Chapter 11
Feasibility Study of Laser Plasma-Assisted Stratified Combustion and Spray Investigations in a Constant Volume Chamber

Aaishi Ashirbad, Dhananjay Kumar, and Avinash Kumar Agarwal

Abstract Due to their great efficiency and fuel economy, gasoline engines, particularly Direct Injection Spark Ignition (DISI) engines, have been extensively developed and employed in passenger vehicles. Stratified and homogeneous modes are the two basic operating modes of the DISI engines. Stratified mode offers superior efficiency at part-load engine operation. Laser ignition coupled with the stratified mode of operation can increase combustion efficiency by enabling multipoint laser ignition. However, there are several challenges associated with optics and laser beam delivery that must be taken into consideration. Since fuel is injected directly, it requires adequate fuel–air mixing, which dictates the combustion characteristics. Hence, spray characterisation is required to assess the potential of laser ignition in the stratified mode operation. For the fundamental spray and combustion investigations, optical techniques such as Shadowgraphy, Schlieren imaging, Laser-Induced Fluorescence (LIF), Mie scattering and Phase Doppler Interferometry (PDI) are used, which are discussed along with their principles. Different spray chamber types are also discussed, along with design considerations and a demonstration of the horizontal cylindrical combustion chamber. This chapter also covers the fundamentals of laser ignition and associated challenges for a stratified mode DISI engine operation.

Keywords Laser ignition · Optical investigations · Stratified mode combustion · DISI

Abbreviations

PFI	Port fuel injection
SI	Spark ignition
CI	Compression ignition
NO_x	Oxides of nitrogen

A. Ashirbad · D. Kumar · A. K. Agarwal (✉)
Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh 208016, India
e-mail: akag@iitk.ac.in

P. C. Shukla et al. (eds.), *Renewable Fuels for Sustainable Mobility*, Energy, Environment, and Sustainability, https://doi.org/10.1007/978-981-99-1392-3_11

GDI	Gasoline direct injection
DISI	Direct injection spark ignition
BSFC	Brake-specific fuel consumption
TDC	Top Dead Centre
CO_2	Carbon dioxide
THC	Total hydrocarbon
LIF	Laser-induced fluorescence
PDI	Phase Doppler interferometry
CVC	Constant volume chamber
CVCC	Constant volume combustion chamber
FoS	Factor of safety
SG	Spray guided

