

# Investigation of the Ignition by Repetitive Streamer Discharges Using Time-resolved OH LIF Measurements

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## 1 Introduction

Non-equilibrium plasmas like in streamer discharges have a significant influence on ignition and combustion processes [1,2]. The formation of electronically excited species using non-equilibrium plasmas can enhance burning velocities [3] and reduce ignition delay times [4] or autoignition temperatures [5], respectively. The promotion of the ignition and combustion processes is mainly explained by the production of atomic oxygen either by quenching electronically excited N<sub>2</sub> or by the electron impact dissociation of O<sub>2</sub> [6,7].

Streamer discharges occur at atmospheric pressures as the initial process of the temporal evolution of an electrical breakdown [2]. Considering AC voltage with high frequency, streamer discharges occur only at the peak voltage. Depending on the electrode configuration, the discharge time is possibly too short for a complete breakdown within the electrode distance. Therefore, a spark breakdown can not occur. While a single streamer discharge has only minor influence on the combustible gas mixture concerning gas temperature and mixture composition, repetitive streamer discharges can ignite combustible/air mixtures. This has to be avoided in hazardous areas [8].

The ignition of combustible/air mixtures by electrical sparks, which has been examined experimentally and numerically in detail [9,10], is mainly dominated by the local heating of the gas mixture. However, for a detailed understanding of the ignition by streamer discharges, it is essential to examine additionally the production of radicals in the non-equilibrium plasma and the accumulation of energy considering repetitive streamer discharges. A numerical simulation of the ignition processes requires more detailed experimental information. Therefore, this work presents experimental investigations of the ignition of H<sub>2</sub>/air mixtures by repetitive streamer discharges at atmospheric pressure using a rod/plane electrode configuration with alternating current at high frequency ( $f = 740$  kHz). Time-resolved high speed imaging of laser induced fluorescence (LIF) of OH radicals after the ignition of different H<sub>2</sub>/air mixtures in the mixture range from 10 Vol.% to 40 Vol.% H<sub>2</sub> in air is performed to examine the temporal flame kernel growth after ignition. The experimental results are compared to numerical simulations using a one-dimensional approximation, which will be used in future work to yield detailed information about the energy densities inside the ignition volume.

## 2 Experimental setup

A rod/plane configuration with an electrode distance of 40 mm is applied to produce streamer discharges. Due to the highly inhomogeneous electrical field and the high frequency of 740 kHz,

streamer discharges occur only for several nanoseconds during each voltage cycle. Hence, an electrical breakdown is avoided. The necessary sinusoidal alternating voltage of up to 20 kV is generated by means of a frequency generator, a power amplifier and an air-cored coil. An oscilloscope records the voltage and current signals. More details about the setup are given in [11]. During one experiment, several cycles of the alternating current are supplied. As can be seen in Figure 1, filamentary streamer discharges can be observed, which depend on the amount of cycles and the mixture composition.

