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A novel approach to laser-induced spark ignition of liquid fuel-air mixture

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Abstract

Reliable laser ignition of liquid fuel sprays remains challenging because the stochastic interaction between the laser-induced plasma and the atomized fuel–air mixture results in poor ignition repeatability and necessitates high laser pulse energies. In the present study, a temporally synchronized laser ignition strategy is proposed to improve the reliability of laser ignition at a reduced laser pulse energy. Instead of generating the laser-induced spark directly within the spray, the laser is fired slightly ahead of the incoming fuel–air mixture to form the plasma in air. The timing is adjusted so that the fuel–air mixture reaches the plasma region during its early evolution. Schlieren imaging was employed to investigate the evolution of the breakdown plasma and its interaction with the spray, while particle image velocimetry (PIV) was used to quantify the flow field of the fuel droplets. Direct laser energy deposition into the spray failed to produce ignition even at a pulse energy of 100 mJ because a significant fraction of the deposited energy was consumed by blast-wave propagation, secondary droplet atomization, droplet vaporization, and convective heat losses. In contrast, the proposed synchronization strategy reduced the droplet velocity at the ignition location by approximately 50 %, increased the residence time of the combustible mixture within the high-temperature plasma region, and achieved successful ignition in all 50 consecutive experiments conducted under the investigated operating conditions. The results demonstrate that controlling the temporal interaction between the laser-induced plasma and the arriving spray provides a practical and energy-efficient pathway for improving the reliability of laser ignition in liquid fuel sprays.

Keywords: Laser-induced spark ignition, Spray Ignition, Plasma kernel, Blast wave

1 Introduction

To meet increasingly stringent environmental regulations, modern gas turbine combustors are increasingly operated with lean fuel–air mixtures to reduce pollutant emissions. However, lean combustion is inherently more susceptible to ignition failure and flame blowout. In this context, laser-induced spark (LIS) ignition has attracted considerable attention because it can deposit energies substantially higher than the minimum ignition energy (MIE), thereby extending the lean operating limit and improving ignition reliability [1]. Compared with conventional electrical spark plugs, LIS offers several advantages, including precise control of ignition timing and location, rapid energy deposition, operation at high pressures and compression ratios, multi-point ignition capability, improved high-altitude relight performance, and the absence of electrode erosion, resulting in enhanced durability and reliability [2–4].

When a high-energy laser pulse is tightly focused into a small volume, optical breakdown occurs through multiphoton absorption followed by inverse Bremsstrahlung absorption, producing a high-temperature and high-pressure plasma. The rapid energy deposition generates a blast wave that initially propagates spherically outward at supersonic velocity [5]. The plasma and its associated high-temperature chemical environment provide the energy required to initiate and sustain an ignition kernel. Laser-induced breakdown and ignition have been extensively investigated in air and gaseous fuel–air mixtures using both experimental and numerical approaches [6–13]. These studies have established that the surrounding flow field plays an important role in determining ignition success. In particular, investigations under hypersonic [14], supersonic [15], and turbulent flow conditions [16] have consistently shown that the ignition threshold increases with increasing flow velocity. A higher flow velocity can convect the ignition kernel away from the breakdown region, reduce its residence time, and increase the rate of heat and radical loss to the surrounding flow. Thus, the local flow velocity at the ignition location is an important parameter governing the success of laser ignition.

The influence of flow becomes even more important for liquid fuel sprays, where ignition is governed by the coupled evolution of the gas phase, liquid droplets, and plasma. Unlike gaseous mixtures, spray ignition depends on the local and global equivalence ratio, droplet size and spatial distribution, vapor fraction, and local flow characteristics such as velocity and turbulence [17, 18]. In addition, the interaction of the laser-induced plasma and its associated blast wave with the liquid phase can substantially modify the spray in the vicinity of the ignition region. Consequently, the ignition process is not determined solely by the energy deposited by the laser, but also by how the plasma interacts with the surrounding spray.

