IGNITION OF COMBUSTIBLE MIXTURES BY NANOSECOND SURFACE DIELECTRIC BARRIER DISCHARGE

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ABSTRACT

Ignition in a stoichiometric acetylene-air mixture after a nanosecond surface dielectric barrier discharge was studied experimentally and numerically. Ignition was analyzed at 1 atm and 300 K by means of a high speed ICCD camera that allowed snapshot series in the microsecond time scale. Ignition delay time after the discharge and velocity of the combustion wave were measured for various electrode shapes, applied voltages and polarities. It was shown that the mixture is much easier to ignite by pulses of negative polarity and when the discharge develops from the cog-wheel-like electrode. The properties of the discharge were numerically simulated based on a 2D model. Using this model, the evolution in time of the spatial distributions of gas temperature and densities of active species produced in the discharge and in its afterglow was studied. The analysis of calculated results showed that the mixture is ignited due to active species production and local gas heating near the high-voltage electrode edge.

1. INTRODUCTION

Non–equilibrium discharge plasma has been widely used for plasma–assisted ignition (PAI) and plasma–assisted combustion (PAC) [1, 2]. Experiments and numerical simulation showed that nanosecond discharge plasmas have profound effect on ignition delay reduction and flame stabilization due to efficient production of active species in combustible mixtures. Therefore, ignition with non–equilibrium discharges is perspective for applications under conditions of high speed flows and under conditions similar to automotive engines.

Surface dielectric barrier discharge was successively used for ignition in a stoichiometric C_2H_6-O_2 mixture under standard conditions [3]. For practical purposes, it is more interesting to consider ignition in fuel-air mixtures. The aim of this work was to study ignition in a stoichiometric acetylene-air mixture under the plasma produced in a surface dielectric barrier discharge. Discharge and ignition processes were investigated for various electrode shapes, applied voltages and their polarities. Numerical simulation was used to reveal the mechanisms responsible for plasma-assisted ignition under the conditions studied.

2. EXPERIMENT

A detailed description of the experimental setup and methods used to study plasma-assisted ignition has been given elsewhere [3]. Figure 1 shows the experimental setup.

We used a stainless steel discharge chamber with three optical windows. The chamber was connected with a dump volume separated by a

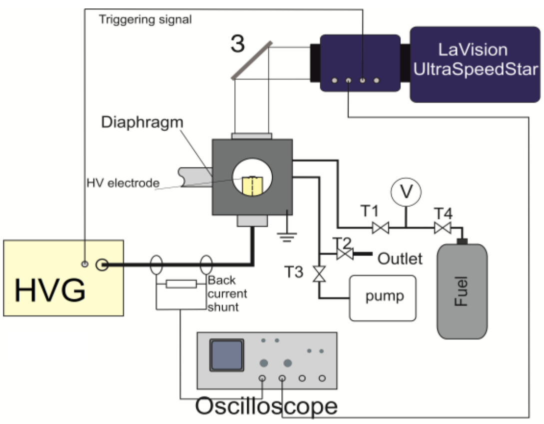


Fig. 1. Scheme of the experimental setup. HVG is a high-voltage generator.

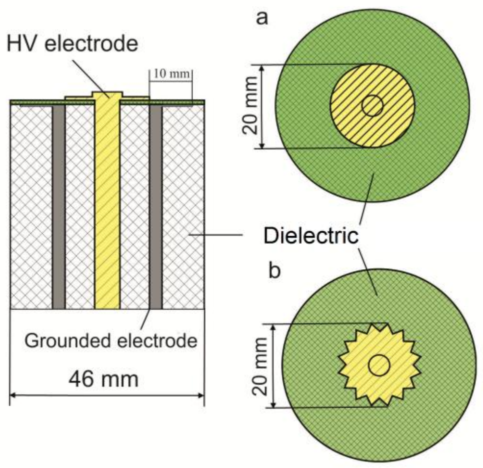


Fig. 2. The electrode system (a) with the disc high-voltage electrode and (b) with the cog-wheel-like high-voltage electrode.

diaphragm. The discharge was initiated in the coaxial two-electrode system (see figure 2). The outer diameter of the high-voltage electrode and the inner diameter of the grounded electrode were 20 mm. A dielectric film (0.3 mm PVH layer) was placed between the high-voltage and grounded electrodes. The high-voltage electrode was a disc or cog-wheel in shape. Negative and positive polarity pulses 6-13 kV in amplitude (in cable), 35 ns halfwidth, and 5 ns rise time were used in the regime of a single shot (see figure 3).