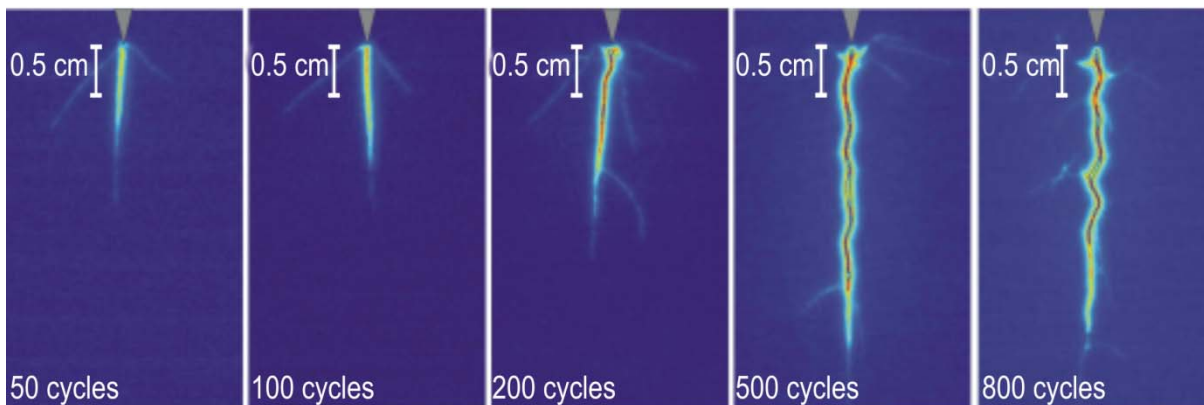


Figure 1. Filamentary streamer discharges in air (peak voltage  $\hat{U} = 12$  kV).

The electrical setup is combined with an optically accessible ignition cell, which can be filled with hydrogen/air mixtures using Bronckhorst mass flow meters. As shown in Figure 2, two Nd:YAG lasers operated at 532 nm are used to excite a Rhodamine 6G dye laser. Using the double pulse mode, the time separation between the two pulses of one Nd:YAG laser can be adjusted from 30 to 150  $\mu$ s. Hence, four consecutive excitation laser pulses were obtained during one ignition event. The laser light was formed into a sheet of up to 35 mm in height and 200  $\mu$ m in width by cylindrical lenses and the light sheets were guided through the ignition cell directly below the rod via two quartz windows. The  $Q_1(8)$  transition in the  $A^2\Sigma^+ \leftarrow X^2\Pi$  electronic band of OH was excited by means of the frequency doubled dye laser output near 283 nm. An intensified high-speed camera (LaVision Ultraspeed Star4) together with a lens-coupled image intensifier (LaVision HS-IRO) was used to image the fluorescence signals, which were focused onto the intensifier with an achromatic  $f/2$  UV lens with a 100 mm focal length (B. Halle Nachfl.). An UG11 filter sufficiently suppressed the recording of scattered laser light from surfaces.

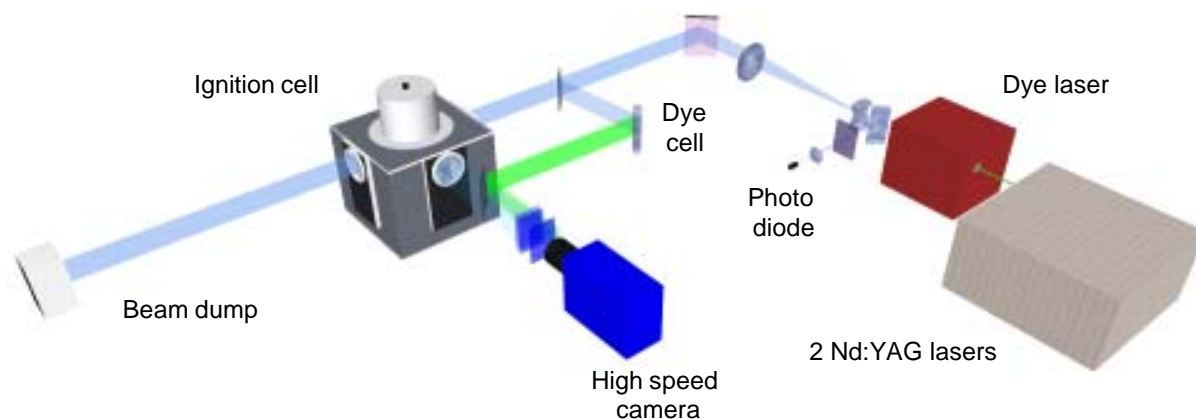


Figure 2. Optical setup used for time-resolved OH LIF measurements.

The optical setup offers high framing speed by the sequential exposure of four individual CCD detectors. Exposure times, gains and trigger delays were individually programmable for each CCD, providing full timing control. The exposure time used for the OH PLIF measurements was 300 ns. Using a beam splitter, a small part of each laser sheet was directed to a fluorescent dye cell. The fluorescence from the dye cell was collected onto the side of the same CCD detector as used for OH LIF detection. Before the measurements both the OH LIF and the dye cell signals were examined concerning their linearity with the laser energy.

