a few tens of microseconds around the gap axis. Stepanyan et al [17] showed that the appearance of a torus occurs only above a certain threshold of the deposited energy density. The presence of such a toroidal structure was also validated using CFD methods [18, 19]. Castela et al [18] showed that intense entrainment of fresh gas into the region of the plasma channel occurs and leads to induced vorticity which can last for several hundreds of microseconds after the discharge initiation. Subsequently, Dumitrache et al [19] described the mechanism of gas recirculation by the presence of baroclinic forces appearing owing to the misalignment of the gas density and pressure gradients at the moment of shock wave detachment from the plasma region. Both of the aforementioned numerical studies were based on the assumption that the deposited energy was homogeneously distributed over the length of the discharge channel.

This recirculation phenomenon leads to a significant increase in the effective volume of the plasma-produced active species. In [20], the authors illustrated that the initiation of the burst of nanosecond pulses leads to synergistic coupling between pulses and significantly extends the dimensions of the activated gaseous medium. The toroidal recirculation pattern induced by a single nanosecond pulse in a quiescent environment has a symmetrical structure with respect to the central plane of the inter-electrode gap. However, this symmetry can be broken while initiating NRPDs consisting of several tens pulses. The asymmetric behavior was observed when a combustible mixture was ignited with a burst of NRP discharges [21]. It was demonstrated in [21] that by applying NRPD for ignition of quiescent lean propane-air mixtures, the ignition kernel distinctively shifted towards one of the electrodes. A similar behavior was observed in [22]. Opacich et al [23–25] demonstrated the effect of symmetry breaking on the ignition of combustible mixtures in flowing environments. The authors claimed the presence of discharge-induced jetting behavior that causes the kernels to grow preferentially in the direction of the anode. In [25], the authors reported that discharge-induced jetting motion depends on the inter-electrode gap distance, pulsation frequency, and discharge train length. It was demonstrated that jetting behavior was observed for all considered PRFs (\( \geq 10 \, \text{kHz} \)) for a gap distance of 1 mm. When the gap was increased to 2.5 mm the discharge-induced axial jetting was observed only for PRF \( \geq 50 \, \text{kHz} \). Although the axial jetting phenomenon has been reported in the literature, the physics of this effect remains unexplored.

This paper discusses the mechanism of the axial flow induced by high-frequency NRPD. Section 2 presents the experimental setup and diagnostics used in this study. Section 3.1 contains the description of the hydrodynamic effects produced by the NRPD when a burst containing several hundreds of pulses is applied. Section 3.2 presents an OES study of NRPD. Based on these results, the electron number density \( n_e \) and electron temperature \( T_e \) were measured in the anode and cathode regions using the local thermal equilibrium (LTE) approximation. In section 3.3, 0D kinetic modeling was used to characterize the LTE plasma regime under different initial conditions. In section 4, we summarize the results of our study and suggest a mechanism for axial flow generation and maintenance while initiating high-frequency NRPD.

2. Experimental setup

For all experiments presented in this work, nanosecond discharges were initiated by applying high-voltage pulses in ambient air in ‘pin-to-pin’ electrode geometry. Tungsten lanthanum alloy (W-La2O3 (1%)) pin electrodes have a conical shape with a curvature radius between 100 and 300 \( \mu \text{m} \). No noticeable difference in the energy deposition or in hydrodynamic effects produced by NRPD was observed for electrodes with different radii of curvature. The inter-electrode
The gap was varied between 0.5 and 5 mm using a translation stage equipped with a standard micrometer. NRP discharges are initiated by a commercial high-voltage pulser FPG30-100NM10X2 (FID GmbH) which generates pulses of positive and negative polarities with amplitudes of up to 15 kV and PRF of up to 100 kHz. The pulse width and front rise time were equal to 10 and 2 ns, respectively.

The schlieren method was utilized to characterize the hydrodynamic effects produced by NRPD. A schematic of the setup is shown in figure 1(a). Schlieren imaging was carried out with a light source LED illuminator IL104, providing non-coherent light centered at 462 nm. The output of the light source was collimated with a 1.25 m focal length 12 inches in diameter parabolic mirror. The beam, partly deflected in the discharge region owing to refractive index gradients, was directed to a $f = 400$ mm plano-convex lens with a diameter of 4 in. A knife edge was placed horizontally at the focal spot of the lens to cut 60–80% of the light. LaVision SstarX camera equipped with a Nikon ED AF Nikkor (180 mm, 1:2.8) lens was used as detector. To eliminate the major fraction of the discharge optical emission to avoid saturation of the camera, a narrow band $450 \pm 5$ nm filter was associated with the camera lens. The optical system used for schlieren imaging resulted in a spatial resolution of 45 pix mm$^{-1}$. The discharge, LED, and camera triggering were synchronized using a delay generator (Berkeley Nucleonics BNC Model 577) as shown in figure 1(a).

OES was used to obtain the emission spectra during the discharge and near afterglow. The spatially and time-resolved optical emission was collected and transmitted through the optical system shown in figure 1(b) to the entrance slit of the IsoPlane-320 (Princeton Instruments) spectrometer with 1800 I mm$^{-1}$ diffraction grating associated with the intensified PI-MAX4 camera. To avoid the contribution of buoyancy to the hydrodynamic effect produced by the NRPD, pin electrodes were installed horizontally. The AR-coated Dove prism was used for image rotation and was placed between 150 and 300 mm lenses as shown in the figure 1(b). To obtain spatially-resolved emission spectra along the discharge channel, the axis of the electrode system was aligned with the entrance slit of the spectrometer, and the image of the inter-electrode gap was focused on the plane of the monochromator slit. The total spatial resolution of the spectral images was 145 pixels mm$^{-1}$.

The electrical characteristics of the discharge were measured using a high-voltage probe (Lecroy PPE20kV) and current probe (Pearson model 6585) installed in the electrode system. The HV signal was transmitted through a 75 $\Omega$ coaxial cable connecting the electrodes and a high-voltage pulser. Current and voltage waveforms were recorded using an oscilloscope (Tektronix MDO3104) with a bandwidth of 1 GHz. Sample waveforms of voltage, current, and deposited energy are provided in figure 2 for discharges initiated in ambient air with a 20 kHz PRF and 10 kV amplitude. The distance between the electrodes was 2 mm. The time lag between the voltage and current waveforms was accounted for by reducing the applied voltage down to the values when there is no breakdown, and aligning the time derivative of the applied voltage signal with the measured current trace. The time lag was evaluated for all the considered discharge conditions. The displacement energy was also measured and found to be negligible compared to the discharge energy under all conditions.

It should be noted that NRPD is highly reproducible from shot to shot. The jitter of the discharge initiation is lower than 0.5 ns. Such reproducibility allows obtaining sequences of phase-locked images of schlieren, OES, and
direct discharge visualization. For phase-locked ICCD imaging of the discharge, the PI-MAX4 ICCD camera was equipped with a long-focal-distance, high-performance zoom lens (50× to 500×) VH-ZS50L and was placed in front of the electrode system (not shown in figure 1).

3. Results

3.1. Hydrodynamic effects induced by NRPD

This section presents the hydrodynamic effect induced by NRPD in a symmetric pin-to-pin electrode configuration when a burst containing at least a few hundred pulses was applied to the electrode system. The discharge was initiated in ambient air between the electrodes separated by a 0.5–5 mm gap.

3.1.1. Polarity effect. The hydrodynamic effect produced by a single-shot nanosecond spark discharge was recently studied in [16, 17, 19, 20]. It was shown in [17] that a toroidal gas recirculation pattern may occur around the discharge channel after a single nanosecond spark. This recirculation leads to radial expansion of the hot gas region and convection of the active species produced by the nanosecond plasma outwards from the discharge region. This phenomenon of hot gas expansion and formation of a torus occurs similarly in different gases, and pressures and is almost independent of the shape and material of the pin electrodes [20]. In addition, one of the key conclusions in [20] is that the size of the heated zone increases linearly with the number of applied pulses. By applying several tens of NRPD, it is possible to reach a significantly larger volume of the hot gas region. However, only the case of a burst containing 30 pulses was presented.