11.1 Introduction

Spark-ignition (SI) engines have dominated the passenger vehicle segment of the global transport sector for a long time. An increase in demand for petroleum products and deteriorating environmental conditions motivate the advancements in engine technology and improvements in emission control technologies. Most engine research and development activities focus on reducing fuel consumption and emissions and maximising engine performance and thermal efficiency (Kumar and Agarwal 2022). These factors are influenced by the fuel–air mixture formation processes, either internal or external. In the latest gasoline direct injection (GDI) engine technology, fuel–air mixing occurs in the combustion chamber by delivering high-pressure gasoline directly into the in-cylinder air. However, fuel–air mixing occurs in the intake manifold, i.e. externally, in the port fuel injection (PFI) engine technology, which powers most gasoline engines today. PFI systems have evolved extensively over the decades. However, they have some limitations. In PFI systems, throttled engine operation leads to pumping losses, which are significant at part loads. PFI engines knock at higher loads/lower speeds. Hence, they generally have lower compression ratios. Their higher in-cylinder combustion temperature increases the NO_x emissions because the PFI systems mainly use a stoichiometric mixture. Charge in the crevices of the PFI engines lead to higher hydrocarbon (HC) emissions. In PFI, the injector sprays fuel into the intake manifold, mixing it with the air inducted (Kumar and Ashok 2021). The time lag between the intake valve opening and fuel injection leads to considerable cylinder wall wetting, specifically closer to the intake valve (Kumar et al. 2022). Direct Injection Spark ignition (DISI) technology offers superiority in performance and emission controls over the PFI. DISI engines deliver better fuel economy, lower BSFC, compliance with strict emission standards, reduced engine noise, wider speed limit, improved start-ability and lower NO_x than PFI engines. DISI engines tend to achieve BSFC closer to diesel engines while maintaining higher specific power output closer to gasoline PFI engines. DISI engines operate in stratified lean mode at part loads, resulting in lower BSFC than PFI engines (Duronio et al. 2020). Simultaneously, the DISI engines deliver higher power output than PFI engines in homogenous mode at high-load conditions. Fuel injection in the combustion chamber during the intake stroke can effectively cool the incoming charge due to fuel vaporisation. Charge cooling increases the mixture density, enabling the engine to induct more air, leading to higher volumetric efficiency and more power output. Charge cooling also decreases the in-cylinder temperature at the TDC, reducing the possibility of knocking and allowing a higher compression ratio, improving engine efficiency. DISI engines combined with turbochargers or superchargers in the homogeneous mode accomplish significant engine downsizing without compromising the power output. Hence, summarising the advantages of DISI engines includes lower pumping losses, lower heat losses and higher compression ratio on account of charge cooling, increased volumetric efficiency, superior control over the air–fuel ratios, ease of cold starting with lesser fuel enrichment and lower CO_2 emissions. Although DISI engines have a few drawbacks, namely, difficulty in managing the stratified charge conditions, increased injector deposits, higher THC emissions at lower loads, and higher soot and NO_x emissions at higher loads. Further in research and development will focus on lowering BSFC, meeting emission standards and transitioning between stratified and homogeneous charge modes.

11.1.1 DISI Engines

DISI engines, also known as GDI engines, operate mainly in stratified and homogenous modes. Fuel is injected into the combustion chamber early in the intake stroke in homogenous charge mode. Early fuel injection offers adequate time for mixing fuel and air; hence, a homogenous charge is formed. This mode is used at high engine loads and speeds. While in stratified mode, fuel is injected later in the compression stroke to make an ignitable charge in the vicinity of the spark plug. Stratified mode is used at lower engine loads and speeds; therefore, less fuel is injected in stratified mode than in homogenous mode. Stratified charge mode fulfills low-speed and low-load requirements without any acceleration. However, the combustion of the lean mixture results in higher NO_x emissions due to the ineffectiveness of the catalytic converter. Therefore, the stratified charge mode is augmented with EGR to limit NO_x emissions. Charge stratification is not feasible at higher speeds due to increased in-cylinder turbulence. Homogenous charge mode is used at high-load and high-speed conditions and during acceleration since this mode produces higher torque and power. While transiting from stratified-to-homogenous charge mode, the homogeneous lean mode also caters to medium speeds and loads. In this mode, fuel is injected early in the intake stroke, keeping the mixture slightly leaner. EGR is not required in the stoichiometric mode as the catalytic converter can easily control NO_x emissions at $\lambda = 1$. Homogenous stratified mode is operated under low-speed, high-load conditions. In this mode, split injections are done, in which a portion of the fuel is injected early during the intake stroke, and the remaining fuel is injected later to achieve the charge stratification. This injection strategy is adopted during acceleration when a large fuel quantity is injected. Homogeneous mode is achieved by injecting fuel early in the intake stroke, allowing it to evaporate and mix uniformly with ambient air. The amount of injected fuel and air intake controls the engine load in each cycle. The intake air mass must be monitored to maintain the air–fuel mixture within the ignitable range. A throttle is generally used to limit the intake airflow. Engines typically operate at a stoichiometric air–fuel ratio. The intake airflow restriction causes significant pumping losses, increasing fuel consumption. There is a need to reduce these pumping losses. One possible way is to allow more air than necessary to enter the combustion chamber, thereby increasing the air–fuel ratio. However, this can cause the mixture to go beyond the ignition limit, leading to partial burns or misfires. Injecting the specified amount of fuel at such lean air–fuel ratios with the same injection timing as in homogeneous mode would result in fuel over-dilution and misfire. Hence, a concentrated charge cloud in the spark plug region enables successful ignition. This is accomplished by adding fuel later in the compression stroke and igniting the cloud before it becomes too dilute. It produces an ignitable charge cloud near the spark plug, surrounded by ambient air or recirculated exhaust gas.

