On filamentary nanosecond surface dielectric barrier discharge for flame initiation.

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Abstract: The investigation of the nanosecond surface dielectric barrier discharge (nSDBD) at elevated gas pressures is the aim of the work. The hydrodynamic effects and the initiation of combustion of lean H2:air mixtures, (ER=0.5) are studied experimentally. The discharge was studied in different gas mixtures for the pressure range 1–10 bar. The ignition is initiated by two different discharge modes: streamer or filamentary nSDBD. The influence of the discharge structure and energy deposition on the ignition is demonstrated.

Keywords: Nanosecond surface dielectric barrier discharge, plasma-assisted combustion

1. Introduction

Initiation and sustaining of combustion of lean mixtures at high gas densities is a challenge for the combustion community. One of the possible solutions is the ignition/combustion assisted by low temperature nonequilibrium plasma, or so–called plasma assisted ignition/combustion (PAI/PAC) [1]. The mechanisms of plasma assisted ignition and combustion [2,3] include dissociation of molecular species by electron impact, energy transfer from electronically excited species, like N2(B3Πg), N2(C3Πu), O(1D) and others to dissociation or to fast increase of gas temperature [4] and partial reforming of fuels [5].

The spatial distribution of active species is characterised by discharge morphology. Sustaining homogeneous plasmas at high gas density is a complex technical problem. A lot of conditions should be fulfilled: it is necessary to provide significant pre-ionization of gas mixture by UV or fast electrons [6], to keep the voltage rise time short enough and so to provide the conditions when the local field is higher than the critical ionization field [7] etc.

In nanosecond SDBD the deposited energy is equally distributed over the set of 100–200 streamers or 40–60 filaments. The nanosecond SDBD was suggested for PAI/PAC [8] due to the fact that a quasi-uniform plasma pattern is produced at elevated pressures in the plane of high voltage electrode for a typical time much shorter than the ignition delay for combustible mixtures; the produced plasma is a non-equilibrium plasma acting on the gas via the production of atoms/radicals/excited species and temperature increase due to their recombination and relaxation, and via possible hydrodynamic effects. Although the advantages of nSDBD for the initiation of combustion were clearly demonstrated, the discharge in high–pressure combustible mixtures was practically not studied and the picture of ignition of gas mixtures by nSDBD plasma was not clear.

The aims of the present work are (i) to develop a high pressure high temperature (HPHT) discharge cell providing a broad optical access to the discharge and combustion experiments; (ii) to study the nSDBD morphology and the conditions of streamer-to-filament transition at pressures up to 12 bar; (iii) to demonstrate, on the example of lean hydrogen/air mixtures, a correlation between the discharge appearance and the behaviour of the ignition pattern; (iv) to check if the ignition along the multiple channels, over the maximum possible surface, can be achieved at elevated pressures.

2. Experimental setup

Dielectric barrier discharge (DBD) is a discharge originating in a discharge gap at the conditions when at least one of the electrodes is covered by a dielectric layer. The current in the DBD is limited by charging of the dielectric. One of the modifications of DBDs is a surface DBD (SDBD). In this case, the electrode system has a "sandwich-like" structure, consisting of the low-voltage electrode, covered with a thin (fraction of mm) dielectric layer, and high-voltage (HV) electrode of a smaller surface, placed upon the dielectric. The discharge starts from the edge of HV electrode and propagates along the dielectric surface.

Fig. 1. Cylindrical electrode configuration for initiation of nanosecond SDBD.
The cylindrical configuration of SDBD is presented in Figure 1. The HV electrode has a disk-like shape. In such electrode geometry the discharge propagates in the radial direction from the edge of HV electrode.

The high voltage pulse generator (FID Technology, FPG20-03NM) used in the experiments provided the following parameters: 2 ns front rise time, 20 ns pulse duration on the half-height and ±(12 - 30) kV voltage amplitude in the cable. All experiments were performed in a single shot regime.

To study the discharge at high pressure the cubic chamber was used. The schematic representation of the high-pressure chamber is demonstrated in figure 2. The chamber and all flanges are made of stainless steel. The chamber is equipped with three optical quartz windows, with a thickness of 15 mm and a diameter of 50 mm. One optical window is situated in front of the electrode. The gas was uploaded from the bottom of the chamber (black arrows in figure 2). The experiments in the chamber were performed for ambient temperatures and for gas pressures up to 10 bar.

