# Experimental Study of the Ignition Process of Kerosene Droplets by Laser-Induced Breakdown

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## 1 Introduction

The ignition of flames by electric spark plugs or focused high-power laser beams (laser-induced breakdown) is a complex process that starts with the generation of a plasma which rapidly develops to a flame kernel and finally to an expanding flame. Spark igniters are extensively used in internal combustion engines and aero engine combustors. Laser ignition is less frequently applied but it has the potential to replace the conventional electric spark plugs in some applications [1]. In this contribution, laser ignition has been used in a generic labscale setup to study fundamental aspects of the ignition process of kerosene sprays.

A particular requirement for aero engines is the ability to restart after blowout in high altitudes (altitude relight) where air temperature and pressure are less favorable for ignition than at ground level. Altitude relight is of actual interest because of the current development of increasingly leaner combustion concepts which may have a detrimental effect on ignition performance and because of the investigation and testing of alternative fuels for aviation [2-4]. Here, one of the research goals is the development of computer codes for a reliable prediction of the performance of aero engines with respect to ignition and re-ignition. In co-operation with industrial partners, the German Aerospace Center (DLR) performs research in this area and applies numerical as well as experimental techniques [5,6]. In addition to experiments under realistic conditions [7] fundamentally orientated investigations are currently performed in order to better understand the development of the flame kernel and to provide experimental data for the validation of numerical combustion models. Measurements were performed in a labscale flow channel with well-defined boundary conditions. Ignition was accomplished by laser-induced breakdown because it enabled a better adjustment of the location and time of ignition and the amount of energy input. Further, the flow field was not disturbed by electrodes and optical access to the ignition location was not obstructed.

Flame ignition by laser-induced breakdown has been studied previously by different research groups, see for example the review article by Phuoc and the citations therein [1]. Those studies reported the influence of pressure, temperature, fuel composition, fuel-to-air ratio, laser energy and other parameters on the ignition process. One particular aspect concerned the amount of energy that was transferred from the laser pulse to the plasma and how much of it was taken away by the blast wave. A general finding was that a major part of the absorbed laser energy was dissipated by the blast wave [8,9].

In the current study, laser-induced breakdown was used to ignite fuel droplets that were injected into an air co-flow by a monodisperse droplet generator. High-speed schlieren imaging was applied to

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capture the temporal development of the plasma and the blast wave from the time of laser ignition to the establishment of a flame. Mie scattering was imaged by a long-distance microscope to visualize the instantaneous shape of the droplets when they were exposed to the blast wave. Further, temporally resolved spectral analysis of the plasma and flame emissions was applied to study the transition from a plasma-dominated kernel to a flame.

## 2 Experiment

The flow channel was vertically arranged and had a cross section of 80 mm × 80 mm and a length of 1.255 m. It consisted of several elements, each equipped with quartz windows on 3 sides which were held by a metal frame [5,6]. The back was mounted to a translation stage. At the top, different spray injectors could be installed. Most of the results presented here were obtained with a vibrating orifice aerosol generator (TSI 3450) which generated 5 co-planar parallel droplet chains of kerosene Jet A-1 with a center-to-center distance of 1.125 mm between each other. The droplets had a diameter of 100 µm and the vertical inter-droplet distance was 250 µm. The total fuel mass flow was 3 g/min. The droplet chains were surrounded by an air co-flow at atmospheric pressure and room temperature. Alternatively, a commercial air-assisted atomizing nozzle (Delavan SN 30609-2) could be mounted in place of the vibrating orifice droplet generator to generate a full cone kerosene spray.

Laser-induced breakdown was initiated by a frequency doubled Nd:YAG laser (InnoLas Spitlight 600) that delivered pulses at λ=532 nm with a duration of 6 ns. After expansion to a diameter of 40 mm the laser radiation was focused by an achromatic doublet lens (f=120 mm) into the flow channel close to the outermost droplet chain, resulting in multiphoton ionization followed by electron-cascade breakdown. The applied pulse energy for the results presented here were between 193 mJ and 231 mJ. A schematic of the setup is shown in Fig.1.