The significant advantage of stratified combustion mode over homogenous combustion mode includes reduced pumping and wall heat transfer losses and increased volumetric efficiency (Huegel et al. 2015). Engines operating in stratified mode attain a higher specific heat ratio ($k = 1.4$) than those operating in homogeneous mode ($k = 1.3$). Stratified operation eliminates the need for an air restrictor to limit air intake, reducing pumping losses and fuel consumption. In stratified mixture combustion, the flame does not reach cylinder walls directly due to the insulating layer of air surrounding the charge cloud. This also reduces the cylinder wall heat transfer losses and improves the engine efficiency. As the fuel is injected later, after the closure of the intake valve, the volumetric efficiency is increased by maximising the air inducted. Moreover, charge cooling occurs as the heat of the air inside the cylinder enables fuel evaporation, reducing the knocking tendency of the engine.

Stratified charge mode enables the engine to run at a higher compression ratio because lean end gas increases the knock limit, leading to higher efficiency. In the homogeneous mode, the mixture cannot be leaned any further. This condition shows an increase in fuel efficiency in the stratified mode compared to the homogenous mode. Three types of combustion systems are used for generating charge stratification in DISI engines: wall-guided, air-guided and spray-guided (SG), as shown in Fig. 11.1 (Baumgarten 2006). These three systems employ different ways of transporting fuel spray in the vicinity of spark plug.

In a spray-guided combustion system, charge stratification occurs mainly due to the spray dynamics, with little contribution from the interactions between bulk air charge motion and piston cavity profile. In this combustion system, the spark plug is located near the injector, so the fuel injected in the vicinity of spark plug gets ignited easily. In a wall-guided combustion system, stratification is obtained from the spray's interaction with the piston cavity. The spark plug is generally located in central position, while the injector is on the side. In an air-guided system, charge stratification results from the interactions between fuel spray and air charge motion induced in the

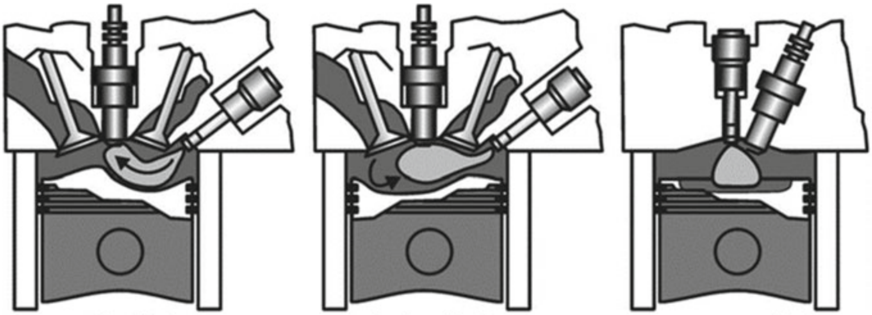


Fig. 11.1 Different combustion system designs for stratified mode engine operation (Baumgarten 2006)