### 3 Numerical simulations

Even though an ignition along a larger streamer volume can be observed for larger number of voltage cycles or higher voltage amplitudes, respectively [8], near the minimum energy necessary for ignition, the ignition process takes place only in a small volume near the rod. Therefore, a spherical configuration of the ignition volume is assumed, which facilitates a one-dimensional description of the ignition process. Influences of the rod electrode such as heat losses are neglected. The solutions of the well-known mass, species and energy equations were obtained using a time integration method [12]. The boundary conditions were zero gradients at the inner and outer boundary, except for a constant outer radius representing a constant volume. The ignition source was represented using a source term in the energy conservation equation with a radius of 230  $\mu\text{m}$ , which is in accordance with experimental results [11]. The kinetic scheme is a detailed reaction mechanism consisting of 9 chemical species and 37 elementary reactions by Maas and Warnatz [12]. This representation considers only the local heating of the gas inside the ignition volume, non-equilibrium plasma effects are neglected.

Numerical simulations have been performed to determine the minimum energy necessary for ignition using the described configuration for  $\text{H}_2/\text{air}$  mixtures in the range of 10 to 40 Vol.%  $\text{H}_2$ . Flame front positions from the numerical results have been determined in accordance with the experimental method using the criterion of full width at half maximum (FWHM).

### 4 Results

The laser sheet was placed directly under the tip of the rod. Hence, some scattered light is still visible in the LIF images, even though an optical filter has been applied. The raw images of the LIF signal were adjusted using the simultaneously measured dye cell signals to correct spatial inhomogeneities of the laser sheets and fluctuations of the laser intensity. A time sequence of four consecutive OH LIF images is shown in Figure 3a to Figure 3d. As can be seen in the images, ignition takes place near the tip of the rod. Each image is converted into the polar coordinate system as shown in Figure 3e to Figure 3h. Here, the fixed point is the tip of the rod which corresponds to the origin of the Cartesian system. For each angle the flame front position is determined as full width at half maximum.

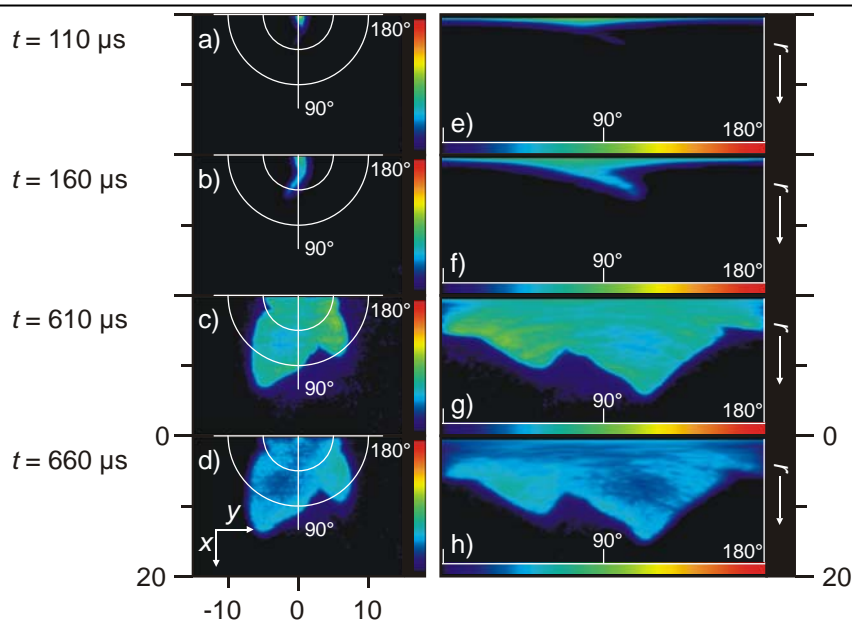


Figure 3. Determination of flame front position converting OH LIF images (a) – d)) into the polar coordinate system (e-h)) (25 Vol.% H<sub>2</sub>,  $\hat{U} = 11$  kV, 100 voltage cycles, all dimensions in mm).