It turns out that if we apply a high frequency (several tens of kHz) burst containing several hundreds of pulses, the well-distinguished axial gas flow from one electrode to another is induced. Figure 3 shows schlieren images of the hydrodynamic distortions for two inter-electrode gaps of 0.5 and 2 mm. The first row of the images corresponds to the hydrodynamic patterns after 10 subsequent positive polarity pulses of 20 kHz NRPD. It can be seen that for both inter-electrode distances, the pattern is symmetrical with respect to the middle plane of the gap. The NRPD of negative polarity produces a similar symmetric distortion. During the first several tens of pulses, the heated gas propagates in a radial direction. While increasing the number of applied pulses, the hydrodynamic distortion becomes asymmetrical. Such symmetry breaking is accompanied by induced axial flow.

The transition to the regime with axial flow from one electrode to another does not occur abruptly, and it requires from several tens to several hundreds of applied pulses, depending on the PRF and gap distance. The polarity of the applied pulses only affects the direction of the induced axial gas flow. As shown in figure 3, while applying negative polarity pulses of −10 kV, the hot gas propagates from the high-voltage cathode to the grounded anode. When the high-voltage electrode was the anode, the direction of the axial flow was reversed, and the gas propagated towards the high-voltage electrode. While obtaining schlieren images in figure 3, the electrode system remained intact, and only the polarity of the HV pulser was changed. As shown in figure 3, the high-voltage electrode is always on the right side. For the experimental data presented further, practical reasons dictated the use of positive polarity of applied pulses.

3.1.2. Effect of inter-electrode distance. In a single nanosecond spark, the hydrodynamic effect induced by the discharge is significantly affected by the distance between the electrodes. As shown in [17] the toroidal recirculation pattern was formed more likely with an increase in the linear deposited energy, which in turn is achieved by reducing the inter-electrode distance at fixed parameters of the applied pulse. In other words, the combination of the energy input and aspect ratio of the discharge channel defines the dynamics and morphology of the hydrodynamic distortion observed after a single nanosecond spark.

In the pulse periodic regime, induced axial flow was observed in all experiments, regardless of the gap distance and applied voltage (above the breakdown voltage). Figure 4 shows the schlieren images of the hydrodynamic distortions for three different gap distances: 0.5, 2, and 5 mm. For all three cases, the PRF and voltage amplitude were fixed and equal to 20 kHz and +10 kV, respectively. Each row of the image corresponds to the moment between \( n_p \) and \( n_p + 1 \) pulses of the applied burst. After the first pulse, the discharges
initiated within the gap distances of 0.5 and 2 mm produce a toroidal recirculation pattern similar to [17, 19]. For a 5 mm gap, torus formation was not observed. Instead, the axially symmetric kernel expands slowly. This expansion is accompanied by the development of gas-dynamic instability and the associated rise in intensive turbulent motion [26] (Rayleigh–Taylor instabilities) at the boundary of the heated kernel. With an increase in pulse number, the volume of the expanded hot gas increased but the shape remained quasi-symmetrical with respect to the middle plane of the gap. As can be seen in figure 4, for \( n_p = 50 \), for all three gap distances, a quasi-symmetrical hydrodynamic pattern is formed similar to that reported in [20]. For \( n_p \geq 100 \), a well pronounced induced flow from one electrode (cathode) to another (anode) is observed for gaps of 0.5 and 2 mm. For a 5 mm gap the induced axial flow is observed at larger \( n_p \).

For more detailed consideration of the velocity fields before and after the transition to axial flow (TAF), the schlieren image velocimetry (SIV) method [27, 28] was used. Unlike the classical particle image velocimetry (PIV) in SIV techniques, eddies in a turbulent flow field serve as PIV ‘particles’. SIV uses spatial cross-correlation method that is analogous to traditional PIV analysis. For sufficiently turbulent flows, this turbulence involves refractive index gradients in the image plane, leading to a wrinkled schlieren structure. When performing an SIV analysis, such a highly turbulent flow field is called self-seeding. The main assumption of this method is that the evolutionary timescale of turbulent eddies is longer than the temporal resolution of the detection system, for example, the time separation between successive schlieren images must be small enough; otherwise, cross-correlation is impossible. The cross-correlation between two successive schlieren images allows reconstruction of the global convective velocity field.

The velocity field can be obtained from the displacement field at a given time interval between two consecutive schlieren images. A sequence of images representing successive states of the flow field must satisfy the following requirements for the temporal and spatial resolution of the images:

- The time interval between consecutive frames must be sufficiently small compared with the characteristic time of the local velocity change in any area of the considered region of interest. Which means that camera frame rate must be higher than the characteristic time formation and dissipation rate of the eddies.
- The spatial resolution must be sufficiently high to resolve eddies that are used for measuring the velocity field.

The camera frame rate of 100 kHz and exposure time of 1 \( \mu \)s are relevant settings for a subsonic flow with a sub-millimeter scale and velocities of approximately 10 m s\(^{-1}\). The spatial resolution of the schlieren images was 45 pix mm\(^{-1}\). The PIVlab [29, 30] open-source MATLAB code was used for the SIV analysis. A FFT-based multipass algorithm [31] was used, which allows the computation of the correlation matrix in the frequency domain. The density of the schlieren ‘particles’ defines the size of the interrogation area held just enough ‘particles’ to reduce the bias error. Window sizes of 48 \( \times \) 48, 24 \( \times \) 24, and 12 \( \times \) 12 pixels were selected for the first, second, and final passes. We also used the Canny edge detection algorithm built-in MATLAB Image Processing Toolbox to ensure the minimum ‘particle’ density requirement by identifying the ‘particle’ edges area during the
pre-processing step. The interrogation window sizes for multiple passes were empirically chosen to reduce the errors. The largest window size was chosen to capture the highest velocity in the flow. A large window was chosen first and then gradually decreased until the velocity profiles and magnitude stopped changing.

It should be mentioned that the velocity field may contain both large spatial gradients and sharp local changes in time values. Such inhomogeneities in a velocity field are difficult to analyze with a given time and spatial resolution. Therefore, they are considered as outliers. At this stage, we did not aim to study the detailed temporal dynamics of the velocity field. In the present work, we focus on a quantitative description of the induced axial flow effect and the physics sustaining gas flow. For this purpose, a phase-averaged velocity field carries all the relevant information.

Figure 5 shows the phase-averaged velocity field and the fields of the axial \(v_x\) components before the TAF for gap distances of 2 and 5 mm. The phase shown in figure 5 corresponds to the instant immediately after the applied pulse. Phase-averaging was performed over 10 periods of the applied burst. It can be seen that for both gaps, there is a stagnation point between the electrodes, where \(v_x\) the local axial flow velocity is zero. In all cases, the intense heat release near the electrodes leads to expansion of the heated region from the surface of the electrode towards the middle of the gap. This can be explained by the strong concentrated heat released near the surface of the electrodes. The inhomogeneity of the discharge parameters and the thermal effect of plasma will be considered in section 3.2.

Figures 6(a) and (b) show the schlieren images obtained 5 \(\mu s\) after the 10th discharge pulse with the corresponding velocity fields retrieved from the two subsequent frames recorded at 5 and 15 \(\mu s\) for gap distances of 2 and 5 mm. Local gas expansion regions were observed near the high voltage and ground electrodes. For a 2 mm gap, the gas propagates outwards of the inter-electrode region in both radial and axial directions. For a 5 mm gap, the gas expansion regions are more concentrated near the electrodes, and the hot gas propagates in both directions towards the center of the gap and in opposite direction from the tips of the electrodes. The toroidal-like structure of the heated gas is visible when the gap is 2 mm. For a 5 mm gap, the heated gas forms an irregular structure. Figures 6(c) and (d) show the divergence of the velocity field \((\nabla \cdot \mathbf{u})\). It is seen that the main ‘sources’ are concentrated near the electrodes for a 5 mm gap and more homogeneously distributed when the gap is 2 mm. For a gap of 2 mm, one can see the ‘drains’ (blue regions) surrounding ‘sources’ (red regions) along the entire perimeter of the hydrodynamic distortion. For gap distance of 5 mm, the ‘sources’ take place only in the
Figure 7. Phase-averaged schlieren images with velocity fields and axial component of the velocity fields after the TAF for 2 and 5 mm gap.

Figure 8. Instantaneous schlieren images and velocity field 5 μs after the 200th discharge (a), (b). Divergence of the corresponding velocity fields (c), (d). Gap distances are 2 and 5 mm. Applied voltage and PRF are 10 kV and 20 kHz respectively.

vicinity of the electrodes, and the highest ‘drain’ intensity is observed in the middle of the gap.