Several studies have demonstrated the strong interaction between laser-induced plasma, shock waves, and fuel droplets. Kawahara *et al.* [19] showed that the lensing effect of droplets can alter the plasma location and, in some cases, produce multiple

breakdown events within transient iso-octane and ethanol sprays. They also observed that the blast wave generated by the plasma displaced droplets surrounding the breakdown region. Gebel *et al.* [20] reported catastrophic breakup of isolated droplets with a diameter of approximately 130 μm, located about 5 mm from focal region, due to the shock wave generated by the laser-induced spark at a pulse energy of 193.1 mJ. Subsequent studies by Sharma *et al.* [21], Rao *et al.* [22], and Lokini *et al.* [23] further investigated laser–droplet and shock wave–droplet interactions and demonstrated their influence on droplet breakup dynamics. These plasma–spray interactions can strongly influence the outcome of laser ignition. When the local droplet density is high, a significant fraction of the energy deposited by the laser-induced plasma is transferred to the surrounding droplets through shock–droplet interaction, droplet breakup, and vaporization, rather than contributing directly to the development of the ignition kernel. This energy redistribution can therefore reduce the energy available for ignition and make successful ignition more difficult.

The location of the ignition region within the spray is also important. Gebel *et al.* [24], Kawahara *et al.* [19], and Singh *et al.* [25] identified the velocity shear layer near the spray boundary as a favorable region for laser ignition, where the local fuel vapor concentration and flow characteristics provide suitable conditions for flame-kernel development. However, many of these investigations relied on relatively high laser pulse energies to overcome the stochastic nature of liquid fuel sprays and achieve reliable ignition.

Most previous approaches to improving ignition reliability have primarily relied on increasing the laser pulse energy or optimizing the spatial location of the breakdown. Comparatively less attention has been given to controlling the temporal interaction between the laser-induced plasma and the incoming spray. In the present study, a temporally controlled ignition strategy is investigated for liquid fuel sprays. Instead of depositing the laser energy directly into the atomized fuel–air mixture, the laser is fired slightly ahead of the incoming spray to generate the plasma in air, and the timing is adjusted so that the fuel–air mixture reaches the plasma region during its early evolution. This approach provides controlled temporal interaction between the evolving plasma and the incoming spray.

2 Experimental Setup

A laboratory-scale combustor consisting of a vertical flow channel with a hexagonal cross-sectional area of 115 cm^2 and a length of 138 cm was used for the experiments. The combustor had a total length of 138 cm, and all six sides were fitted with rectangular quartz windows to provide optical access for flow visualization and laser diagnostics. The fuel injector (PulsaJet AA10000JJAU-VI, spray setup: SU1A-SS) was mounted at the geometric center of the flow channel using a metallic supporting assembly that allowed vertical adjustment of the injector position. The injector was capable of operating at frequencies up to 10,000 cycles min^{-1} and incorporated with an internal solenoid valve for controlling the liquid fuel supply. It produced a weakly swirling, full-cone spray with an approximate cone angle of 18° and droplet diameters ranging from 10 to 100 μm.

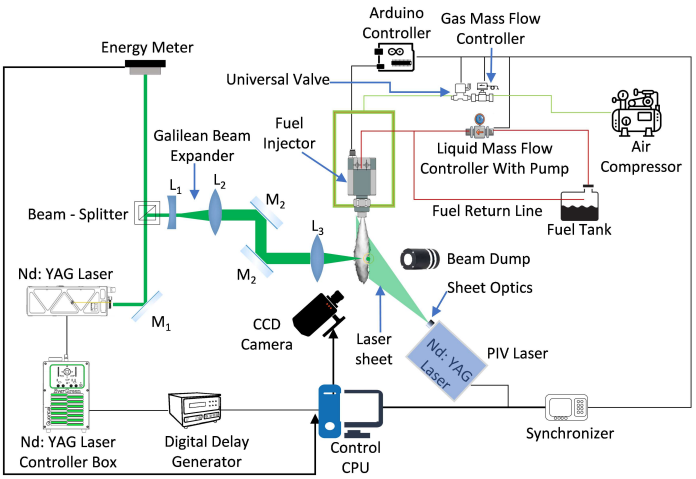


Fig. 1 Schematic of the experimental setup.

The liquid fuel and atomizing-air flow rates were regulated using digital mass flow controllers (Bronkhorst M13 mini CORI-FLOW for fuel and AALBORG GFC-37 for air). A normally closed solenoid valve was installed downstream of the air mass flow controller to ensure that atomizing air was supplied only during the experiments. The injector and air-line valves were actuated independently using an Arduino-based controller. The timing of fuel injection, atomizing-air delivery, and laser firing was controlled using a digital delay generator (BNC Model 745) in conjunction with the Arduino controller. Appropriate temporal delays between the injector and air-line valves were selected to ensure that the fuel and atomizing air reached the laser-induced breakdown region simultaneously. To prevent overpressure in the liquid fuel line, a return line was incorporated downstream of the liquid fuel mass flow controller to recirculate excess fuel back to the storage tank.