3. Results

Streamer-to-filament transition. The nanosecond surface barrier discharge develops as a set of streamers propagating synchronously and in parallel. In general, surface streamers represent a complex 3D structure with strong gradient of electric field and electron density in the direction perpendicular to the surface. However, in most cases the distance between streamers is significantly smaller than their diameter. Therefore, for numerical simulation 2D model is used and represents the results that coincide pretty well with experiment.

With increase of gas pressure nanosecond surface DBD can transform to another, filamentary form when voltage and/or gas pressure is increased. Transition to filamentary regime, if it exists in the combustible mixtures, can be extremely important for re-distribution of energy in the discharge during the ignition processes. The experiments of the present work, conducted at higher pressures, and at lower rise time of the high voltage pulse, show that filamentation in air and in H₂/air happens at both negative and positive polarity of applied HV pulses and the parameters (pressure and applied voltage) significantly depend on the composition of gas mixture.

The filamentation occurs within a few nanoseconds after the discharge start. For filamentary nSDBD there is no closing of the discharge gap. So, it is not a spark but a kind of transient plasma. Figure 3 demonstrates the integral ICCD images of streamer (at P=2 bar and U=−25 kV) and filamentary (P=6 bar and U=−50 kV) nSDBD. For the corresponding conditions the energies per channel are demonstrated below (Fig.3).

The energy deposition per channel for two applied voltages U = −25 and −50 kV as a function of gas pressure are shown in figure 3 for the discharge in air. In the first case, when applied voltage is U = −25 kV, the discharge always is in quasi-uniform mode. When the voltage amplitude is U = −50 kV, the discharge in air at pressures 5, 6 and 8 bar is filamentary. It is clearly seen that the deposited energy is higher for the filamentary discharge and is not very dependent on gas pressure for streamer SDBD in the pressure range 1−4 bar. It can be noticed, that for filamentary discharge the energy...
deposition has a maximum at $P = 5-6$ bar, and then decreases with pressure, despite that the discharge remains filamentary. As far as the deposited energy is proportional to the product $j \cdot E$, there are two possibilities to get high deposited energy in the filamentary mode: (i) the electric field in the filaments is higher than in streamers; (ii) the electron density $n_e$ is higher in filaments.

In surface discharges, the electron emission from the surface of dielectric under the action of UV radiation of the streamer head can be an important additional process sustaining the discharge propagation. So, the experimental study of parameters and of a structure of the surface dielectric barrier discharge with a different fraction of hydrocarbons or $H_2O$ molecules in the mixture at fixed high voltage pulse characteristic, pressure and temperature is an important task in the problem of plasma–assisted combustion.

**Hydrodynamic effects.** Gas heating and electrostatic body force generation are two basic mechanisms controlling the flow by SDBD plasmas. In AC SDBDs the dominant mechanism of the effect on the low–speed flows is associated with ions acceleration in a space charge region of the plasma, so–called electrohydrodynamic (EHD) force. In SDBDs powered by high–voltage nanosecond ($\sim 10–100$ ns) pulses, the EHD accelerations can be neglected. It was suggested in [9] that in the case of nanoseconds SDBDs the dominant effect of the discharge on the flow is caused by localized heat generation.

Figure 4 demonstrated the Schlieren images of the compression waves produced by streamer and filamentary nSDBD. The shock wave propagates from the plane of electrode, in the direction perpendicular to discharge propagation. During the first few microseconds the wave’s velocity slightly exceeds the sound speed, $M=1.2$ for streamer nSDBD and $M=1.7$ for filamentary discharge. As far as the streamer discharge covers the dielectric layer homogenously, the propagating wave can be considered as a plane disk–like wave. The radius of the "disk" is practically equal to the discharge radius. Therefore for $P=1$ bar the diameter of the compression wave is higher than that of the streamer discharge at 6 bar.

![Fig. 4. Schlieren images of the shock wave produced by streamer and filamentary discharges at P=1 and 6 bar.](image)

The first thing that catches an eye is high contrast of the compression wave produced by filamentary nSDBD. The ratio between drops for the three considered cases was estimated and is $\Delta P_{s,1 \text{ bar}} / \Delta P_{s,6 \text{ bar}} / \Delta P_{f,6 \text{ bar}} = 1/1.2/3$. That underlines that fast gas heating processes are considerably more intense in filamentary nSDBD.