Figure 7 shows the phase-averaged velocity field and the axial component of the velocity after TAF. For both inter-electrode distances, a well-pronounced airflow was directed from the grounded cathode towards the high voltage anode. The fields of $v_x$ velocities also show positive $v_x > 0$ values along the entire length of the inter-electrode gap.

Instantaneous schlieren images with corresponding velocity fields 10 μs after the 200th discharge pulse are shown in figures 8(a) and (b) for gap distances 2 and 5 mm. It can be seen that an intense expansion region takes place near the ground cathode for both the 2 and 5 mm gap distances. The vector velocity field shows how the gas expanding at the cathode propagates towards the anode, circumflexing the latter and spreading further downstream from the anode tip. Figures 8(c) and (d) show the divergence of the velocity fields for the 2 and 5 mm gaps. Unlike the divergence field shown in figure 6, here we observe the ‘source’ concentrated mostly near the cathode and gas expansion near the anode vanishes. Such intense pulsations of gas expansion near the cathode lead to the generation of an axial flow towards the anode.

3.2. Optical emission of the NRPD

In this section, we present the results of the OES of NRPD in ambient air. The discharge parameters, in particular, the electron number density $n_e$ and electron temperature $T_e$, to a greater extent determine the dynamics of heat release, which in turn determines the hydrodynamic effect produced by the discharge. To reveal the physical mechanism of the initiation and maintenance of the induced axial flow, which was discussed earlier, in this section we carry out a spatio-temporal analysis of the discharge parameters.

3.2.1. Emission spectra of the nanosecond spark. It is important to mention that in all considered experimental conditions before and after the TAF we observed the LTE [6–8, 32, 33] plasma that was produced in the near electrode regions for all considered inter-electrode gap distances. In additional tests, the amplitude of the applied voltage was also varied, but it did not lead to any noticeable changes in the discharge regime. Once the voltage was above the breakdown threshold, the LTE plasma regions were always observed.

The transition to the fully ionized regime described in [8] is accompanied by intense continuous radiation and well-distinguished lines of N$^+$, N$^{++}$ and O$^+$ ions. Under our conditions, the transition from partially ionized to LTE plasma occurs at approximately 5 ns or shorter. According to [8], the transition to a fully ionized LTE plasma channel occurs as follows: (a) first, a weakly ionized non-equilibrium plasma channel (non-thermal spark) 200–300 μm in diameter was
produced. The optical emission at this stage was dominated by the $2^+$ system of molecular nitrogen; (b) then, 5–6 ns later, a thin filament was generated in the vicinity of the cathode. The formation of the filament occurs abruptly on a timescale below 0.5 ns and its optical emission is dominated by N$^+$ and a broadband continuum; (c) a few nanoseconds later, a similar filament is observed in the anode region. Both the cathode and anode filaments propagated towards the middle of the gap and merged. A similar dynamic of the plasma channel is observed in a single shot filamentary nanosecond SDBD at elevated pressures [32, 34, 35]. The electron number density and temperature under LTE conditions in both configurations, nSDBD and pin-to-pin, were $\sim 10^{19}$ cm$^{-3}$ and 3–4 eV respectively.

Figure 9 shows the spatially resolved spectra of the 200th discharge initiated within a 4 mm gap. The gap axis was projected onto the entrance slit of the monochromator. To avoid second-order diffraction, a 500 nm cut-on filter was mounted at the entrance slit while obtaining the spectra in the 480–620 nm spectral range. The regions of spatial averaging are indicated by the rectangles in the spectral images. Figures 9(a) and (b) show the emission spectra integrated over the first 5 ns of the applied HV pulse. The optical emission was dominated by the second positive system of molecular nitrogen which corresponds to the non-thermal phase of the discharge. Subsequently, 5 ns later, as shown in figures 9(c) and (d), the N$_2$(C→B) emission was no longer detected. Instead, the broadband continuum and the lines of O, N, and N$^+$ are distinguishable. Intense emission takes place in the anode and cathode regions. This abrupt change in the discharge optical emission corresponds to the transition from a partially to a fully ionized plasma. Discussions on the nature of continuous emission can be found in [34]. The absence of optical emission of the second positive system of molecular nitrogen is caused by the intense dissociation of the latter and a drop in the $E/N$ values by almost a factor of two (see section 3.3).

Notably, the spectra shown in figure 9 were acquired during the 200th pulse of the applied burst. In all experiments when the gap $d = 4$ mm and PRF = 20 kHz, axial flow was induced before the 200th pulse. As shown in the previous section, the induced axial flow causes strong inhomogeneity in the gas density along the axis of the electrode system. These axial inhomogeneities are produced by the heated gas which is convected towards one of the anode. Thus, at the moment of initiation of the subsequent pulse, the temperature of the gas surrounding the anode is higher than near the cathode. Temperature gradient along the gap leads to the fact that the intensity of the optical emission near the cathode is significantly higher than near the anode, as can be seen in figures 9(c) and (d). This fact is discussed in more detail below.

3.2.2. ICCD imaging of the discharge. The spatial distribution of the discharge intensity serves as an indirect marker of both the trail of electron avalanches and spatial distribution of the specific energy. Short-gated ICCD imaging was used to study discharge dynamics before and after TAF. High spatial resolution of the images is achieved using a high-performance zoom lens with adjustable magnification from 50× to 500×. The camera gate is fixed at 0.5 ns. Figure 10 shows the set of phase-locked images of the discharge during the 10th and 200th pulses for the inter-electrode gaps 2 and 4 mm. The lens magnification was adjusted depending on the gap distance to project the latter on the entire photo-detector size.
while capturing the tips of the electrodes. The delay of the camera trigger was counted from the moment the discharge glow appeared.

The transition from the non-thermal to thermal spark regime can be observed in all sets of images presented in figure 10. First, we consider the discharge evolution during the 10th pulse. During the first 2–4 ns, the diffuse low-intensity channel takes place. The optical emission of this stage of the discharge is mostly dominated by the second positive system of molecular nitrogen. Then, bright spots appear near the edges of the electrodes. In our experiments, for the discharges initiated by 10th pulse of the applied burst we were not able to capture the successive appearance of cathode and then anode spots as it was reported in [8, 36]. At our conditions, the time lag between the appearance of the anode and cathode spots is less than 0.5 nanoseconds, which in our case are both the camera gate and the time step. In the vast majority of our experiments, the bright spots appeared simultaneously. Our results are consistent with the results reported in [33] where authors demonstrate that both the cathode and the anode spots appear with an extremely short time lag. The authors in [9, 33] underlined the fact that depending on both the curvature of the electrodes and the quality of the surfaces, the time interval between the instants of the cathode and anode spot initiation may vary significantly from parts to several nanoseconds. After the formation of the bright spots near the electrodes, these regions expand towards the center of the gap with a relatively low velocity of 50–70 µm ns$^{-1}$. The velocities of the expansion of the cathode and anode regions are comparable for the 10th pulse of the applied bursts for both 2 and 4 mm gap distances.

Once axial flow was induced, a noticeable delay between the initiation of the cathode and anode spots was observed. In figure 10, the second and fourth rows of the phase-locked images demonstrate the cases of discharge dynamics during the 200th pulse for 2 and 4 mm gaps respectively. Regardless of the inter-electrode distance, pronounced high-intensity spots first appeared on the cathode. Anode spots arise 1.5–2 ns later. For both inter-electrode distances, the cathode filaments grew towards the middle of the gap, while the anode spots remained concentrated near the electrode. The volume of the near-cathode filament significantly exceeded the volume of the bright anode spot by the end of the applied pulse. To this extent, one can expect that the energy deposited in the cathode part of the discharge channel exceeds the energy in the anode region during the 200th pulse.

From the spectra shown in figure 9, it can be seen that the intense emission lines are located near 500 nm, corresponding to the transitions from N$^+$ (3S, 3P, 3F$^0$). According to the kinetic mechanisms suggested by Minesi and Laux [37–39], N$^+$ is the dominant ion after transition to the LTE regime. Approximately 70% of the electrons are produced by electron-impact ionization of the N$^+$ excited states. Thus, the optical emission of the N$^+$ ion may serve as a good indicator of the LTE plasma region.
To identify the spatial distribution of the \( \text{N}^+ \) emission, images were acquired with a 500 ± 5 nm narrow band filter capturing the emission lines of the \( \text{N}^+ \) ion. Figure 11 shows the spatial distribution of the emission intensity near 500 nm before and after TAF for the gap distances of 2 and 4 mm. The camera gate was increased to 5 ns to allow the accumulation of more light. It can be seen that the intensity profiles look very similar near the cathode and anode for the 10th pulse of the applied burst for both gap distances. After the flow is induced, both the intensity and the overall volume of the region of \( \text{N}^+ \) emission are a few times higher near the cathode. The characteristic distributions of the discharge emission near 500 nm on a logarithmic scale were also inferred from the inlays presented in figure 11.