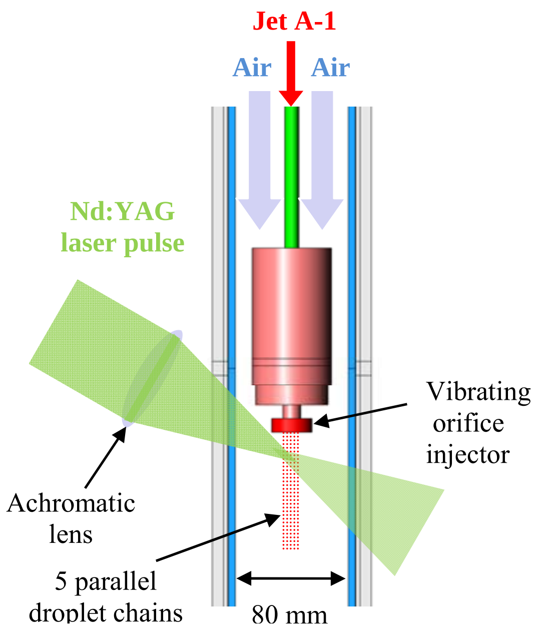


Figure 1: Schematic of the flow channel, nozzle, droplet chain and laser beam.

Schlieren imaging was applied to visualize density gradients in the flow field. A projector lamp was used for illumination and a high-speed CMOS camera (LaVision HSS 6) for detection at a sustained frame rate of 50 kHz (corresponding to 20 µs interframing time). The exposure time was 1 µs, the field of view 46 mm × 42 mm and the pixel resolution 320 × 288. The reproducibility of the breakdown process was very good so that results from different measurement runs could be combined. Thus, the delay time between the ignition laser pulse and the start of the camera recording could be varied in order to achieve a temporal resolution better than 20 µs. The laser sheet for the Mie scattering was generated by a second frequency doubled Nd:YAG laser (InnoLas Spitlight 600). The scattered light was imaged by a long distance microscope (LaVision QM100) into a high-speed camera (LaVision HSS 8). The field of view was 0.573 mm × 0.513 mm with a pixel resolution of 384 × 344.

The optical emissions from the plasma and flame were spectrally analyzed using an echelle spectrometer with a detection range from 200 to 870 nm (LLA Instruments ESA 4000 EV/i). The light was collected with a ½” collimator lens (Thorlabs) made of glass with reduced transmission for wavelengths below 400 nm. For the detection of the plasma emissions, an exposure time of 100 ns was applied, and for the flame emissions 200 µs.

# 3 Results and Discussion

Figure 2 shows three images from a sequence of schlieren measurements taken at different times τ after laser-induced breakdown. In the first frame at τ = 5 µs the white circle at x = 0, y = 0 with a diameter of approximately 4 mm represents the breakdown plasma which is visible for approximately 25 µs. The surrounding circle with a diameter of approximately 10 mm represents the blast wave which initially expanded with a velocity of approximately Mach 2. In the second frame at τ = 20 µs the blast wave exhibits a diameter of about 24 mm, the central plasma size decreased slightly and is

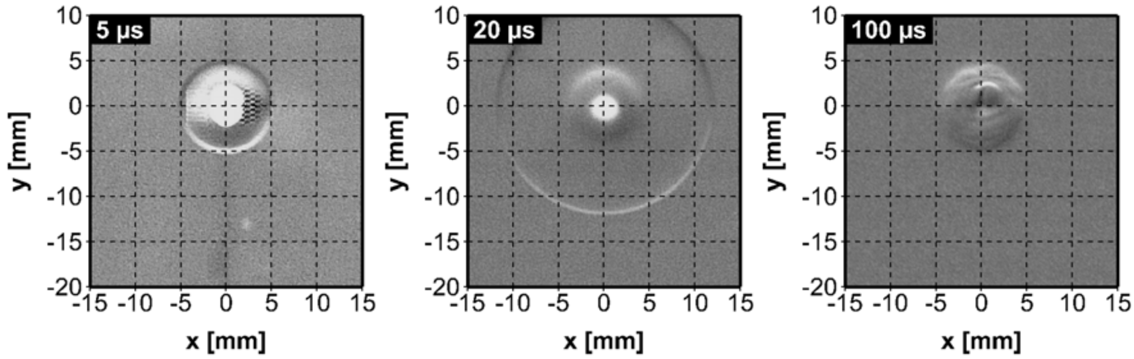


Figure 2: Three images of schlieren measurements performed at different times after laser-induced breakdown. The white area at x=y=0 reflects to the plasma kernel, the circular structure represents the expanding blast wave.