**Flame initiation.** Lean hydrogen/air mixtures were selected for the PAI experiments because $H_2$ combustion is one of the most classical and the most studied processes.

Both discharge modes, streamer and filamentary, are of interest for plasma assisted ignition. The conception of the distributed, multi–point ignition at high pressures is of particular value. As it was demonstrated, the discharge morphology is directly related to gas density. In real systems such as SI engines, we have to deal with elevated gas pressures. So, to analyze the efficiency of flame initiation with both discharge modes is a very important problem.

![Fig. 5. Flame propagation initiated by streamer and filamentary nanosecond SDBD.](image)

To analyze a correlation between the discharge appearance and the behaviour of the ignition pattern, imaging of combustion was made for the initial period of flame development in the discharge cell for two different amplitudes of the high–voltage pulse. To acquire well developed filamentary nSDBD the following conditions were selected: positive polarity HV pulses, $P=6$ bar,
equivalence ratio (ER) is 0.5. For streamer discharge the amplitude of applied pulses was +33 kV, for filamentary - +52 kV on the HV electrode.

Figure 5 presents ICCD images of ignition by streamers and filaments. The first column demonstrates the ignition by streamers. The combustion kernels are distributed evenly along the edge of the high-voltage electrode, and ignition starts from a quasiuniform structure near the electrode. In this case, maximal energy release is presumably concentrated near the high-voltage electrode, whatever polarity is, and synchronous structure of combustion waves propagates with a high visible velocity. Emission from excited OH appears approximately 50 µs after the discharge initiation. The repetitability of the experiments in this mode is high enough: the scattering of ignition delay time did not exceed 10%. Total energy deposition was $W = 11±2$ mJ.

For filamentary mode of off the discharge the flame initiation is demonstrated right column of Figure 5. This regime has not been observed before. The total energy deposition was $W = 21±2$ mJ. In this mode, similarly to streamer mode of the discharge, the initial distribution of energy is inhomogeneous along the discharge channel: a few bright spots in the near–electrode region can be easily seen in the frame corresponding to time period $t < 150$ µs. The bright spots do not expand and decay in 150–250 µs (see figure) not influencing the morphology of the ignition. Combustion starts along entire length of each filament. We believe that quenching of the bright spots near the electrode can be explained by heat removal to the electrode or by non–sufficient size of the ignition kernel. The ignited channels expand in three directions: (i) in radial direction, that is elongation of the ignition channels; (ii) in azimuthal direction; (iii) in direction perpendicular to the electrode, in the volume of the discharge chamber.

4. Conclusion

The nanosecond surface dielectric barrier discharge was studied at elevated pressures. It was found that depending on the gas pressure and amplitude of applied pulses the discharge has two modes: streamer and filamentary. The parameters of the transition to contracted phase, $(P_{ab} U_{ab})$, depend on the gas nature and polarity of the applied pulse. We conclude that the filamentation is the common and general phenomenon for the nanosecond surface discharges at high pressures. The energy deposition per channel in filaments is at least one order of magnitude higher than in the streamer mode. Produced regular structure of the discharge channels with “concentrated” specific energy is of particular interest for high–pressure combustion applications. For the first time, plasma parameters in the channel of a filamentary nsDBD have been studied.

High energy release in the filament was confirmed by analysis of hydrodynamic effects. The compression wave produced by filamentary nsDBD propagates with high velocities (about $M = 1.7$) at the very beginning and decreases to approximately sound speed within a few µs. The pressure drop in the front of the compression waves is ~3 times higher when the wave is produced by filamentary nsDBD. More intense heat release is observed near the dielectric surface for the case of filamentary nsDBD.

It was found that depending on deposited energy and discharge mode two different regimes of flame initiation can be observed: (ii) when energy deposition is high enough, ~10 mJ, but the discharge is still in streamer mode, the quasiuniform ignition of the combustible mixtures occurs along the perimeter of HV electrode; (iii) when the discharge is filamentary and energy deposition is about 15–22 mJ, the ignition starts uniformly along entire lengths of the filaments.

5. References