3.2.3. \( T_e \) and \( n_e \) measurements. To understand the spatial behavior of the plasma parameters, particularly in the vicinity of the cathode and the anode, OES was utilized to measure the electron number density and temperature during the discharge and near afterglow. The emission lines of \( \text{N}^+ \), \( \text{O}^+ \) and \( \text{H}_\alpha \) were analyzed. The results presented below were acquired for the following experimental conditions: discharge in ambient air, gap distance of 4 mm, voltage amplitude, and PRF are 10 kV and 20 kHz respectively. The emission spectra of \( \text{N}^+ \) and \( \text{O}^+ \) ions near 500 nm were acquired with the 5 ns ICCD camera gate and 100 on-CCD accumulations. The emission of the \( \text{H}_\alpha \) line near 656 nm was recorded with a 10 ns camera gate. The raw spectra were corrected to the spectral sensitivity of the system. The spectral ranges of the considered emission spectra were sufficiently small to detrend the continuum emission as a straight line.

Typical emission spectra used for \( n_e \) and \( T_e \) measurements are shown in figure 12. The electron number density during the discharge and afterglow until 50 ns was measured from the Stark broadening of the \( \text{N}^+ \) lines. After ~50 ns, the emission of \( \text{N}^+ \) ions becomes too weak. Meanwhile, the emission of \( \text{H}_\alpha \) line appeared at ~20 ns after the discharge starts and is well observed until ~100 ns. Therefore, both lines were used for \( n_e \) to cover the time interval 0–100 ns. Synthetic spectra were modeled using NIST database [40] with the electron temperature as a fitting parameter. The atomic and ionic emission lines taken from the NIST database were convolved with the instrumental broadening lineshape (measured with PI calibration light source) and Lorentzian (a function of \( n_e \)). The technical details of this approach have been described in [8, 38].

For the emission lines of \( \text{H}_\alpha \), accurate fits were achieved using the Voigt profiles, as shown in figure 12(a). The Gaussian component of the profile is primarily due to Doppler broadening and is negligible compared to other types of broadening, including instrumental broadening. The main broadening mechanisms contributing to the Lorentzian components are van der Waals, resonant, and Stark broadening. In the discharge under investigation, the resonant broadening was always negligible [8] and the maximum van der Waals broadening FWHM was estimated to be 0.3 nm according
The electron temperature $T_e$ was retrieved from the relative emission intensity of the three major groups of N$^+$ lines near 480, 500, and 519 nm and one O$^+$ group near 470 nm, as shown in figure 12(b). The excited states of N$^+$ and O$^+$ ions are assumed to follow a Saha-Boltzmann distribution under LTE conditions, as considered in previous studies [6–8, 32].

The methods described above have been used to measure $n_e$ and $T_e$ near the anode and cathode before (10th pulse) and after (200th pulse) the transition to induced axial flow. The optical signals were integrated over a 0.5 mm in width near each of the electrodes. The electron densities and temperatures are shown in figure 13. Before axial flow is induced, the dynamics of the electron number densities exhibit similar trends near the cathode and anode. During the discharge, from 5 to 25 ns, the electron number density decreases from $3 \times 10^{19}$ to $1.7 \times 10^{19}$ cm$^{-3}$. In the discharge afterglow, the decay rate decreases, and by 100 ns after the start of measurements, the $n_e$ values remain high $\sim (1.1–1.2) \times 10^{18}$ cm$^{-3}$. These values correlate well with the spatially resolved $n_e$ measured in a single-shot thermal spark discharge [8], where the decrease in $n_e$ from $4 \times 10^{19}$ to $2 \times 10^{19}$ cm$^{-3}$ during 100 ns after the transition to the thermal spark regime was measured. The measured $T_e$ values are also consistent with the data presented in the same study. The reason for this slow decay rate was discussed in [8]. Under similar conditions, the authors analyzed the decay rate of the electron density by considering the ionization from 8 excited states of atomic nitrogen as a source term and three-body recombination with N$^+$ ions as a sink term. An isentropic expansion of the LTE plasma volume was considered as an additional sink term in the kinetic equation for the electron number density. It was shown that ionization nearly compensated for the chemical recombination of the electrons during the expansion because of the high $T_e$ values in the discharge until $\sim 100$ ns.

Figure 13(b) shows the dynamics of $n_e$ near the cathode and anode during the 200th applied pulse. Starting from the beginning of the measurements (5 ns), the electron density near the cathode exceeded the near-anode $n_e$ by $\sim 50\%$ which are $n_e' = 3 \times 10^{19}$ and $n_e'' = 2 \times 10^{19}$ cm$^{-3}$ respectively. The difference between $n_e'$ and $n_e''$ gradually decreases over time, and in the afterglow, the electron number density in the plasma channel is redistributed such that by the end of the measurements ($\sim 100$ ns), the $n_e$ values near the cathode and anode become nearly equal. Figures 13(c) and (d) show the dynamics of $T_e$ before and after the TAF. The maximum value of the electron temperature right after the transition to the LTE discharge regime 4.1 $\pm$ 0.2 eV, then decreases to $\sim 2.8$ eV during the first 50 ns. The evolution of temperature near both electrodes has very similar dynamics during both the 10th and 200th applied pulses.

$\text{3.3. 0D kinetic modelling}$

In the previous section, it was shown that nanosecond discharges generate a high electron density plasma ($\sim 10^{19}$ cm$^{-3}$) in the near-electrode regions, which corresponds to the LTE regime. The induced axial flow leads to a decrease in the

to the procedure described in [7]. In fact, the magnitude of the van der Waals broadening is a function of gas temperature. However, as it is shown further, the gas temperature of LTE plasma regions near the cathode and anode are nearly the same.

For the Stark broadening of the N$^+$ emission lines in the first approximation, the relationship is linear for all emission lines. Using the data presented in [41], the electron number density can be derived from the Stark width:

$$\omega_{\text{Stk}} = \frac{n_e}{10^{17}} \omega_{\text{Stk},0},$$  \hspace{1cm} (1)

where $n_e$ is the electron number density in cm$^{-3}$, $\omega_{\text{Stk},0}$ is the reference value of Stark broadening for $n_e,0 = 10^{17}$ cm$^{-3}$ obtained from [42] for N$^+$ emission lines near 480 and 500 nm, and from [8] for lines near 519 nm. Stark broadening is defined from the Lorentzian width as $\omega_{\text{Stk}} = \omega_{\text{Lor, total}} = \omega_{\text{VdW}} = \omega_{\text{resonant}}$, and according to [8], the ratio $\omega_{\text{Stk}}/\omega_{\text{VdW}}/\omega_{\text{resonant}} \sim 4/10^{-3}/10^{-4}$.

\hspace{1cm} Figure 12. Examples of the experimental spectra and corresponding simulated lines. (a) H$\alpha$ and N$^+$ lines; (b) N$^+$ and O$^+$ lines used for $T_e$ and $n_e$ measurements.
electron number density by a factor of 1.5–2 in the anode region. In this section, we present the results of 0D kinetic modeling based on two experimental facts: (a) after the TAF, the heated gas shifts towards the anode, while in the near-cathode region, the initial gas temperature at the moment of initiation of the subsequent pulse remains approximately 300 K; (b) after the TAF, both the intensity of optical emission of N$^+$ ions and the density of electrons in the near-anode region decrease, but the plasma remains in the LTE regime; (c) cathode and anode spots appear almost simultaneously (time lag $\lesssim 2$ ns) before and after generation of the anode-directed axial flow.

It was recently shown that ionization from the electronically excited states of atoms and molecules plays a major role in the transition to the LTE regime on nanosecond and subnanosecond time scales [32, 37]. It was suggested in [32], that the ionization rate in nanosecond discharges can be significantly accelerated by considering the direct electron impact on the ionization and dissociation from the excited N$^*_2$ states. Later, it was found [37] that by considering additional ionization channels from eight states of N and three states of O-atoms, the transition time to a fully ionized plasma regime can be reduced to 0.5 ns, which is in a good agreement with the experimental data.