As explained above, several voltage cycles and, therefore, several streamer discharges are necessary for ignition. During these voltage cycles an accumulation of energy in the streamer volume is assumed possibly leading to ignition. Figure 4 shows the ignition of a 20 Vol.% H<sub>2</sub> in air mixture near the rod. Here, 30 voltage cycles with a peak voltage  $\hat{U}$  of 11 kV have been supplied, which is the minimum number leading to ignition for this mixture composition and peak voltage [11]. Thirty voltage cycles correspond to an energy deposition time of 40  $\mu$ s. Figure 4 consists of eight single images taken in three different experiments A, B and C but using the same electrical parameters. In all these experiments the first two images were taken 180  $\mu$ s and 230  $\mu$ s after the beginning of energy deposition. The second laser was used with variable time settings. The first four consecutive images are yielded from experiment A, and from experiments B and C only the results at the later points of time are shown. To avoid problems due to e.g. the reflection of laser light near the tip of the rod which could result in a misinterpretation of the data, flame front positions have been derived from images as shown in Figure 4 at  $x = 1$  mm to examine the flame propagation in the  $y$ -direction.

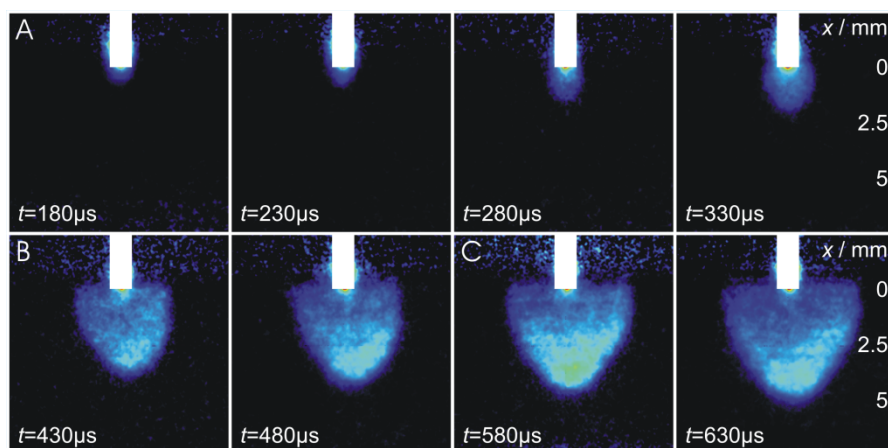


Figure 4. Sequence of single-shot OH LIF images after the ignition of 20 Vol.% H<sub>2</sub>, ( $\hat{U} = 11$  kV, 30 voltage cycles) yielded from three experiments: A, B and C.

A scatter plot of flame front positions at  $x = 1$  mm after ignition of 40 Vol.%  $H_2$  in air yielded from several experiments is shown in Figure 5. Forty voltage cycles, which correspond to an energy deposition time of  $54 \mu s$ , are the minimum number of voltage cycles using a peak voltage of  $\hat{U} = 11$  kV to ignite this specific mixture [11]. Two hundred micro seconds after the first voltage cycle the growth of a flame kernel is visible. The ignition delay strongly depends on the energy density inside the streamer channel. Hence, small fluctuations of this density lead to different ignition delay times. However, a nearly linear flame kernel growth can be observed from the experiments until  $500 \mu s$ . Figure 5 also shows the development of a numerical flame front position at  $x = 1$  mm, yielded from radial OH concentration profiles after the ignition of 40 Vol.%  $H_2$  in air. The numerical spark duration  $t_s$  was  $54 \mu s$ , the minimum energy necessary for ignition  $E_s$  was  $4.71 \cdot 10^{-5}$  J. Using a linear fit, a global spatial flame velocity can be determined from the flame kernel growth. Considering 40 Vol.%  $H_2$  (see Figure 5), the experimental flame velocity  $v_{SG}$  is  $14.7 \pm 0.6$  m/s, which is in very good agreement with the numerical flame velocity  $v_{SG}$  of  $15.1$  m/s and with values given in literature [13]. Although only local heating inside the ignition volume was considered in the presented numerical simulation, sufficient consistence between experimentally and numerically determined flame kernel growth and ignition delay times as shown in Figure 5 was yielded for all examined  $H_2$ /air mixtures.