combustion chamber. The spark plug and fuel injector configurations are like wall-guided combustion system. Despite the advantages of lower fuel consumption and improved thermal efficiency, stratified combustion has drawbacks. The most significant downsides of stratified combustion include combustion instability, higher particulate emissions and interference with exhaust gas after-treatment systems (Whitaker et al. 2011; Farron et al. 2011). This chapter focusses on investigating the parameters which affect combustion instability. Successful stratified combustion depends on various factors. In stratified mode, considerable air–fuel mixing occurs before ignition. The ignition and fuel–air mixing systems control the combustion predominantly. Fuel–air mixing can be controlled by injection duration, ignition delay, fuel type, fuel injection pressure, air motion and fuel properties. The proximity of ignition and injection can lead to adverse conditions at the spark gap, such as fuel vapour fluctuations, gradients in air–fuel ratio and wetting of the spark plug electrodes due to liquid fuel droplets (Piock et al. 2010). These factors may lead to poor ignition and unstable flame kernel evolution, eventually leading to combustion instability due to misfire or partially burnt cycles. Therefore, it is necessary to understand the ignition and early flame evolution processes to improve combustion stability.

11.2 Optical Techniques for Combustion and Spray Investigations

Several optical techniques are used to investigate the spray and combustion in the constant volume chambers. Broadly, these optical techniques can be (i) direct visualisation and (ii) laser based. Some of these techniques and their working principles are discussed in the following sub-sections.

11.2.1 Shadowgraphy Technique

Because of its ease of use and low cost, this method is widely used for spray visualisation. Pressure, temperature and mixture gradients create non-uniform refractive index patches in the spray zone. To use this technique, one needs a light source, an object in the region of interest and a sufficiently flat reflecting screen, onto which the shadow can be projected. The speed of light in the medium divided by the speed of light in the vacuum gives us the refractive index. When an angled beam of light is passing through a substance with a higher refractive index, the light is refracted to a point in the substance's direction. According to theory, shadowgraphy approach finds the second derivative of density, while the Schlieren approach identifies the first derivative of the density (Settles 2001).

11.2.2 Schlieren Imaging Technique

Besides placing a sharp edge stop in front of the camera at the focal point of the optics, the Schlieren imaging technique shares the same optical configuration as the shadowgraphy. Schlieren imaging technique offers benefit that cut-off by sharp edge may be readily altered. In contrast, optical path length primarily determines the sensitivity of shadowgraphy. Vapour phase sprays are often seen using the Schlieren method. This approach involves refracted light beams, which convert density changes into light intensity variations. Bright and dark zones are created in the camera. An intense pointed light source, two concave mirrors, a sharp edge and a fast camera make up the Schlieren setup. Two spherical focussing mirrors are the main components of this Schlieren imaging technique experiment. A schematic of the experimental setup is shown in Fig. 11.2.

The reliability of the Schlieren system relies on the larger focal lengths of the two concave mirrors. This technique helps understand the spray and combustion and can be applied to gaseous and liquid fuels. Lee et al. (2021) analysed the behaviour of hydrogen spray at different ambient pressures via a hollow cone injector. They reported that spray collapsed severely at high ambient pressures due to the substantial pressure differential between inner and outer surfaces of hollow-cone-shaped spray. Images of the spray boundaries and computed spray cone angles are shown in Fig. 11.3. Spray cone angle is reduced with increasing ambient pressure. The aerodynamic action at the nozzle region caused a reduction in static ambient gas pressure spray's inner and outer parts as flow motion was generated. Beyond 2 MPa, the centroid position shifted in the other way as pressure rose.

Because of the extreme spray contraction at the injector, the spray plume collided instead of mixing. In this way, injected hydrogen lost its velocity and spreads outward. Spraying hydrogen in its gaseous state offers a similar feel to spraying gasoline in its liquid form. However, aerodynamic effects are more likely to be felt by the spray. Since hydrogen has a weak spray stiffness, it is essential to regulate and design the