Laser-induced spark (LIS) was generated inside the combustor using a double-pulse, frequency-doubled (532 nm), Q-switched Nd:YAG laser (Quantel, EVG00145). The laser was capable of delivering pulse energies ranging from 10 to 145 mJ with a pulse duration of 7 ns (FWHM). The laser beam emerging from the laser head was first redirected using a 45° mirror (diameter = 12.5 mm) and subsequently expanded to approximately 30 mm using a Galilean beam expander. The expanded beam was then guided by two additional 45° mirrors (diameter = 50.8 mm) and focused inside the combustor using an achromatic doublet lens (focal length = 100 mm, diameter = 50.8 mm). The focal point was positioned 8 cm below the injector exit. The focusing lens was mounted on a precision optical rail, allowing the horizontal position of the laser-induced spark to be adjusted relative to the spray axis. A pulse energy of 50 mJ was used for generating the LIS in all experiments.

Particle image velocimetry (PIV) measurements were performed to quantify the effect of the proposed ignition strategy on the velocity field of the fuel–air mixture.

A separate double-pulse, Q-switched, frequency-doubled Nd:YAG laser (LLE Jena GmbH) was used to generate the laser sheet using sheet-forming optics attached to the laser head, as illustrated in Fig. 1. The scattered light from the fuel droplets was recorded using a TSI PowerView 4MP-HS camera (Model 630091) equipped with a Camera Link PCI-e frame grabber. The camera was positioned perpendicular to the laser sheet. Synchronization between the PIV laser and the camera was achieved using a TSI LASERPULSE synchronizer (Model 610036). Image acquisition was performed using TSI Insight 4G software, while timing signals from the digital delay generator were used to synchronize the PIV measurements with the fuel injector operation.

Schlieren imaging was employed to visualize the laser-induced breakdown region and the associated transient flow-field evolution. Following each experiment, nitrogen was supplied to the combustor to purge the combustion products before the subsequent test. A schematic of the complete experimental setup is shown in Fig. 1. Further details of the experimental setup and the visualization methodology are available in our previous work [25].

3 Results and discussions

3.1 The effect of the bulk velocity of atomizing air on LIS

The effect of atomizing-air flow on the evolution of the laser-induced breakdown kernel was first investigated independently, with the fuel line kept closed and only atomizing air supplied through the injector. Immediately after laser-induced breakdown, a plasma is generated at the focal region and rapidly expands into a high-temperature gas region. The Schlieren images in Fig. 2 captures the subsequent evolution and convection transport region at different atomizing-air flow rates.

A clear dependence of the kernel evolution on airflow rate is observed. At 0 gpm, the kernel remains relatively compact during the initial stages, whereas increasing the airflow progressively stretches and displaces the kernel from its initial breakdown region. This effect is most noticeable at 22 gpm, where substantial deformation occurs within 63 μs after laser energy deposition. In comparison, the kernel remains well defined for 4 and 9 gpm flow rates. These observations indicate that higher atomizing-air flow enhances the convective transport of the breakdown-induced hot region and reduces its residence time near the breakdown location.

However, reducing the atomizing-air flow rate is undesirable as insufficient atomization increases the droplet size and adversely effects ignition. Aggarwal *et al.* [17] reported that the minimum ignition energy increases with droplet diameter, while Lefebvre and McDonell [26] showed that increasing flow velocity from nearly quiescent conditions to approximately 15 m s^{-1} can increase the required ignition energy by nearly four times. Thus, an appropriate balance between effective atomization and minimizing flow-induced kernel transport is required.

To address this trade-off, the present study focuses on controlling the timing of atomizing-air delivery rather than reducing its flow rate. The air-line valve was actuated with a controlled delay relative to fuel injection, allowing sufficient time for the fuel spray to reach the breakdown region. This strategy reduces the high-velocity airflow present during the initial ignition period while maintaining sufficient atomizing