Here, we perform zero-dimensional modeling of plasma kinetics using ZDPlasKin [43]. The solver uses BOLSIG+ to calculate the electron energy distribution function at every time step, solving a two-term approximation of the Boltzmann equation [44]. The cross-sections of the electron impact reactions were obtained mostly from the LXCat database [45]. The aims of kinetic modeling are (a) to analyze the dynamics of $T_e$ and $n_e$ of the LTE plasma for different initial conditions; (b) to provide the analysis of the power density for different initial gas temperatures; (c) and based on the obtained results, to provide the mechanism responsible for the maintenance of the induced axial flow. The simplified kinetic mechanism described in [38] was used. The model includes 38 reactions listed in [39] supplemented with 60 additional reactions.
such as electron impact ionization, dissociation, and excitation of molecules, ion-molecular reactions, and reactions between electronically excited atoms and molecules. Ionization by direct electron impact is complemented by the ionization of four excited N₂ states, eight states of N (including a ground state), and three electronic levels of O. The ionization of N and O is considered only to the ground state of the ions, N⁺(3P) and O⁺(4S). The dissociation of N₂(A, B, C, a'), the excitation and dissociation by the electron impact of N₂⁺ electronic states (X, A, B, C) are also included.

To retrieve the key concept of plasma behavior, we used a synthetic profile of a constant electric field of 15 ns in duration with a 2 ns front rise time, as suggested in [37]:

\[
E = E_0 \left( \frac{t}{t_{\text{ns}}} \right) \quad \text{for } t \leq 2 \text{ ns}
\]

where \(E_0\) is the electric field in V cm⁻¹. A reduced electric field \(E/N\) is recalculated at each time step, considering the changing number density of the heavies. In [37], the authors defined the density of heavy particles as \(N = N_{\text{ion}} + N_{\text{neutral}}\). In our study, we chose the same definition for \(E/N\). Since the transition to the LTE regime is faster than 1 ns, the heavy particle density is recalculated within an isochoric process.

The dynamics of the electron and gas temperatures together with \(E/N(t)\) profile, are shown in figure 14. The gas temperature starts to increase between 12 and 12.5 ns. During approximately 0.5 ns the LTE regime is achieved and the gas temperature increases from 300 to 32 000 K.

The dynamics of the N⁺, O⁺ densities and electron density profiles are shown in figure 15. Quasi-neutrality of the plasma is mostly achieved by N⁺ ions. The second most important ion is O⁺ which contributes \(\sim 8\%\) of the positive charges. The fraction of NO⁺ is about 2% and the contribution of other ions is less than 1%. It is important to mention that doubly ionized N⁺⁺ and O⁺⁺ are not considered in the model. As mentioned in [38], its contribution does not have any substantial effect on the overall dynamics of the transition and final LTE state. It can also be clearly seen that the increase in gas temperature is synchronized with the sharp dissociation of N₂ and O₂. In weakly ionized non-thermal nanosecond discharges (\(n_e = 10^{15} - 10^{17} \text{ cm}^{-3}\)) the temperature increase is due to the fast gas heating [4, 5]. In LTE sparks, the main mechanism of rapid temperature increase is the elastic collisions between electrons and heavies. Fast thermalization is achieved owing to elastic electron-ion Coulomb collisions [37, 46]. Therefore, under our conditions, when LTE plasma is observed near the electrode, hydrodynamic effects are mostly defined by ultrafast thermalization rather than by fast gas heating from chemical reactions.

The initiation of multiple discharges leads to the expansion of the heated gas outwards of the discharge region. When axial flow is induced, the heated by the previous pulses gas is ‘pushed’ towards the anode. The schlieren images show how the ‘hot’ gas surrounds the anode when the subsequent pulse is initiated. It is well known that the electric field in the cathode layer is rather high (several hundreds of Td) because of the cathode voltage drop. However, the structure and dynamics of E/N in the anode region are not well understood. Nevertheless, in figure 11, it can be seen that the intensities of N⁺ emission appear similar near both electrodes before the TAF and significantly lower near the anode when axial flow is induced.

According to the results of kinetic modeling, for the same initial conditions (gas composition, temperature, and pressure), the amplitude of the reduced field in the range of \(E/N = 150–300 \text{ Td}\) significantly affects the moment of transition to the LTE regime. However, the final values of \(n_e\) and \(T_e\) after the transition to the thermalized regime depend only slightly on \(E/N\). It was found that the increase in \(\Delta n_{\text{ion}}\) after the transition to LTE did not exceed 0.02% while increasing \(E/N\) from 190 to 250 Td, while the moment of LTE transition shortens from 13–14 to 5–6 ns. Therefore, we base our reasoning on the following considerations. First, the cathode and anode spots appear almost simultaneously (time lack is 1–2 ns) as can be seen from the time-resolved short gated images of the discharge before and after TAF. Second, the gas near the anode is hotter than that near the cathode after TAF. Therefore, in our model, we adjusted the amplitude of the electric field
mobility, where 300 K to 1000 K.

density of the LTE plasma decreases from the maximum value can be observed, that with an increase in the gas temperature, the transition to the LTE regime are given in the same plot. It shown in figure temperatures as functions of the initial gas temperature are and 900 K). The values of the maximum and final electron temperature to match the moment of transition to the LTE regime.

Figure 16. (a) Dynamics of $T_e$ and $n_e$ during the transition to LTE regime for different initial conditions ($T_{gas}$ and $E_0$). (b) Maximum and final values of $T_e$ and final values of $n_e$ as a function of initial gas temperature for the given moment of the transition to LTE regime.

$E_0$ in equation (2), to have a transition to the thermal regime at a fixed time moment of $\sim 13$ ns for different initial gas temperatures.

Figure 16(a) shows the dynamics of $n_e$, $T_e$ and the discharge power density for three different initial $T_{gas}$ and $E_0$. The value of $E_0$ was adjusted accurately for each gas temperature to match the moment of transition to the LTE regime. For clarity, only three cases are demonstrated ($T_{gas} = 300, 500,$ and 900 K). The values of the maximum and final electron temperatures as functions of the initial gas temperature are shown in figure 16(b). The electron number densities $n_{e fin}$ after the transition to the LTE regime are given in the same plot. It can be observed, that with an increase in the gas temperature, the maximum value $T_{e max}$ increases. Meanwhile, the final electron temperature $T_{e fin}$ slightly decreases. The electron number density of the LTE plasma decreases from $4 \times 10^{19}$ cm$^{-3}$ to $1 \times 10^{19}$ cm$^{-3}$ as the initial gas temperature increases from 300 K to 1000 K.

The specific plasma power $\omega$ (W cm$^{-3}$) is defined as:

$$\omega = jE = e\mu_e n_e^2 n_e/(E/N)^2,$$

where $j$ is the current density, $\mu_e = \mu_e (E/N)$ is the electron mobility, $n_e$ is the electron number density, and $N$ is the number density of heavy species. It can be seen, that even though $T_{e max}$ is higher for higher initial $T_{gas}$ or $E/N$ values, this does not have any substantial effect on the maximum value of power density. The latter is mostly defined by the electron number density, which increases from $10^{16}$ to $\sim 10^{19}$ cm$^{-3}$ between 12 and 14 ns, as shown in figure 16(a).

From the above discussion, we can see that the power density is significantly affected by the initial gas temperature. In addition, it can be seen in figure 10 that when axial flow is induced, the volume of the bright near-cathode plasma region is significantly larger than that near the anode. This leads to a higher total energy release on the cathode side of the plasma channel. A significant difference in the plasma power density leading to a greater heat release in the cathode region is the main reason for the axial flow maintenance between the electrodes.

The values of the final power density of the LTE plasma and field amplitude $E_0$ for a fixed value of the transition time to the LTE mode are shown in figure 17. The solid lines correspond to the moment of LTE transition demonstrated in figure 16, and the dashed lines correspond to the values for the LTE transition 2 ns later. The electric field required for plasma thermalization in the specified time interval decreases by more than two times, and the final power is almost an order of magnitude with an increase in the initial gas temperature from 300 to 900 K.

In the considered model, we took into account only the influence of the initial gas temperature on the power density of the LTE plasma. It should also be noted that for high-frequency pulse periodic discharges, the residual effect of the previous pulses is also determined by the initial pre-dissociation, pre-ionization, and the presence of metastable states. However, all these effects should only accelerate the transition into the LTE mode. For all cases, when an axial flow was induced, both the emission of N$^+$ intensity and the measured electron number density were lower in the anode region. In addition, the transition to LTE plasma near the anode appeared 1–2 ns later than that near the cathode. By considering other residual effects of
the previous pulses, the amplitude of the electric field $E_0$ and the discharge power density would decrease even faster with an increase in $T_{gas}$ than the profiles shown in figure 17.