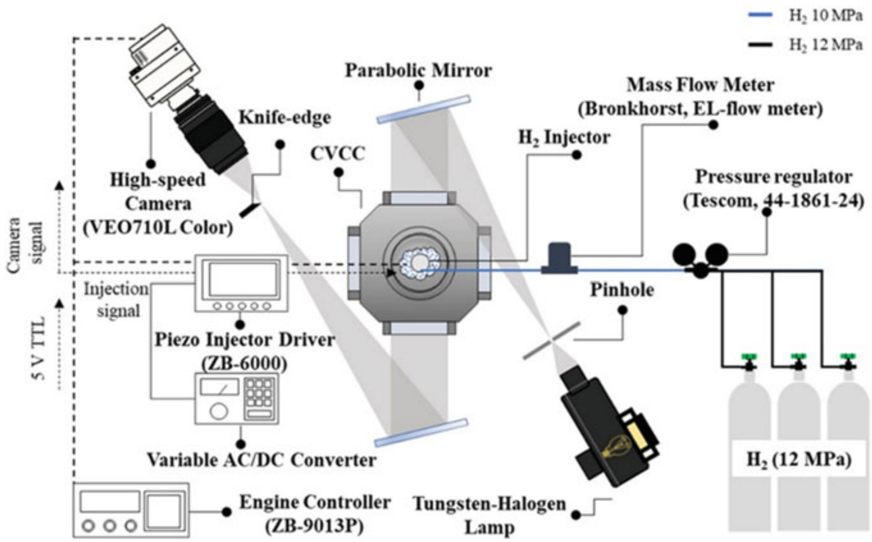


Fig. 11.2 Z-type two-mirror Schlieren imaging system for visualising high-pressure hydrogen spray (Lee et al. 2021)

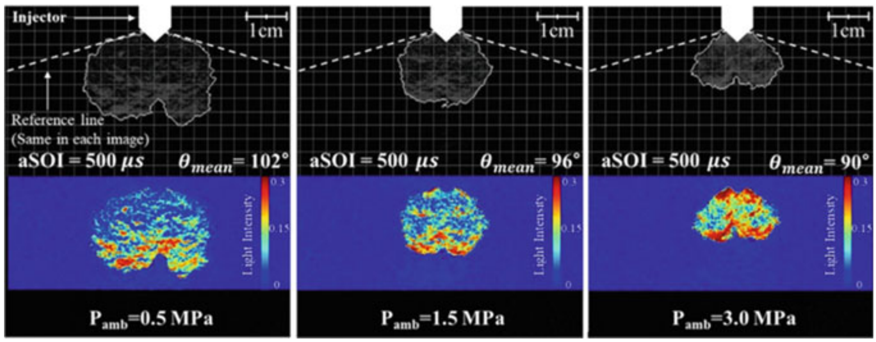


Fig. 11.3 Spray cone angle at different ambient pressures (Top: spray images with boundary detection in the same background, Bottom: grey scaled light intensity images) (Lee et al. 2021)

spray while considering environmental factors carefully. Combustion efficiency may decrease if hydrogen accumulates near the injector and remains in a rich mixture. To counteract the reduction in spray area caused by hydrogen's shrinking atomisation, the nozzle's angle should be widened. Hydrogen dispersion may be solved in several ways, including changing the injector's geometry and lowering the surrounding pressure. Since the injection evolution characteristics are known, a hydrogen-injection method can be designed.

11.2.3 Laser-Induced Fluorescence (LIF) Technique

LIF is a very sensitive laser imaging method for measuring species concentration, mixture fraction and temperature in fluid mechanical processes, sprays and combustion systems. Sometimes it is also referred to as planer laser-induced fluorescence (PLIF). High spatial and temporal resolution are two hallmarks of LIF imaging, a technique for seeing molecules of interest. Flow seeding using fluorescent markers (also known as tracers LIF) is utilised for scalar flow-field imaging if the fluid does not include any LIF-active species (such as N_2, CH_4 or water). A laser photon is absorbed, and a fluorescence photon is emitted from the excited state. This is primary mechanism of LIF. Absorption requires a laser wavelength compatible with a permitted energy transition of LIF-active chemical (atom) (https://www.smart-piv.com/en/techniques/lif-plif/#:~:text=Planar%20Laser%20Induced%20Fluorescence%20(PLIF,processes%2C%20sprays%20and%20combustion%20systems). However, only a small percentage of these stimulated molecules glow, while the rest calm down and stop becoming fluorescent.