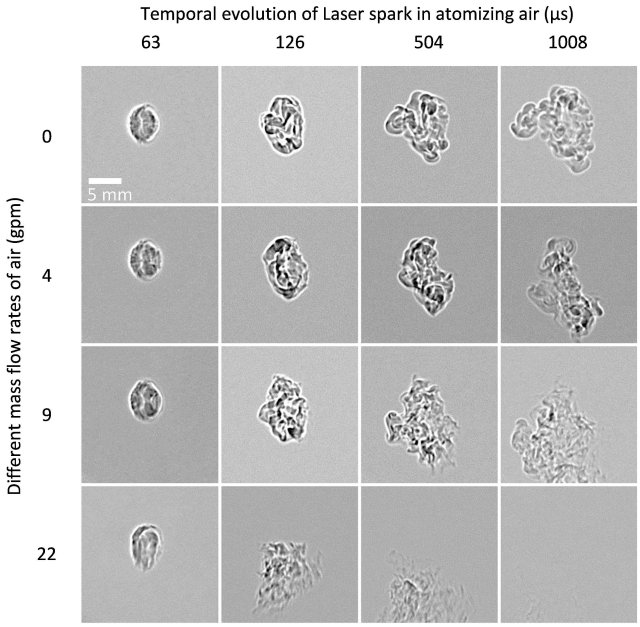


Fig. 2 Temporal evolution of the laser-induced breakdown kernel at different atomizing-air flow rates in the absence of fuel injection.

air for effective spray breakup. The resulting local velocity field and its influence on the residence of the fuel-air mixture near the ignition location are investigated using PIV in the later section.

3.2 Direct deposition of LIS in atomized kerosene-air spray

To investigate the ignition characteristics of a near-stoichiometric kerosene–air spray, LIS was generated at different time delays relative to the fuel-injection event. The breakdown location was fixed at 8 cm below the injector exit along the combustor centerline. Kerosene was supplied at a mass flow rate of 6 g min^{-1}, while the atomizing-air flow rate was maintained at 15 g min^{-1}. The normally closed solenoid valve in the atomizing-air line was removed in this configuration, allowing the fuel to be introduced into a continuous stream of atomizing air, similar to conventional air-assisted atomization. A uniform downward co-flow was established using a honeycomb flow straightener, with the co-flow air mass flow rate maintained at 78 g min^{-1}. The temporal evolution of the laser-induced breakdown kernel within the spray is shown in Fig. 3.

Despite increasing the laser pulse energy to 100 mJ, no ignition was observed at any of the investigated fuel-injection delays. At 0 and 1.4 ms delay, the fuel spray had not yet reached the breakdown location, and the breakdown kernel evolved in the surrounding air with no significant droplet interaction. With increasing injection delay,

progressively more fuel droplets reached the breakdown region and interacted with the high-temperature kernel. This interaction is evident from the stronger density-gradient structures observed in the Schlieren images. The enhanced density gradients indicate increased interaction between the breakdown kernel and the evaporating fuel droplets. However, despite the increasing droplet population and apparent fuel evaporation near the breakdown region, no self-sustaining flame kernel was established.

The evolution observed in Fig. 3 indicates that droplet density near the breakdown location plays an important role in the ignition process. As more droplets enter the high-temperature region, their heating and vaporization modify the local density field and produce stronger Schlieren signatures. The breakdown-induced blast wave also promotes droplet deformation and secondary atomization, increasing the available surface area for evaporation. Thus, the breakdown event generates fuel vapor in the vicinity of the ignition region; however, the resulting vapor does not establish a sufficiently persistent and reactive mixture to initiate self-sustaining combustion.

The failure to ignite despite the relatively high laser pulse energy indicates that only a fraction of the deposited energy is effectively utilized for ignition-kernel development. During laser-induced breakdown, a substantial fraction of the absorbed energy is transferred to the blast wave, while only a smaller fraction remains in the hot plasma core after blast-wave propagation and associated heat losses [27]. In the denser spray environment, additional energy is consumed by droplet deformation, secondary atomization, heating, and vaporization, further reducing the energy available for ignition.

These results demonstrate that direct laser energy deposition does not necessarily result in ignition even when substantial fuel vaporization occurs near the breakdown region. The deposited energy is distributed among blast-wave formation, droplet breakup, heating, and vaporization, leaving insufficient energy and residence time for the formation of a self-sustaining flame kernel. Increasing the laser pulse energy may compensate for some of these losses, but increases system complexity and cooling requirements and may approach the damage limits of optical components [28]. Therefore, improving the utilization of the deposited energy through control of the temporal and local spray environment provides a more practical approach.