4. Discussions

Based on the obtained results, in this section, we address two main questions related to the effect of induced axial flow during the initiation of high-frequency NRPD. The first is related to the fact that once axial flow is induced, it is maintained until the end of the applied burst. None of the experimental results showed swapping of flow direction. The second issue considered in this section is directly related to the mechanism of the TAF.

In all the experiments presented in this study, LTE plasma was generated in the vicinity of the electrodes as the cathode and anode spots. These regions of highly ionized plasma either slowly grow into the body of the discharge channel, as occurs with the anode and cathode spots before the TAF, or they remain in the near-electrode region, as happens with anode spots after the TAF. The formation of such dense plasma regions leads to nonuniformly distributed energy deposition along the channel length. Such an inhomogeneity of the input energy along the gap can have little effect on the hydrodynamic disturbances of the single pulse discharge compared to the case of uniformly distributed deposited energy. However, it can lead to accumulated effects that affect the hydrodynamics after a significant number of discharge initiation events.

Figure 18(a) shows schlieren images of the discharges initiated with 2 and 5 mm gaps acquired 45 and 45 $\mu$s after the 1st and 10th pulses of the 20 kHz applied burst. After the first pulse, a symmetric torus is formed and propagated in the radial direction for a 2 mm gap. For a gap of 5 mm, the body of the heated zone expands in the radial direction without the formation of a torus. Previously [17, 19], the appearance of recirculating toroidal distortion in a single shot nanosecond spark was explained by a baroclinic torque [19] leading to the axial collapse of the heated gas. Such a baroclinic effect becomes significant only if the value of lineic energy exceeded a certain threshold [17, 19]. Nevertheless, under our conditions, the cold gas axial inflow from the electrodes towards the middle of the gap is well distinguished, even for a 5 mm gap. The high energy density near the electrodes induces a local baroclinic effect regardless of the value of the lineic energy. The heated gas fills the inter-electrode gap after a few pulses. By the 10th applied pulse, subsequent discharges are initiated in a turbulent cloud of preheated gas with axial and radial density gradients. The spatial dynamics of the reduced electric field $E/N(x, y, t)$, and, accordingly, the production of electrons and excited species differ from the discharge in quiescent air. Consequently, the plasma channel bends stochastically from one pulse to another, as shown in figure 10, in contrast to the straight channel presented in [8]. The stochastic nature of the change in channel geometry leads to the inconspicuous influence of the hydrodynamic distortions produced by the central part of the channel on the mean velocity field. Before the TAF, the discharges provoke abrupt pushes of the gas from the near electrode regions towards the center of the gap. After the TAF, a convective component of the directional flow appears, which carries the heated gas towards the anode, and the cathode-directed thrusts from the anode region are no longer observed. Figure 18(b) shows the schlieren images of the axial flow during the inter-pulse time. It is clearly seen, that by the time of $N_p + 1$ pulse initiation, the heated gas after the $N_p$th pulse is pushed towards the anode. Meanwhile, due to the entrainment of the fresh gas from the cathode side, the temperature near the latter remains at the level of ambient temperature.

For proper visualization of the flow field dynamics between the electrodes, a 5 mm gap is further considered. Figure 19 shows the dynamics of the phase-averaged flow field. Phase-averaging was performed over 10 pulses. The pulse ranges used for phase-averaging are indicated in the lower left corner of each image. Before the TAF, each pulse produces a counter flow from each of the electrodes towards the center of the gap. The stagnation point with zero axial velocity is indicated by a blue circle. It can be seen that with an increase in the pulse number, the stagnation point moves towards the anode.
Figure 19. Phase-averaged flow fields for different sets of pulses within the applied 20 kHz burst. The camera frame rate is 100 kHz. The applied voltage is 10 kV.

After 130–140 pulses the zero-velocity point is located in the vicinity of the anode. All subsequent pulses induced axial flow surrounding the anode, and cathode-directed thrusts from the anode side were no longer observed. Meanwhile, the velocity field near the cathode did not undergo any noticeable changes when the pulse number was increased.

Different source terms of the vorticity equation were analyzed in [19]. It was shown that the term inducing the baroclinic torque was dominant during the first $\sim 10$ µs owing to the high misalignment between the density and pressure gradients. The vorticity induced by the baroclinic term is expressed as follows:

$$\frac{d\omega_{bc}}{dt} = \frac{1}{\rho^2} \left[ \nabla \rho \times \nabla p \right] \sim -\frac{1}{p} \left[ \nabla T \times \nabla p \right],$$

(4)

where $\rho$ is the gas density, $p$ is the pressure and $T$ is the gas temperature. As the stagnation point in figure 19 approaches the anode, the anode is surrounded by the heated gas. However, the gas near the cathode remains relatively cold. When axial flow is induced, the following inequality is fulfilled for near-electrode regions: $T_{cr} > T_{ar} \gg T_{sa} > T_{sc}$, where $T_{cr}$ and $T_{ar}$ are the temperatures in the cathode and anode regions, respectively. In these regions, the LTE plasma is produced. $T_{sc}$ and $T_{sa}$ are the temperatures of the gas surrounding the cathode and anode, respectively before discharge initiation. First, as shown in the previous section, the final temperature after the LTE transition was slightly higher than that for the lower initial gas temperature, thus $T_{cr} > T_{ar}$. Since the hot gas is pushed towards the anode, one can expect that $T_{sa} > T_{sc}$. Therefore, it is reasonable to assume that a higher temperature gradient $\nabla T$ and thus higher values of baroclinic torque occur near the cathode. The difference in near-electrode temperature gradients establishes a quasi-stationary state between the flows directed from the anode and cathode, which leads to the induction of a flow that does not change its direction to the opposite direction until the end of the NRPD initiation.

An interesting fact is that before and after TAF, no change in the deposited energy is observed. Figure 20 shows the deposited energy per pulse as a function of the pulse number for three inter-electrode distances of 0.5, 2, and 5 mm. Each data set was obtained during a single experiment initiating 200 pulses with PRF = 20 kHz. To identify the number of pulses required for the TAF, each experiment was repeated 10 times with schlieren visualization. The ranges of the pulse number $\Delta n$ required to achieve TAF are given in the plot for every considered gap. The general trend is that the shorter the gap, the fewer pulses are required to induce the flow. A noticeable increase in input energy is observed at the beginning of the applied burst. This is caused by the fact that during the first few pulses, the gas temperature in the gap gradually increases. When the equilibrium between heat release and heat transfer

Figure 20. Deposited energy per pulse for different gap distances acquired during the applied burst containing 200 pulses. PRF is 20 kHz, applied voltage is 10 kV.
during the inter-pulse time is established, the energy deposition does not substantially change with the pulse number. As the distance between the electrodes increases, a larger number of pulses is required to stabilize the energy input per pulse. As shown in figure 20, for 0.5 mm gap, approximately 2–3 pulses are required to reach the stabilized input energy level, whereas for a distance of 5 mm, it takes 8–10 pulses.

To get closer to understanding the mechanism of TAF, it is necessary to delve into the processes occurring in the near-electrode regions, since the highest energy density is released in these regions. The discharge channel is a self-consistent structure that adapts to the applied voltage. The discharge dynamics are determined to a greater extent by the principle of minimum power [47]. This principle states that for a given current and channel diameter, the spatial distributions of $n_e$ and $E/N$ are established such that the power spent on maintaining the plasma is minimal. The cathode region is the main source of electrons and its main role is to create conditions for maintaining the current in the channel. However, the mechanisms of electron production in the cathode region may differ depending on the applied voltage waveform, material, and geometry of the cathode. The roughness of the cathode also plays an important role. Parkevich et al. [33] demonstrated that micron-sized (10–50 µm) cathode spots appear in the form of highly ionized plasma with an electron density of $n_e = 10^{19} – 10^{20}$ cm$^{-3}$. Some studies [48–50] have considered explosive electron emission as the main mechanism of the formation of cathode spots. Regardless of the electron production mechanism in the cathode region, a high electric field is provided by the large positive space charge of the ions. The electrons produced in the cathode region further propagate to the quasineutral plasma column, where the electric field values are supported to sustain the balance of ionization and recombination. The voltage drop along the channel body can be rather low comparing the cathode voltage drop because its main purpose is to close the electrical circuit between the cathode layer and anode. Nevertheless, the electric field in the vicinity of the anode can be rather high, because of the negative space charge of electrons and negative ions. There are practically no positive ions near the anode surface since they are repelled by the latter. This creates a fundamental difference between the anode and cathode regions. While the cathode is autonomous and emits electrons from its surface, the structure of the anode region and electric field values are vastly defined by the electron number density in the channel.