It can differentiate between the sprays in liquid to vapour phase. In the absence of oxygen, quenching has a negligible effect on fluorescence intensity and may be disregarded. A typical schematic is shown in Fig. 11.4 (Chang et al. 2020). The fluid region of interest, such as flames or sprays, is intersected by a laser beam created into a light sheet (or volume). Excited molecules in the light sheet emit fluorescence, captured by a time-gated digital camera after passing through a filter to isolate specific wavelengths. The LIF signals are amplified using an image intensifier for pulsed UV LIF applications. Calibration measurements are the basis for transforming LIF pictures into interpretable concentration or temperature fields.

Feng et al. (2021) used LIF imaging in a constant volume spray chamber to examine the differences between gasoline and diesel sprays produced by a common rail direct injection (CRDI) system (Feng et al. 2021). In evaporating conditions, fuel injection has minimal effect on the liquid phase penetration. In contrast, vapour phase penetration steadily increased due to the development of a branch-like structure in the downstream vapour phase. The first important observation is that gasoline spray displays a significantly shorter liquid penetration length by approximately 45% than diesel spray. A minor difference between the vapour penetration lengths of gasoline and diesel sprays is observed. It indicates that the difference in physical properties has a small impact on the development of the vapour phase. As for the maximum equivalence ratio of sprays, physical properties have a particular influence on them. The fuel-rich regions in gasoline sprays are likely to generate high soot emissions. This is probably one of the reasons that high soot emissions can be observed when gasoline PPC mode is used at high loads (Manente et al. 2010). Figure 11.5 displays the spray evolution concerning the liquid fluorescence intensity, equivalence ratio and vapour temperature at $P_i = 60$ MPa, $t_i = 1.25$ ms, $T_a = 773$ K and $P_a = 2$ MPa.

The injector nozzle tip is centred on the left side of each image. The fuel is horizontally injected to the right. The region where fuel is in its liquid form is somewhat tiny. The liquid phase disappeared after just a few centimetres of spray penetration.

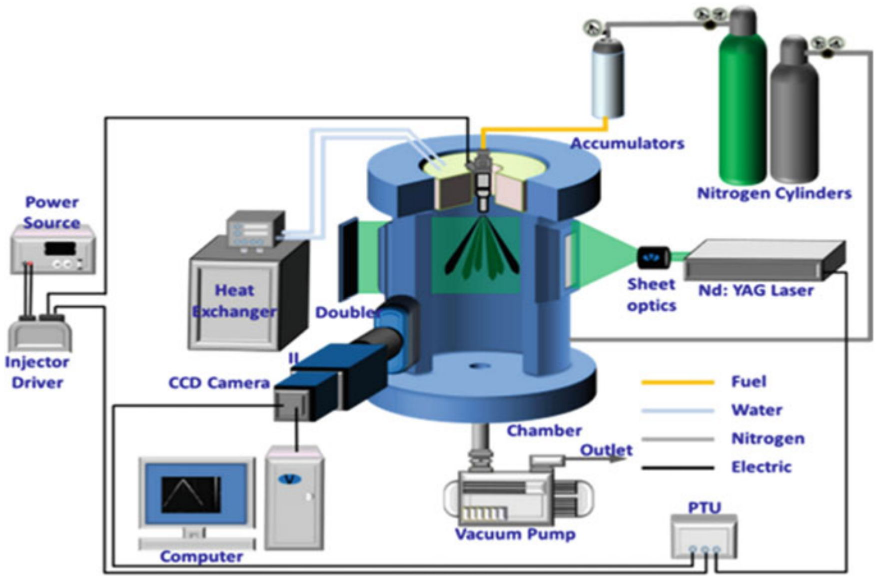


Fig. 11.4 Typical experimental setup for LIF imaging (Chang et al. 2020)

The time it takes for spray velocity and evaporation to equalise is negligible, thanks to the fuel. Hence, there is a slight variation in liquid phase penetration duration over time. They also observed that branch-like structure appeared in the downward liquid phase, highlighted in the white-dotted circle in Fig. 11.5. Locally uneven mixtures, caused by the branched structure formed by shear stress at the interface between liquid phase and surrounding gas, may significantly impact the combustion, performance and emissions (Kosaka et al. 1992).