The results in Fig. 3, together with the air-only observations in Fig. 2, motivate the temporal synchronization strategy investigated in the following section. While Fig. 3 demonstrates that increasing droplet presence near the breakdown region promotes fuel evaporation, it does not lead to sustained ignition. The following section therefore investigates whether controlling the timing of atomizing-air delivery can improve the temporal overlap between the fuel spray and the laser-induced breakdown kernel while maintaining effective spray atomization.

3.3 A novel approach to laser-induced spark ignition of liquid Sprays

After observing the challenges associated with the laser ignition of atomized liquid fuel–air mixtures, both from the available literature and from the extensive experiments performed in the present study, it was found that the primary cause of ignition failure is the direct interaction between the laser-induced spark and the dense spray.

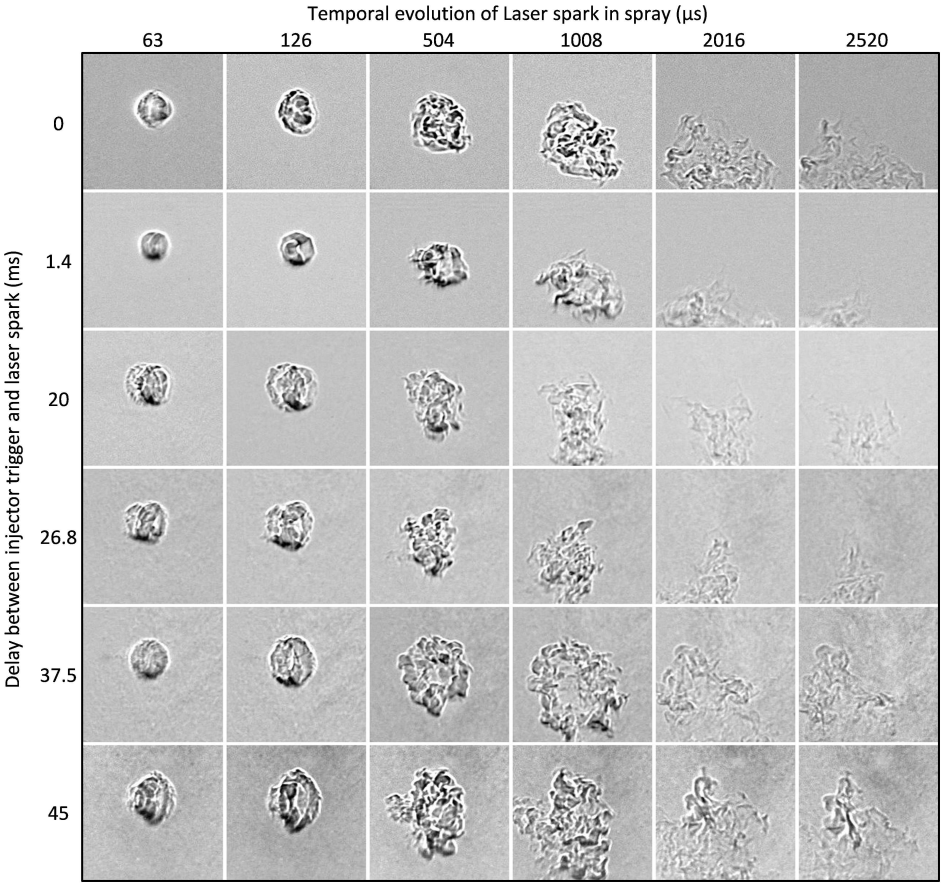


Fig. 3 Temporal evolution of the laser-induced breakdown kernel in a kerosene–air spray at different delays between the injector trigger and laser firing.

Direct laser energy deposition results in strong interactions between the blast wave, the plasma, and the liquid droplets, leading to secondary atomization, enhanced convective heat losses, and reduced plasma residence time. Based on these observations, a different ignition strategy was developed in which the temporal interaction between the laser-induced spark and the atomized fuel–air mixture is controlled instead of directly depositing the laser energy into the spray.