surrounded by a layer of hot gas which encloses the extremely hot high-pressure plasma ball. In the third frame recorded at τ = 100 µs the blast wave has expanded beyond the imaged area. However, when it reached the edge of the imaged area at τ ≈ 50 µs the associated density gradients were already close to the detection limit. The intense plasma kernel is no longer visible and the layer of hot gas has reached a diameter of about 10 mm. The observed phenomena have also been observed by other researchers and it is known that temperatures on the order of 100,000 K and pressures of several hundred MPa are prevailing in the initial plasma kernel [8]. In our study, one important point was the determination of the energy transferred from the laser pulse to the gas kernel that finally developed into a flame. This information was needed not only for the characterization of the ignition process but also as a boundary condition for the numerical simulations. A comparison of the measured blast wave expansion with calculations based on Brode's dimensionless numerical simulations [10] revealed that the blast wave's energy was approximately 93 mJ. The total energy balance averaged over 2000 laser shots was as follows: From the incident laser pulse energy of 193 mJ, 72 mJ passed through the breakdown region and 121 mJ were absorbed from which 77% were taken away by the blast wave. The remaining 28 mJ were partially lost in form of radiation and the remainder was transferred to the developing flame kernel. The radiative energy transfer was not determined in this experiment, however, it can be a significant contribution [1].

One of the issues addressed in the experiments was the influence of the blast wave on the droplets in the vicinity of the breakdown. In these measurements, 173.5 mJ of the incident laser pulse energy were absorbed in the breakdown plasma. Figure 3 exemplifies the temporal development of kerosene droplets from a droplet chain 5 mm away from the location of breakdown. The images display the Mie-scattered light at different times after breakdown. The first frame, recorded at τ = 0.5 µs, shows 2 spherical droplets which are yet unaffected from the breakdown. The glare points at the right and left periphery of the droplets are effects of the Mie scattering from the laser sheet. The bright light from the breakdown region 5 mm above presumably also contributes to the detected Mie signal. At τ = 5 µs the droplets are drastically deformed and disintegrated by the blast wave. The overall shape is disk-like with detached small secondary droplets. The area of high signal intensity is much larger than the original droplet size indicating that the droplets are entirely disintegrated into a cloud of small droplets and vapor. At τ = 40 µs (third frame) these clouds have grown further and apparently the droplets have been completely atomized into a very fine mist. These images demonstrate the dramatic effect of the blast wave on the droplets in the vicinity of the breakdown location. The extreme atomization by the blast wave and the high-temperature gas that immediately follows the shock front certainly facilitate the ignition of the fuel/air mixture and the propagation of the flame kernel at a later point in time.