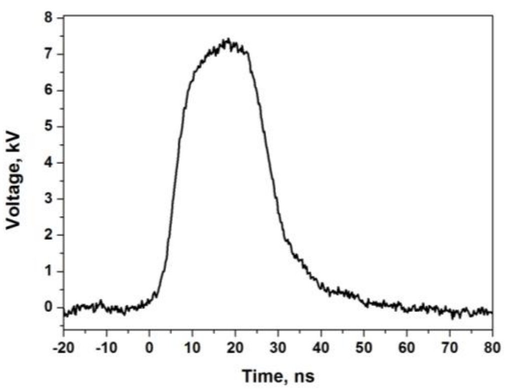


Fig. 3. Typical high-voltage pulse of the high-voltage generator used.

Discharge development and ignition processes were studied, respectively, with a PicoStar HR 12 (La Vision) ICCD camera and with a La Vision Ultra Speed Star ICCD camera. In both cases, the discharge and combustion regions were focuses onto the photocathode of the camera with a mirror and UV lenses (see figure 1). To study the discharge phase, we used a camera gate of 5 μs and hence obtained still photographs of the discharge with a ~35 ns duration. In the ignition phase, photographs were taken with an exposure time of 5 μs and a time of 200 μs between frames.

3. EXPERIMENTAL RESULTS

The energy deposited in the discharge phase was defined as the difference between the energy of the incident electromagnetic wave and that of the reflected electromagnetic wave. The energy of the incident wave was around 55-60 mJ at a voltage amplitude of 25 kV. Figure 4 shows the deposited energy as a function of the amplitude of applied voltage. This energy was independent of voltage polarity and the shape of the high-voltage electrode. The value of the deposited energy increased linearly with the voltage. Figure 4 shows the energy deposited during the main discharge impulse. As a rule, this impulse was followed by additional impulses due to a partial reflection of the incident electromagnetic wave from the high-voltage generator. The total deposited energy was around 30% higher than that shown in figure 4. The additional energy was deposited within 500 ns after the main discharge impulse. This time is required for the electromagnetic wave to propagate along the cable from the discharge cell to the generator and in the opposite direction.

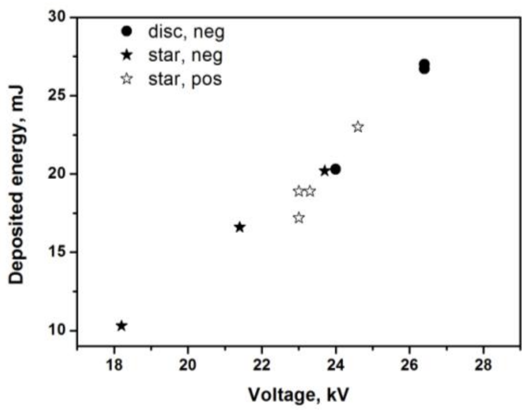
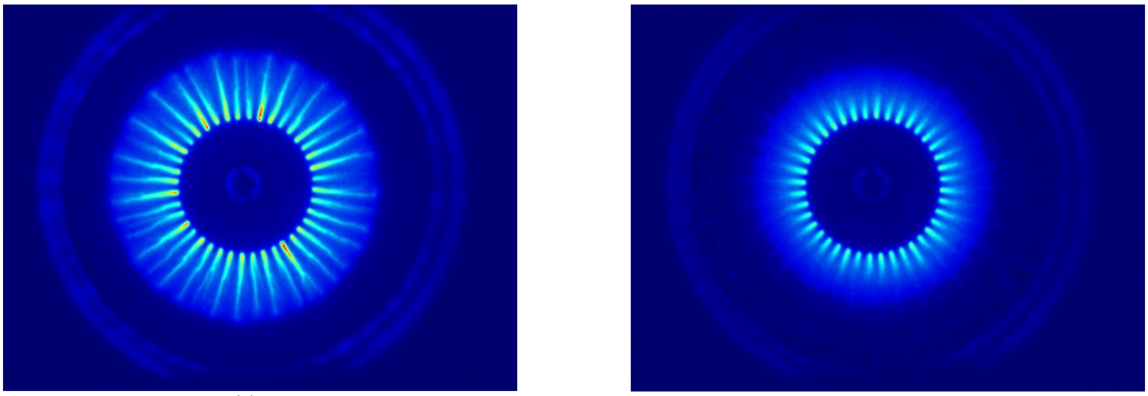