The working principle of the proposed approach is illustrated in Fig. 4. The laser pulse is fired such that the subsequent blast wave and the radially outward flow induced behind it interact only minimally with the incoming fuel–air mixture. Consequently, the majority of the atomized mixture encounters the high-temperature plasma region

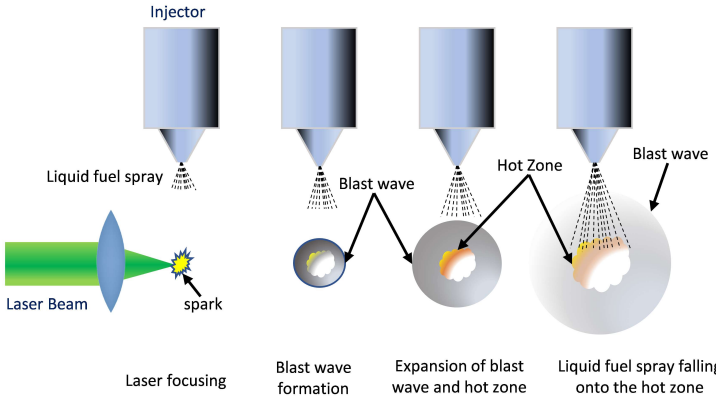


Fig. 4 Schematic of physical scenario just until the physical contact of liquid fuel with hot core zone

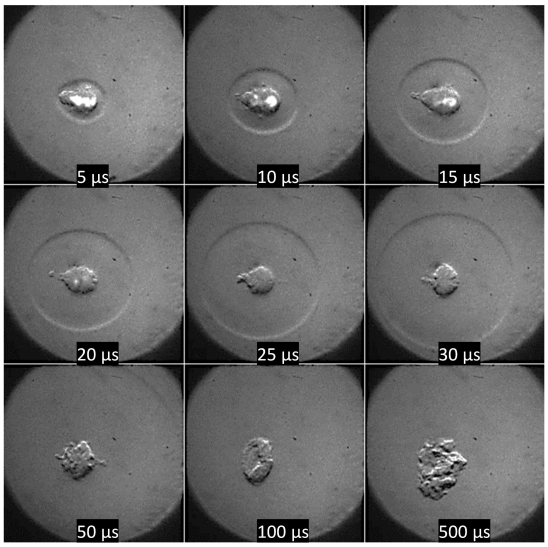


Fig. 5 Temporal evolution of LIS in kerosene–air mixture

after the blast wave has propagated away from the focal volume. This indirect interaction increases the effective residence time of the combustible mixture within the hot core while minimizing droplet dispersion caused by the blast wave.

To better understand the temporal evolution of the laser-induced spark, a sequence of Schlieren images for LIS in a kerosene–air mixture is presented in Fig. 5. The images were acquired using an ICCD camera with an exposure time of 200 ns, while the laser pulse energy was maintained at 100 mJ. The plasma radiation is visible only during

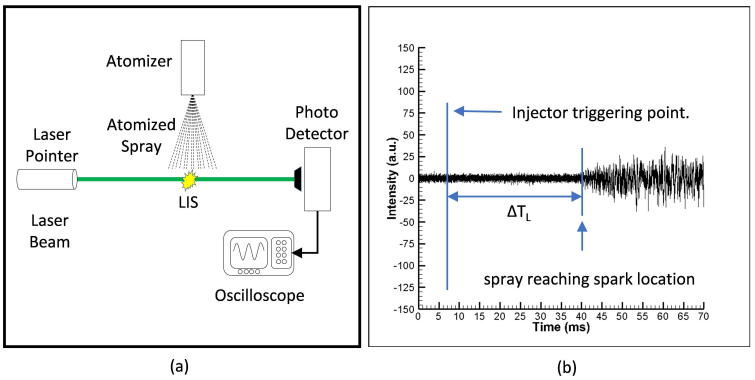


Fig. 6 (a) Schematic of delay detection setup, (b) Intensity vs. Time plot

the first 20–25 μs following optical breakdown. During this initial stage, the blast wave propagates at supersonic speed, as reported in previous studies [3]. As the blast wave moves away from the focal region, the remaining hot plasma core gradually loses heat through thermal conduction, radiation, and convection. In conventional laser ignition, the atomized fuel–air mixture interacts with both the blast wave and the rapidly decaying plasma, resulting in significant energy losses. In the proposed approach, however, the timing of the spray is adjusted such that the fuel–air mixture predominantly interacts with the hot plasma after the blast wave has weakened, thereby improving the conditions for flame kernel formation.