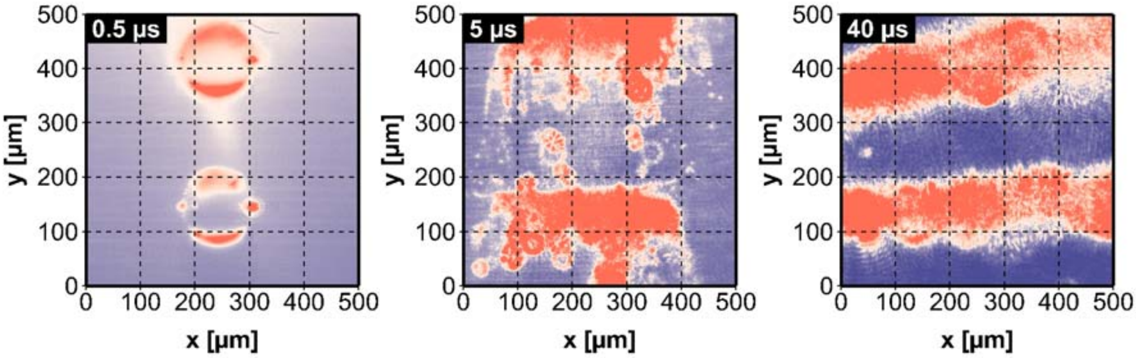


Figure 3: Images of Mie scattering at different times after breakdown. The breakdown location was approximately 5 mm above and slightly on the left side of the displayed droplets.

The impact of the blast wave on droplets 10 mm away from the breakdown location is exemplified in Fig. 4. During the first 10 µs, the droplets were unaffected because the blast wave had not yet reached their position. At $\tau$ = 60 µs (first frame), the droplets have flattened to a disk-like shape but are still intact. As a result of an oscillation, they underwent a transition to an elongated shape at 120 µs (second frame). At 200 µs (third frame), a constriction and detachment of secondary droplets is seen. Thus, also at a distance of 10 mm from the breakdown location there is a significant impact of the blast wave on the fuel droplets. At a distance of 20 mm, no effect could be observed. From these measurements it can be concluded that the energy of the blast wave is not completely lost for the ignition process because it creates a fuel state and temperature increase that are more favorable for ignition than without the influence of the blast wave.

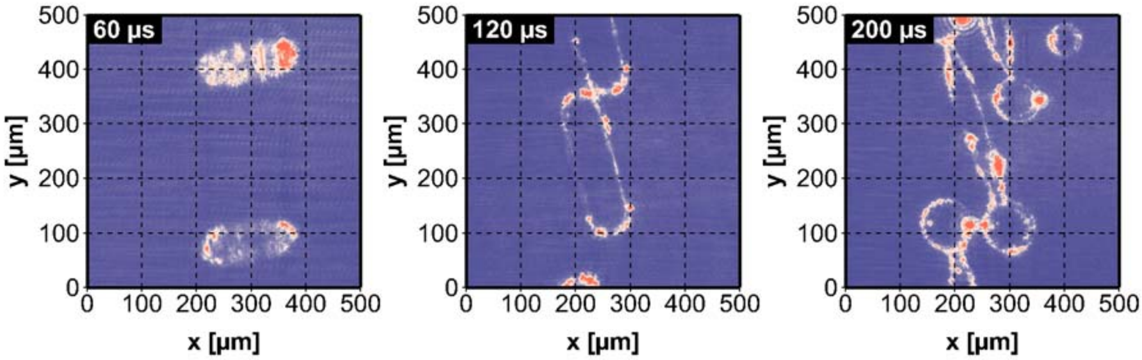


Figure 4: Images of Mie scattering at different times after breakdown. The breakdown location was about 10 mm above and slightly on the left side of the displayed droplets.

With respect to diagnostic techniques, the question arises to what extent the optical emissions from the plasma and the flame kernel can be used to retrieve information about the development of the ignition process. Therefore, the optical emissions were spectrally analyzed. The results presented in the following have been obtained from laser-induced breakdowns in a kerosene spray generated by an air-assisted atomizing nozzle (Delavan SN 30609-2) mounted in place of the droplet generator into the flow channel. The different droplet distributions generated by the different nozzles were observed to have no significant influence on the breakdown process and the early phase of the formation of a flame kernel [Gebel6]. Both nozzle configurations have been studied in the flow channel but the spectral emission analysis was only performed for the spray nozzle configuration. In Fig.5 the spectra emitted from the breakdown location are displayed for 3 different times after breakdown, i.e. $\tau$ = 0.1 µs, 1 µs and 5 µs. The laser pulse energy absorbed by the breakdown was 123 mJ. At $\tau$ = 0.1 µs, a broadband emission is seen covering the complete detected spectral range. It is superposed by spectral lines from singly ionized nitrogen, as well as indications of lines from (neutral) H, N and O atoms. The broadband continuum emission presumably stems from bremsstrahlung and recombination processes. In principle it is possible to estimate the plasma temperature from such spectra [Böker9], however, it was not attempted in this study. The gaps seen in the spectra in some wavelength regions are caused by the echelle spectrometer which does not cover the complete spectral range continuously. With increasing delay time, the total emitted intensity drops due to the decrease of the plasma temperature (note the logarithmic intensity scale in the diagram). At $\tau$ = 1 µs, the lines from ionized nitrogen are no longer seen indicating that the plasma temperature has dropped to a level where the ionization rate of atoms is small. The lines from neutral O, N and H atoms have become more