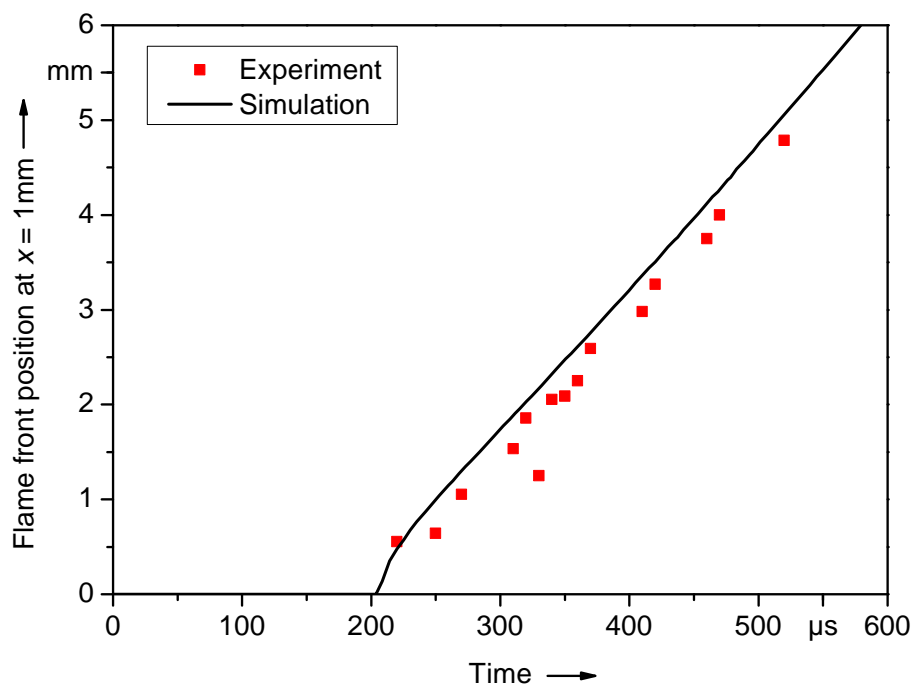


Figure 5. Comparison of experimental flame front positions (40 Vol.%  $H_2$ ,  $\hat{U} = 11$  kV, 40 voltage cycles) and numerical results (40 Vol.%  $H_2$ ,  $E_s = 4.71 \cdot 10^{-5}$  J,  $t_s = 54 \mu s$ ) at  $x = 1$  mm.

## 5 Conclusion

Using time-resolved OH LIF, the ignition due to repetitive streamer discharges were investigated using hydrogen/air mixtures in the range from 10 Vol.% to 40 Vol.%  $H_2$  in air. Due to an asymmetric flame kernel growth, only the radial flame propagation was examined determining the flame front positions. Even though non-equilibrium plasma effects have not been considered yet numerically, the experimental flame velocities, which can be yielded from the temporal development of the flame front positions, are in very good agreement with numerical results and experimentally determined velocities given in literature. Therefore, the experimental results will be used for the validation of further numerical investigations using a detailed kinetic scheme representing the non-equilibrium plasma [7]. This work will give detailed information about the ignition delay times and energy densities necessary

for the ignition by repetitive streamer discharges, also to consider the ignition efficiency of this specific ignition source.

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