The synchronization between the arriving spray and the LIS was achieved using the optical beam-deflection technique shown in Fig. 6 (a). A low-power laser pointer was aligned with the intended spark location, and the transmitted light intensity was monitored using a photodetector connected to an oscilloscope. The arrival of the spray tip caused a change in the transmitted light intensity due to beam deflection, which was recorded as a voltage signal. The parameter ΔT_{L} in Fig. 6 (b) represents the time difference between the injector valve opening and the ignition laser firing, corresponding to the arrival of the spray tip at the spark location. Since the ignition laser exhibits an inherent delay of approximately 138 μs due to flashlamp pumping and Q-switch operation, the firing time was compensated using a digital delay generator. The injector, ignition laser, oscilloscope, and atomizing air valve were synchronized through an Arduino controller and the digital delay generator. By accurately controlling the timing of the injector, atomizing air supply, and laser firing, the atomized kerosene–air mixture consistently entered the hot plasma region after the blast wave had propagated away, resulting in repeatable ignition of the spray. A detailed description of the experimental methodology and synchronization procedure is available in our patent [29].

Representative ignition images obtained using the proposed synchronization strategy with 50 mJ pulse energy are shown in Fig. 7. The images were recorded at a frame rate of 240 fps, corresponding to a temporal resolution of 4.17 ms between successive frames. Frames (a) and (b) show the approaching kerosene spray before laser

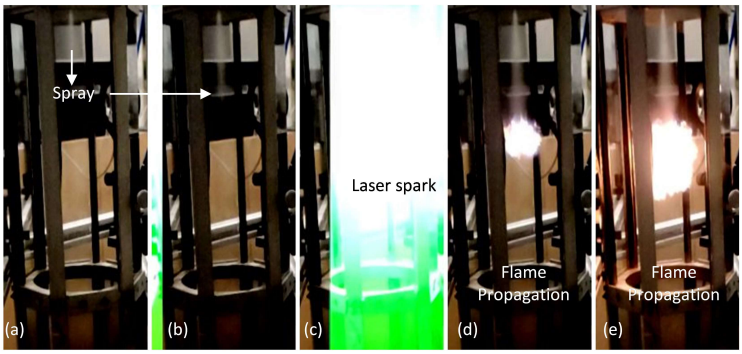


Fig. 7 Successive images of the successful ignition of the kerosene-air spray by 50 mJ energy pulses

firing, whereas frame (c) captures the laser energy deposition immediately before the arrival of the spray at the breakdown location. Subsequent flame development and propagation are visible in frames (d) and (e), confirming successful ignition of the near-stoichiometric kerosene-air mixture.

To quantify the effect of the proposed synchronization strategy on the spray dynamics, particle image velocimetry (PIV) measurements were performed on the fuel droplets and compared with the conventional direct energy deposition approach. Figure 8 summarizes the experimental procedure together with the corresponding velocity measurements. PIV images were acquired using TSI Insight 4G software. In the synchronizer timing sequence, the trigger signal (T) initiated camera exposure E_1 and laser pulse L_1 to record image A, followed by camera exposure E_2 and laser pulse L_2 to record image B. Each laser pulse delivered 25 mJ with a pulse duration of 9 ns. The inter-pulse delay was optimized to 60 μs to minimize the influence of droplet evaporation and out-of-plane motion while satisfying the recommended particle displacement criteria for PIV measurements. The laser sheet thickness was approximately 1 mm. Image processing was carried out in MATLAB using PIVLab [30]. The interrogation window sizes employed during the three processing passes and the resulting velocity vector fields are shown in Fig. 8.

For comparison, the direct energy deposition experiments were performed after the spray had reached a fully developed condition. Accordingly, the corresponding reference velocity field was measured at 1000 ms after injection. In contrast, the proposed synchronization strategy introduced the spray into the laser-induced breakdown region at approximately 55 ms after injection. The measured velocity fields reveal a significant reduction in droplet velocity with the proposed approach. Analysis of the centerline vertical velocity shows that the velocity at the LIS location is approximately half that measured in the fully developed spray. The reduced convective velocity increases the residence time of the combustible mixture in the vicinity of the hot breakdown region, thereby providing a longer time for the ignition kernel to form and develop. For each operating condition, 20 image pairs were acquired, and the mean velocity field was obtained by ensemble averaging.