11.2.4 Mie Scattering Technique

The light elastically scattered by particles with a diameter equal to or bigger than the wavelength of incoming light is called 'Mie scattering'. Mie scattering is directly proportional to the square of exposed particle diameter. Since Mie scattering is much more powerful than Rayleigh scattering, it may act as a source of interference for the latter, which scatters light at a considerably lower efficiency. For practical Mie imaging studies, it is vital to consider the considerable angular dependence of the scattered intensity, which is most pronounced for smaller particles. Mie scattering is a common Particle Image Velocimetry (PIV) method for determining flow speeds. Zhau et al. investigated the spray behaviour in flash boiling conditions for blended alkanes (n-pentane, iso-octane and n-decane) using the Mie scattering technique. A typical schematic of the experimental setup is shown in Fig. 11.6.

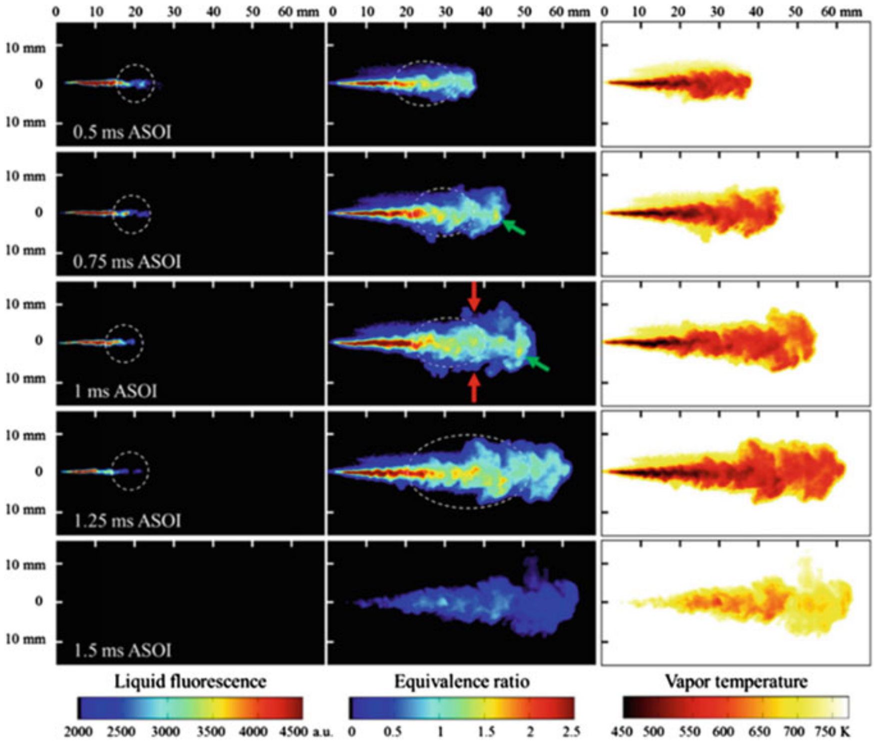


Fig. 11.5 Fluorescence intensity, equivalence ratio and vapour temperature distributions over time for a variety of liquid sprays, while conditions are $P_i = 60$ MPa, $t_i = 1.25$ ms, $T_a = 773$ K and $P_a = 2$ MPa (Feng et al. 2021)