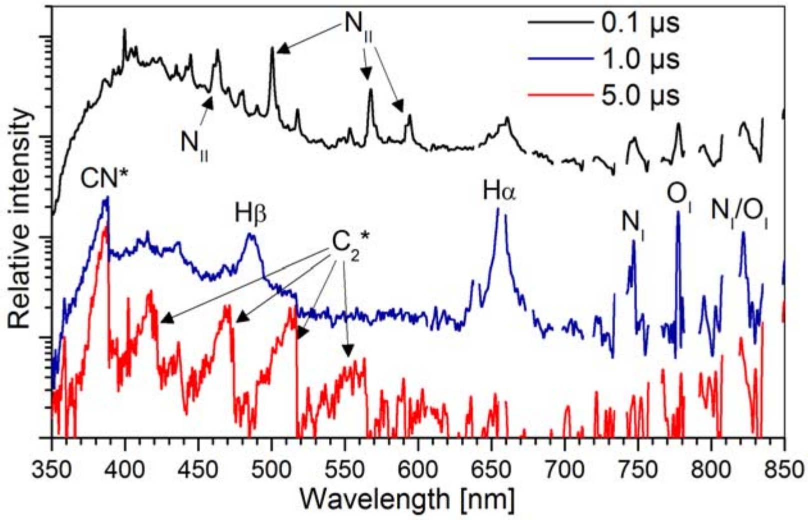


Figure 4: Emission spectra from the plasma at different times after breakdown. $N_{II}$ denotes lines from singly ionized nitrogen. $N_I$, $O_I$ are lines from neutral nitrogen and oxygen atoms. $H_\alpha$ and $H_\beta$ are lines from hydrogen atoms within the Balmer system. $C_2$* and CN* are emissions from $C_2$ radicals in the Swan system and from the CN radical, respectively. The gaps in the spectra are caused by the spectrometer.

prominent and the evolving emission band at 370 – 390 nm is attributed to electronically excited CN radicals. At $\tau$ = 5 µs, atomic lines have become very weak and the spectrum is dominated by emissions from electronically excited $C_2$ radicals in the Swan bands and CN radicals. These emission bands persist until approximately 20 µs and no further lines appear within that time period. Emissions from CH radicals around 390 nm could not be detected before $\tau$ = 100 µs and were quite weak so that the exposure time had to be extended to 200 µs. The emissions from CH are well known as chemiluminescence in flames and are strong indications of the onset of combustion. This assumption was confirmed by measurements where $N_2$ was used instead of air in the flow channel. In that case, the observed emissions from breakdown events comprised the lines of N ions and atoms as well as CN and $C_2$ just as in the case with air, however, the CH emissions did not appear. It can thus be concluded that combustion played no or only a minor role during the first 100 µs after breakdown and that one may use the term "flame kernel" after approximately 100 µs. The further development of the flame kernel into a full flame or its extinction under adverse conditions are beyond the frame of this paper and are not addressed here [11,12].

The investigations showed the complexity of an ignition process in sprays initiated by laser-induced breakdown. Immediately after breakdown, a plasma with extremely high temperature and pressure is present. Its rapid expansion with large density gradients leads to a transition from a plasma to a flame kernel after about 100 µs. One of the key findings of this study was the dramatic effect of the blast wave on the droplets in the vicinity of the breakdown location. The complete atomization of the droplets within a radius of 5-10 mm of the breakdown location assisted the generation of a fuel/air mixture that is favorable for the expansion of a flame kernel.

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