Fig. 4. Deposited energy as a function of the applied voltage for the disc and cog-wheel-like (“star”) high-voltage electrodes.

Figure 5 shows still photographs of the discharge developed form the cog-wheel-like high-voltage electrode at different voltage polarities. The camera gate was 5 μs. It follows from the photographs that the region occupied by the plasma is smaller at negative polarity of the voltage. In this case, the energy deposited per unit volume is higher than that for positive polarity of the voltage.



(a) *(b)*

Fig. 5. Still photographs of the discharge developed from the cog-wheel-like high-voltage electrode (a) at U = 25.1 kV and (b) at U = - 26.6 kV.

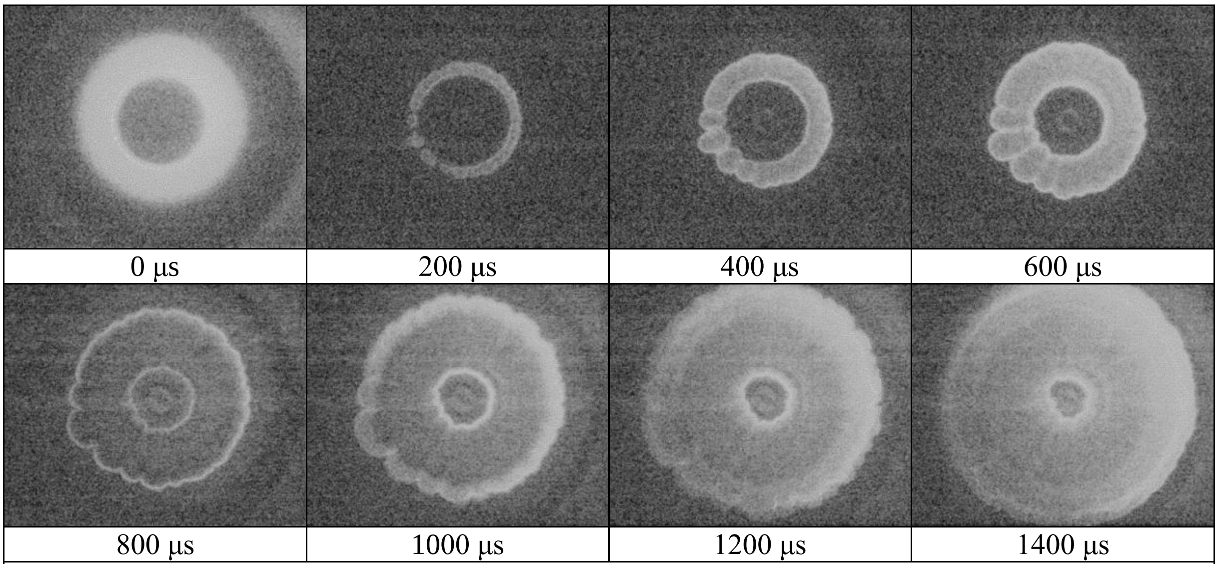


Fig.6. ICCD images of C_2H_2:air mixture ignition from the disc electrode for U = - 26.4 kV.

We studied ignition after the discharge in stoichiometric C_2H_2:air and C_2H_6:air mixtures. Ignition in the C_2H_2:air mixture was replicated much more reliably. Therefore, focus was on the consideration of this mixture. Figure 6 shows ICCD images of ignition in this case. Ignition was initiated near the edge of the high-voltage electrode, in agreement with previous observations in C_2H_6:O_2 mixtures [3].