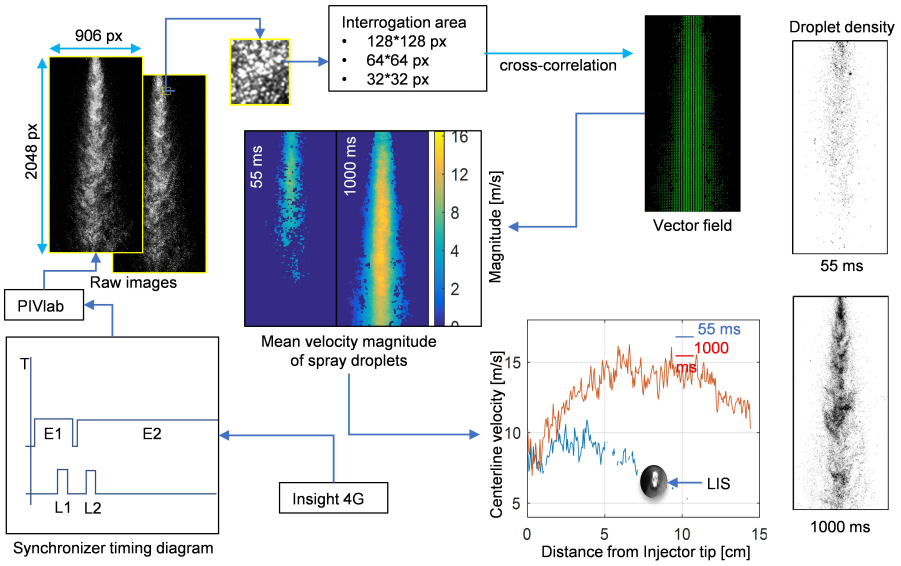


Fig. 8 Detailed description of Centerline velocity calculation using Particle Image Velocimetry of the spray droplets

The same PIV images also provide qualitative information on the spatial distribution of fuel droplets through the Mie-scattering intensity, as shown on the right side of Fig. 8. A noticeable difference in droplet loading is observed between the synchronized condition at 55 ms and the fully developed spray at 1000 ms. The fully developed spray exhibits a higher droplet concentration in the laser-sheet plane, whereas the temporally synchronized spray contains a comparatively lower droplet loading near the LIS location. The higher droplet loading in the fully developed spray can increase the energy demand for ignition because a larger fraction of the deposited energy can be consumed through droplet heating, vaporization, and interactions with the breakdown-induced flow. Thus, the temporal synchronization not only reduces the local convective velocity but also modifies the droplet distribution encountered by the laser-induced breakdown region. These two effects act together to create a more favorable environment for ignition.

4 Conclusions

The present study investigated the ignition characteristics of a near-stoichiometric kerosene–air spray using laser-induced spark (LIS). The experimental results demonstrate that reliable laser ignition of liquid fuel sprays is strongly influenced by the temporal interaction between the laser-induced plasma and the atomized fuel–air mixture. Direct laser energy deposition into the spray was found to result in ignition failure because a significant fraction of the deposited energy was consumed by secondary droplet atomization, droplet heating and vaporization, convective heat losses,

and blast-wave-induced spray dispersion before a self-sustaining ignition kernel could be established.

To overcome these limitations, a temporally synchronized laser ignition strategy was proposed in which the laser-induced spark was generated in air before the arrival of the spray. By controlling the arrival time of the fuel–air mixture with respect to the laser firing, the interaction between the blast wave and the liquid spray was substantially reduced, allowing the combustible mixture to interact predominantly with the high-temperature plasma region. Schlieren visualization confirmed the evolution of the laser-induced breakdown, while particle image velocimetry (PIV) measurements demonstrated that the proposed strategy reduced the spray velocity at the breakdown location to approximately half of that measured for the fully developed spray. The lower convective velocity increased the residence time of the combustible mixture within the hot plasma, thereby promoting flame kernel formation and growth.

Compared with conventional direct laser energy deposition, the proposed synchronization strategy offers several important advantages. It eliminates the direct expenditure of laser energy on secondary droplet atomization, reduces the complexity of plasma–spray interactions, minimizes the influence of the initial high-intensity blast wave on the atomized fuel, and provides a more favorable flow environment for flame kernel development. Using this approach, successful ignition was achieved in all 50 consecutive experimental trials, corresponding to an observed ignition success rate of 100% under the investigated operating conditions.

The experimental observations presented in this study demonstrate that improving the temporal coupling between the laser-induced plasma and the arriving fuel–air mixture can significantly enhance the reliability of laser ignition. The proposed approach therefore provides a practical pathway toward reliable laser ignition of liquid fuel sprays while reducing the requirement for high-energy laser systems.

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Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

- Author contribution
  Sandeep Pandey: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing.
  Abhishek Kumar: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – review & editing.
  Manas Jain: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – review & editing.
  Barnamay Samanta: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – review & editing.

Ratan Joarder: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Writing – review & editing.

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