The size and intensity of the anode spots were greatly reduced after TAF. However, the cathode region of the channel did not undergo any significant changes. Even though the changes in emission intensity and the electron number density near the anode are noticeable, the corresponding mechanism of plasma formation in the near anode region is still a subject for discussion. The processes occurring in the near-anode region of nanosecond discharges at moderate and elevated gas densities, even in quiescent gas, are not fully understood. In [33], the authors assumed that the generation of the near-anode plasma is provided by explosive heating owing to the focusing of the high electron current on the heterogeneities of the anode surface. Another mechanism of high-current anode spot formation in nanosecond discharges involves the runaway electrons produced in the cathode region [51, 52]. Nevertheless, there is currently no robust model describing the processes in the near-anode region, which is in good agreement with the experimental results. The picture is even more ambiguous in the presence of temperature gradients along the gap.

In addition, some physical properties of the anode spots were studied in [53] at moderate gas pressures (50–300 mbar). It was found that the anode voltage drop increased linearly with pressure, and this increase was steeper for discharge in air than in nitrogen. The presence of negative ions makes the anode layer more sensitive to initial gas density. Minessi et al. [8] demonstrated the dynamics of a single-pulsed nanosecond discharge in quiescent air with varying gas pressures between 58 and 1000 mbar. It was demonstrated that the formation of the LTE regime was inhibited while decreasing the pressure or was fully suppressed for $p < 300–400$ mbar. It was also shown that the delay between the anode and cathode spots formation increases with decreasing pressure.

Under our conditions, the gas density is decreased by increasing the temperature first in the middle of the gap, and then the heated gas is progressively shifted towards the anode, as shown in figure 19. In this regard, we assume that a gradual increase in gas temperature in the anode region leads to a reduction in the electron space charge and, consequently, a decrease in the electric field near the anode. This occurs until the magnitude of the baroclinic torque near the anode is insufficient to withstand the oncoming flow from the cathode.

5. Conclusions

We demonstrated that under certain conditions, axial flow is self-induced while initiating NRPDs in quiescent air. The transition to the regime with induced axial flow requires initiation from several tens to several hundreds of applied pulses, depending on the inter-electrode distance. This phenomenon was observed for all considered inter-electrode distances, from 0.5 to 5 mm, while initiating NRPD consisting of 400 pulses with PRF $> 10$ kHz. It was found that the direction of the induced axial flow is determined by the polarity of the applied burst. The flow was directed from the cathode towards the anode for both the positive and negative polarities of the applied pulses. The induced axial flow does not change its direction until the end of the NRPD initiation.

From the analysis of the emission spectra, it was found that the discharge undergoes a transition to the LTE plasma state. In particular, LTE plasma regions are observed near the electrode, appearing in the form of anode and cathode spots. Furthermore, these spots either grow into the body of the discharge channel moving towards each other in the form of bright filaments, as occurs before the TAF. Alternatively, they remain concentrated in the near-electrode region, as for the anode spots after TAF. The presence of these spots indicates strong inhomogeneity in the energy release along the length of the plasma channel. This leads to intense heat release in the near-electrode regions, which significantly affects the
morphology of hydrodynamic disturbances. It was found that the electron number density in the anode region decreases by a factor of 2 when axial flow is induced. However, $T_e$ does not undergo any significant changes before and after the TAF.

Based on the results of 0D kinetic modeling, it was shown that the initial gas temperature significantly defines the dynamics and final state of the LTE plasma, namely, the power density $\omega_{LTE}$ and $n_e^{\text{fin}}$ for a given moment of LTE transition. However, the LTE temperature varies by only ~6% when the initial gas temperature is increased from 300 to 1000 K, which correlates with the experimental observations.

A mechanism describing the emergence and maintenance of self-induced axial flow was proposed. The model is based on the baroclinic effect, already described in the literature, that occurs in the afterglow of a nanosecond spark discharge. This effect is enhanced in the near-electrode regions where the highest energy release is observed. The successive initiation of nanosecond pulses with a high PRF (several tens of kHz) leads to spatially non-uniform gas heating and the temperature gradients along the gap. An increase in the initial gas temperature leads to a decrease in the production of electrons in the plasma channel and near the anode. This in turn leads to a reduction in the electric field and power density in the anode region. The established difference in energy release near the anode and cathode leads to the appearance of an axial gas flow.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

Financial support of the European Research Council under the ERC Consolidator Grant TORCH (No. 820091) is gratefully acknowledged. The authors would like to express their gratitude to Professor Dr Nikolay Popov for helpful discussions about this work.

ORCID ID

Sergey A Shcherbanev https://orcid.org/0000-0002-5977-7506

References

[1] Pai D Z, Lacoste D A and Laux C O 2010 Transitions between corona, glow and spark regimes of nanosecond repetitively pulsed discharges in air at atmospheric pressure $J$. Appl. Phys. 107 093503
[2] Pai D Z, Stancu G D, Lacoste D A and Laux C O 2009 Nanosecond repetitively pulsed discharges in air at atmospheric pressure—the glow regime Plasma Sources Sci. Technol. 18 045030
[3] Pai D Z, Lacoste D A and Laux C O 2010 Nanosecond repetitively pulsed discharges in air at atmospheric pressure—the spark regime Plasma Sources Sci. Technol. 19 065015
[4] Rusterholz D, Lacoste D, Stancu G, Pai D and Laux C 2013 Ultrafast heating and oxygen dissociation in atmospheric pressure air by nanosecond repetitively pulsed discharges J. Phys. D: Appl. Phys. 46 464030
[5] Popov N 2011 Fast gas heating in a nitrogen–oxygen discharge plasma: I. Kinetic mechanism J. Phys. D: Appl. Phys. 44 285201
[6] Lo A, Cessou A, Lacour C, Leocardier B, Boubert P, Xu D, Laux C and Vervisch P 2017 Streamer-to-spark transition initiated by a nanosecond overvoltage pulsed discharge in air Plasma Sources Sci. Technol. 26 045012
[7] Orriëre T, Moreau E and Pai D Z 2018 Ionization and recombination in nanosecond repetitively pulsed microplasmas in air at atmospheric pressure J. Phys. D: Appl. Phys. 51 494002
[8] Minesi N, Stepanyan S, Mariotto P, Stancu G D and Laux C 2020 Fully ionized nanosecond discharges in air: the thermal spark Plasma Sources Sci. Technol. 29 085003
[9] Parvekivch E, Medvedev M, Ivanenko G, Khirianova A, Selyukov A, Agafonov A, Korneev P A, Gas’kov S and Mingaleev A 2019 Fast fine-scale spark filamentation and its effect on the spark resistance Plasma Sources Sci. Technol. 28 095003
[10] Sainct F P, Urabe K, Pannier E, Lacoste D A and Laux C O 2020 Electron number density measurements in nanosecond repetitively pulsed discharges in water vapor at atmospheric pressure Plasma Sources Sci. Technol. 29 025017
[11] Olsen H, Edmonson R and Gayhart E 1952 Microchronometric schlieren study of gaseous expansion from an electric spark J. Appl. Phys. 23 1157–62
[12] Bane S P, M, Ziegler J L and Shepherd J E 2015 Investigation of the effect of electrode geometry on spark ignition Combust. Flame 162 462–9
[13] Kono M, Niu K, Tsukamoto T and Ujije Y 1989 Mechanism of flame kernel formation produced by short duration sparks Symp. (Int.) on Combustion vol 22 (Elsevier) pp 1643–9
[14] Seydou A, Claverie A, Sotton J and Bellenoue M 2016 Experimental investigation of the effects of nanosecond repetitive pulsed (NRP) discharges on ignition of methane-air mixtures 18th Int. Symp. on the Application of Laser and Imaging Techniques to Fluid Mechanics
[15] Xu D, Shneider M, Lacoste D and Laux C 2014 Thermal and hydrodynamic effects of nanosecond discharges in atmospheric pressure air J. Phys. D: Appl. Phys. 47 235202
[16] Stepanyan S, Minesi N, Pannier E, Stancu G D and Laux C O 2018 Hydrodynamic effects induced by nanosecond repetitive pulsed discharges 2018 AIAA Aerospace Sciences Meeting p 0930
[17] Stepanyan S, Minesi N, Tihère-Inglesse A, Salmon A, Stancu G D and Laux C 2019 Spatial evolution of the plasma kernel produced by nanosecond discharges in air J. Phys. D: Appl. Phys. 52 295203
[18] Castela M, Stepanyan S, Fornia B, Coussenent A, Gicquel O, Darabiha N and Laux C O 2017 A 3-D DNS and experimental study of the effect of the recirculating flow pattern inside a reactive kernel produced by nanosecond plasma discharges in a methane-air mixture Proc. Combust. Inst. 36 4095–103
[19] Dumitrache C, Gallant A, Minesi N, Stepanyan S, Stancu G D and Laux C O 2019 Hydrodynamic regimes induced by nanosecond pulsed discharges in air: mechanism of vorticity generation J. Phys. D: Appl. Phys. 52 364001
[20] Stepanyan S, Hayashi J, Salmon A, Stancu G D and Laux C O 2017 Large-volume excitation of air, argon, nitrogen and combustible mixtures by thermal jets produced by nanosecond spark discharges Plasma Sources Sci. Technol. 26 04LT01
[21] Xu D, Lacoste D and Laux C 2016 Ignition of quiescent lean propane-air mixtures at high pressure by nanosecond repetitively pulsed discharges Plasma Chem. Plasma Process. 36 309–27