In the case of the disc high-voltage electrode, the mixture was ignited along the entire edge of the electrode at $|U|$>24.5kV for negative polarity. Ignition by the impulse of positive polarity was not obtained even at 26 kV, the maximum value of the voltage amplitude reached obtained in the generator used. The mixture was easier to ignite when replacing the disc electrode by the cog-wheel-like electrode. Here, the threshold voltage at which the mixture was ignited along the entire edge of the electrode was $|U|$ = 18 kV for negative polarity and U = 24 kV for positive polarity.

Figures 7 and 8 show, respectively, the velocity of the combustion wave and ignition delay time

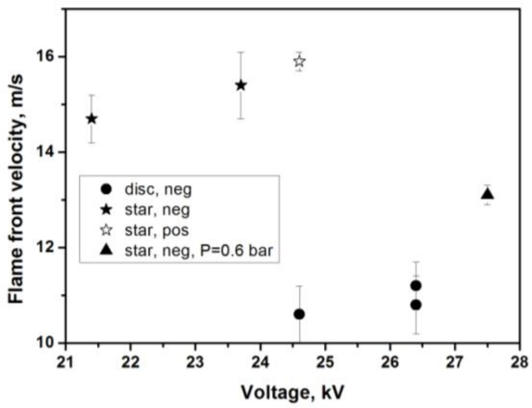


Fig. 7. Velocity of combustion wave as a function of the applied voltage for the disc and cog-wheel-like ("star") high-voltage electrodes.

versus the applied voltage. The velocity is 10-11 m s^{-1} in the case of the disc electrode and 14.5 – 16 m s^{-1} when the wave develops from the cog-wheel-like electrode. These data are in reasonable agreement with the velocity of combustion wave in laminar C_2H_2:air flames [4] that was in the range 12 – 16 m s^{-1}. Higher values of the velocity in the case of the cog-wheel-like electrode may be explained by a non-uniformity of the wave front, the effect that can lead to a more efficient heat transfer [5].

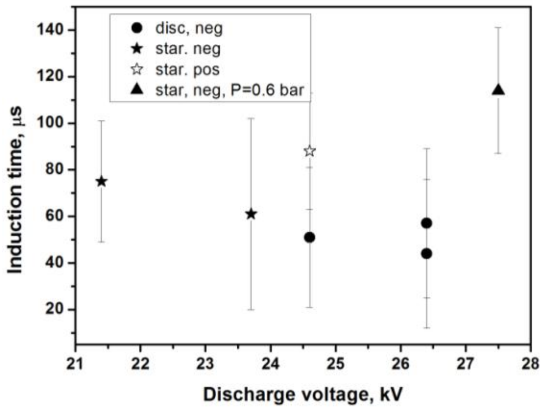


Fig. 8. Ignition delay time as a function of the applied voltage for the disc and cog-wheel-like ("star") high-voltage electrodes.

4. CALCULATED RESULTS

Ignition of cold combustible mixtures by the nanosecond surface dielectric barrier discharge is induced due to production of chemically active species in the discharge plasma and due to fast gas heating. To estimate these effects under the conditions considered, we used a numerical 2D simulation of the discharge on the basis of the model [6, 7]. Calculations showed that the highest energy is deposited near the edge of the high-voltage electrode. In this region, during the discharge phase and in the early discharge afterglow, gas temperature can increase up to 500-700 K and the mole fraction of active species can reach several percent at U = 24 kV. Composition of active species was dominated by O atoms. It follows from the simulation of combustion processes that these values of gas temperature and fraction of active species are sufficient to ignite the C_2H_2:air mixture under the conditions studied, in agreement with observations.

5. CONCLUSIONS

We studied ignition in the stoichiometric C_2H_2–air mixture at 300 K and 1 atm under the action of a nanosecond surface dielectric barrier discharge. The mixture was initially ignited near the edge of the high-voltage electrode from which a radial combustion wave developed. Observations showed that the acetylene-air mixture is much easier to ignite by pulses of negative polarity and when the discharge develops from the cog-wheel-like high-voltage electrode. In this case, the velocity of the combustion wave is 50 % higher that the velocity of the wave developed from the disc high-voltage electrode. Calculations showed that ignition is due to the production of active species in the discharge plasma and due to gas heating in the region adjacent to the edge of the high-voltage electrode.

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