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Optical and spectroscopic diagnostics of laser-induced air breakdown and kerosene spray ignition

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ABSTRACT

This study focuses on the transition from a laser-induced breakdown plasma to a flame kernel in two-phase flows. The test rig was a vertical flow channel with a full-cone spray nozzle installed inside. The fuel was Jet A-1 aviation kerosene. Breakdowns were generated by the focused laser pulses from a frequency-doubled and Q-switched Nd:YAG laser. The investigation of laser-induced breakdowns in ambient air provided valuable supplementary data to understand the interaction of the breakdown plasma and the fuel spray. To determine the breakdown energy, the amount of absorbed laser pulse energy was measured, and the blast wave energy consumption was estimated. Blast waves were visualized with high-speed schlieren imaging. Their energies were estimated by the application of Jones' blast wave expansion model. High-speed imaging of air and spray breakdowns visualized their transient morphologies. Expansion velocities of air breakdowns were determined and revealed a supersonic expansion during the first few microseconds. Air breakdowns decayed and disappeared within 30 μs. Spray breakdowns were observed over a period of 90 μs, which covered their transition into flame kernels. Optical emission spectroscopy was applied to ambient air breakdowns, spray ignitions and spray breakdowns in nitrogen. The temporal decrease of nitrogen ion and atom lines was investigated, and mean lifetimes were determined. CN^*, C_2^* and CH^* radicals were observed in spray ignitions, but no CH^* was confirmed in spray breakdowns in nitrogen, while CN^* and C_2^* occurred with a similar intensity as in spray ignitions. Simulated spectra were fitted to the CN^* $B^2\Sigma^+ – X^2\Sigma^+$ band between 384.2 and 388.4 nm to determine temperatures at the breakdown region during the transition from breakdown plasma into spray flame kernels.

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1. Introduction

The specific background of this study is the relight of aviation gas turbines at high altitude. Their ability to ignite at the low air densities and temperatures at high flight levels is a key certification requirement [1]. Modern low-NO_x combustors run on lean mixtures, which increase the challenge of high altitude relight [2,3]. The development of such combustors can benefit from numerical simulations of the ignition process, because an iterative development including extensive testing is time-consuming and cost-intensive. In the first stage of an ignition, a spark turns into a small self-sustaining combustion, a 'flame kernel'. The involved physical and chemical processes are quite complex and not yet well understood. With the present knowledge, the simulation of a flame kernel generation for a two-phase flow ignition is only possible if the real physics are strongly simplified. Therefore, a better understanding of the involved mechanisms is necessary to develop more accurate models. Experiments in laboratory test rigs with well-defined boundary conditions provide very important contributions. Ignition by electrical spark discharge is the most common method in technical applications. But a spark plug has some disadvantages in a laboratory experimental setup. Shifting of the ignition location is restricted. Boundary conditions are complicated, because the plug is a heat sink and interacts with the flow field. Variation of the ignition energy is restricted and of low repeatability, and the triggering accuracy is low. Therefore, laser-induced ignition is a good alternative. Four different laser ignition mechanisms are known [4]:

- Thermal initiation by the absorption of laser radiation through rovibrational molecule bands.
- Non-resonant breakdown, initiated by multiphoton ionization and followed by electron cascade breakdown.
- Resonant breakdown, initiated by photodissociation and followed by electron cascade breakdown.
- Photochemical ignition through radical production by photolysis.

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The mechanism with the greatest physical similarity to electrical spark discharge is the non-resonant breakdown, although its electric field strength is higher by several orders of magnitude. We applied this mechanism with a Q-switched and frequency-doubled Nd:YAG laser. It offered the following advantages:

1. No spark plug with the above-named restrictions was required.
2. The triggering accuracy was ±1 ns, supporting precise synchronization with diagnostic instruments.
3. A flexible selection of the breakdown location and time.
4. Continuous laser pulse energy adjustment between 30 and 300 mJ.
5. Very good reproducibility.

The first report of laser-induced breakdown was given in 1963 by Maker et al. [5]. Its first usage for the ignition of a gas mixture was reported by Lee and Knystautas in 1969 [6]. Since then, comprehensive research investigated both, laser-induced breakdown in inert gases and laser-induced ignition of gas mixtures. A review of significant results is provided by Phuoc [7]. Considerably less research investigated the laser-induced ignition of two-phase flows. In 1998, Oldenborg et al. [8] reported on the investigation of laser-induced spray ignition for aviation gas turbines. Their intention was to develop a concept for laser-based igniters, which can increase reliability and reduce NO_x emissions. They ignited Jet A sprays using an Nd:YAG and a Cr:LiSAF laser. Various configurations were tested, including ultra-cold conditions, single and multiple laser pulses. They found a high potential of laser-induced spray ignition and developed some concepts for technical application, but those were never introduced to aviation gas turbines. A major disadvantage was the large size of the laser systems available at that time.