[22] Lovasceo S, Hayashi J, Stepyanan S, Stancu G D and Laux C O 2019 Cumulative effect of successive nanosecond repetitively pulsed discharges on the ignition of lean mixtures Proc. Combust. Inst. 37 5553–60

[23] Opacich K C, Ombrello T M, Heyne J S, Lefkovitz J K, Leweke R J and Busby K 2021 Analyzing the ignition differences between conventional spark discharges and nanosecond-pulsed high-frequency discharges Proc. Combust. Inst. 38 6615–22

[24] Opacich K C, Heyne J S, Scholla L, Ombrello T, Gray J A and Busby K 2021 Analyzing the impact discharge type and power loadings have on ignition kernel development in a reactive flow AIAA SciTech 2021 Forum p 1370

[25] Opacich K C, Heyne J S, Ombrello T and Gray J A 2022 Parametric study to elucidate the mechanisms of jetting motion that bolster ignition kernel development from repetitively pulsed discharges AIAA SciTech 2022 Forum p 0978

[26] Leonov S V, Isaenko Y I and Shneider M N 2007 Suppression of the turbulent decay of an afterspark channel with residual current Phys. Plasmas 14 123504

[27] Jonassen D R, Settles G S and Tronsomy D M 2006 Schlieren “PIV” for turbulent flows Opt. Lasers Eng. 44 190–207

[28] Fu S and Wu Y 2001 Detection of velocity distribution of a flow field using sequences of schlieren images Opt. Eng., Bellingham 40 1661–6

[29] Thiellec W and Stamlhuis E 2014 PIVlab—towards user-friendly, affordable and accurate digital particle image velocimetry in MATLAB J. Open Res. Softw. 2 e30

[30] Thiellec W and Sonntag R 2021 Particle image velocimetry for MATLAB: accuracy and enhanced algorithms in PIVlab J. Open Res. Softw. 9 12

[31] Soria J 1996 An investigation of the near wake of a circular cylinder using a video-based digital cross-correlation particle image velocimetry technique Exp. Therm. Fluid Sci. 12 221–33

[32] Shcherbaniev S, Ding C, Starikovskaia S and Popov N 2019 Filamentary nanosecond surface dielectric barrier discharge. Plasma properties in the filaments Plasma Sources Sci. Technol. 28 065013

[33] Parkevich E, Medvedev M, Khirianova A, Ivanenkov G, Selyukov A, Agafonov A, Mingaleev A, Shelkovenko T and Pikuz S 2018 Mechanisms responsible for the initiation of a fast breakdown in an atmospheric discharge Plasma Sources Sci. Technol. 27 11LT01

[34] Shcherbaniev S, Khomenko A Y, Stepyanan S, Popov N and Starikovskaia S 2016 Optical emission spectrum of filamentary nanosecond surface dielectric barrier discharge Plasma Sources Sci. Technol. 25 02LT01

[35] Ding C, Khomenko A Y, Shcherbaniev S and Starikovskaia S 2019 Filamentary nanosecond surface dielectric barrier discharge. Experimental comparison of the streamer-to-filament transition for positive and negative polarities Plasma Sources Sci. Technol. 28 085005

[36] Minesi N, Stepypnan S A, Mariott P B, Stancu G D and Laux C O 2019 On the arc transition mechanism in nanosecond air discharges AIAA SciTech 2019 Forum p 0463

[37] Minesi N, Mariott P, Painier E, Stancu G and Laux C 2021 The role of excited electronic states in ambient air ionization by a nanosecond discharge Plasma Sources Sci. Technol. 30 035008

[38] Minesi N 2020 Thermal spark formation and plasma-assisted combustion by nanosecond repetitive discharges PhD Thesis Université Paris-Saclay

[39] Laux C, Yu L, Packan D, Gessman R, Pierrot L, Kruger C and Zare R 1999 Ionization mechanisms in two-temperature air plasmas 30th Plasmadynamic and Lasers Conf. p 3476

[40] Kramida A et al 2018 NIST atomic spectra database National Institute of Standards and Technology

[41] Konjević N, Lesage A, Fuhr J R and Wiese W L 2002 Experimental Stark widths and shifts for spectral lines of neutral and ionized atoms (a critical review of selected data for the period 1989 through 2000) J. Phys. Chem. Ref. Data 31 819–927

[42] Griem H 1974 Spectral Line Broadening by Plasmas (Pure and Applied Physics vol 39) (New York: Academic) p 421

[43] Pancheshnyi S, Eismann B, Hagelaar G and Pitchford L 2008 ZDPPlasKin zero-dimensional plasma kinetics solver (Toulouse: University of Toulouse, LAPLACE, CNRS-UPS-INP)

[44] Hagelaar G and Pitchford L C 2005 Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models Plasma Sources Sci. Technol. 14 722

[45] Pancheshnyi S, Biagi S, Bordage M, Hagelaar G, Morgan W, Phelps A and Pitchford L 2012 The LXCat project: electron scattering cross sections and swarm parameters for low temperature plasma modeling Chem. Phys. 398 148–53

[46] Almazova K, Belonogov A, Borovkov V, Khalikova Z, Ragimkhonov G, Tereshonok D and Treakin A 2021 Investigation of plasma properties in the phase of the radial expansion of a spark channel in the ‘pin-to-plate’ geometry Plasma Sources Sci. Technol. 30 095020

[47] Raizer Y P and Allen J E 1991 Gas Discharge Physics vol 1 (Berlin: Springer)

[48] Parkevich E, Ivanenkov G, Medvedev M, Khirianova A, Selyukov A, Agafonov A, Mingaleev A, Shelkovenko T and Pikuz S 2018 Mechanisms responsible for the initiation of a fast breakdown in an atmospheric discharge Plasma Sources Sci. Technol. 27 11LT01

[49] Tsventoukh M 2018 Plasma parameters of the cathode spot explosive electron emission cell obtained from the model of liquid-metal jet tearing and electrical explosion Phys. Plasmas 25 053504

[50] Barengolts S, Mesyats G and Tsventoukh M 2008 Initiation of ecton processes by interaction of a plasma with a metal cartridge on a metal surface J. Exp. Theor. Phys. 107 1039–48

[51] Shao T, Tarasenko V F, Yang W-J, Beloplovot D V, Zhang C, Lomaev M Y, Yan P and Sorokin D A 2014 Anode and cathode spots in high-voltage nanosecond-pulse discharge initiated by runaway electrons in air Chin. Phys. Lett. 31 085201

[52] Shao T, Tarasenko V F, Yang W, Beloplovot D V, Zhang C, Lomaev M Y, Yan P and Sorokin D A 2014 Spots on electrodes and images of a gap during pulsed discharges in an inhomogeneous electric field at elevated pressures of air, nitrogen and argon Plasma Sources Sci. Technol. 23 054018

[53] Akishev Y, Karalnik V, Kochetov I, Napartovich A and Trushkin N 2014 High-current cathode and anode spots in gas discharges at moderate and elevated pressures Plasma Sources Sci. Technol. 23 054013