In recent years, the interest in laser-based spray ignition systems has substantially grown for two reasons. First, laser technology has progressed significantly. Compact diode-pumped solid-state (DPSS) lasers feature a high potential for application in engines [9,10]. High-power fibers are available to guide the radiation from the laser to the combustor [11]. Second, present demands on technical combustion systems, such as better reliability, safety, efficiency, lower emissions and fuel flexibility require advanced combustion concepts. This also affects the ignition systems. Therefore, laser-induced spray ignition is considered for reciprocating engines [12–15], aviation gas turbines [16–18], and spacecraft thrusters [19]. In particular, reciprocating engines and aviation gas turbines benefit from the possibility to adjust the ignition position. No spark plugs close to the combustor walls are necessary, which reduces the risk of flame kernel quenching on cold metal parts. Also, ignition at multiple and variable positions is possible. This opens new options for combustor geometries and contributes significantly to increased efficiency and reduced emissions. Moreover, laser-based igniters can be the key to reliable ignition of lean mixtures, and a high potential is seen for the application in lean premixed prevaporized (LPP) combustion [17,18].

In conclusion, the demand for the present study arises from two aspects. First, insights into fundamental processes of two-phase flow ignition are required for technical applications and for the development of advanced numerical models. Second, laser-induced ignition is a state-of-the-art technology with a high potential for the application in future combustion engines. The following questions have to be answered to make effective use of this technology:

- How do fuel droplets affect the formation and subsequent development of the breakdown?
- How does the breakdown develop into a flame kernel (time scales, spatial development, conditions inside the breakdown)?
- What is the impact of the breakdown on fuel droplets in the immediate and wider vicinity of the breakdown site (heat transfer, blast wave)?
- What are the consequences of this impact for the subsequent flame kernel growth?

These questions give raise to our research. The study presented in this paper supplements our previous publications [20–22]. While they focus on the gas dynamics around the breakdown (particularly the blast wave) and their breakup of fuel droplets, this study focuses on the transition of a laser-induced fuel spray breakdown into a flame kernel. The following investigations were performed:

- The amount of laser pulse energy absorbed by air breakdowns was determined with a volume absorber.
- High-speed schlieren imaging was used to track the expansion trajectory of laser-induced blast waves in ambient air, in order to estimate their energy consumption.
- High-speed imaging was used to visualize the transient morphology of laser-induced air breakdowns and spray ignitions.
- Optical emission spectroscopy was used to determine the physical nature of the breakdowns, including species and temperatures.

The investigation of laser-induced air breakdowns provided valuable supplementary data to understand the interaction of the fuel spray and the breakdown plasma. The fuel was Jet A-1 aviation kerosene. The spray was provided by an air-assisted siphon nozzle.

Literature on laser-induced two-phase flow ignition is very limited. But some aspects with particular relevance to the present study were addressed in previous publications, and a short review is provided in the subsequent paragraphs.

Lawes et al. [12] investigated the laser-induced ignition of monodisperse iso-octane aerosols. The aerosols were generated in a Wilson cloud chamber, and the ignition laser was a Q-switched Nd:YAG laser at 1064 nm. Multiple breakdowns occurred along the laser beam path through the cloud at a high pulse energy of 270 mJ. Each breakdown was the origin of a spherical blast wave. A low pulse energy of 32 mJ resulted in a single breakdown at the focal point. A very similar observation was made by Kawahara et al. [15]. They ignited ethanol sprays with a Q-switched Nd:YAG laser at 532 nm. They found multiple breakdown generation along the laser beam path. Each breakdown was the origin of a blast wave, which caused droplet dispersion. Mösl et al. [18] investigated the potential of laser-ignition systems for aviation gas turbines with a Jet A-1 kerosene spray. A Q-switched Nd:YAG laser at 1064 nm and 100 mJ pulse energy was compared to a spark plug of 1.8 J spark energy. The ignition probabilities at different breakdown locations were determined. High ignition probabilities for both methods were obtained at the spray cone edge and in the recirculation zone. But due to the significantly higher energies, electrical spark discharges revealed slightly lower lean ignition limits than the laser-induced breakdowns. The cited investigations show that, laser-induced breakdowns should be located near the spray cone edge on the laser beam incident side. Energy losses by laser pulse scattering on droplets are avoided, and the good mixing at the spray cone edge supports the ignition process.

The experiments of El-Rabii et al. [16] gave indication of the minimum laser pulse energies required to ignite fuel sprays. They measured minimum ignition energies (MIE) in n-heptane and JP-4 (military jet fuel) droplet clouds. The clouds were created by an ultrasonic atomizer, which generated a mean droplet diameter of

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