They systematically analyse the macro-spray characteristics for the mixture containing n-pentane, iso-octane and n-decane in different superheated conditions, creating flash boiling phenomena. They also suggested a new superheated index of multicomponent fuel and its impact on the spray structure. Figure 11.7 represents the spray structure of different fuels in ternary plot at various fuel temperatures and 1.0 ms after the start of injection. Subcooled spray refers specifically to spray that mainly retains a single liquid phase. For this scenario, the primary factor in fuel plume separation is the injector orifice's orientation, which determines the flow of fuel plumes. This allows us to differentiate between spray plumes by looking at their cross sections. Figure 11.7 shows that at a fuel temperature of 30 °C, the spray cross patterns of all 15 test fuels are differentiated.

The component percentages of fuel do not heavily impact the spray cross-pattern geometry. Still, n-pentane stands out from the rest of test fuels because its spray plumes are visibly larger and closer together. Although the spray plumes of all test fuels tend to widen and get closer as the fuel temperature rises from 30 to

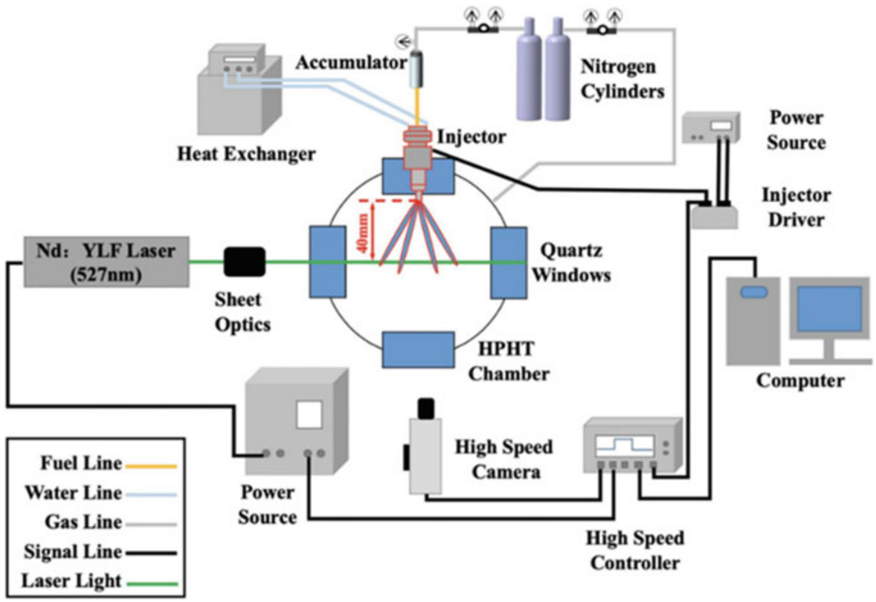


Fig. 11.6 Typical experimental setup for spray imaging using Mie scattering (Zhou et al. 2021)

50 °C, the spray cross pattern of n-pentane goes from being separated to being joined considerably more clearly than other fuels.

11.2.5 *Phase Doppler Interferometry (PDI) Technique*

PDI is an advanced technique for the microscopic characterisation of liquid sprays. It enables measuring the droplet size and velocity distribution, and volume flux at a point within the spray plume. Characterising each droplet that travels through the probe volume and constructing precise ensemble statistics provides the most comprehensive data on the sprays. High spatial resolution measurements may be taken with little disruption owing to the probe volume generated by two (or four) laser beams crossing at a single point. Moving the instrument or nozzle to gather data at many predetermined places is one way to characterise a spray pattern. Data is combined to show spray pattern's overall droplet size and velocity distribution or volume flow. PDI device contains a laser transmitter that sends out two laser beams of same wavelength with a phase difference to intersect at a small point called 'focal volume'. The constructive and destructive interference of two lasers at the intersection creates an interference pattern of a particular frequency. A typical schematic of 3D-PDI is shown in Fig. 11.8.

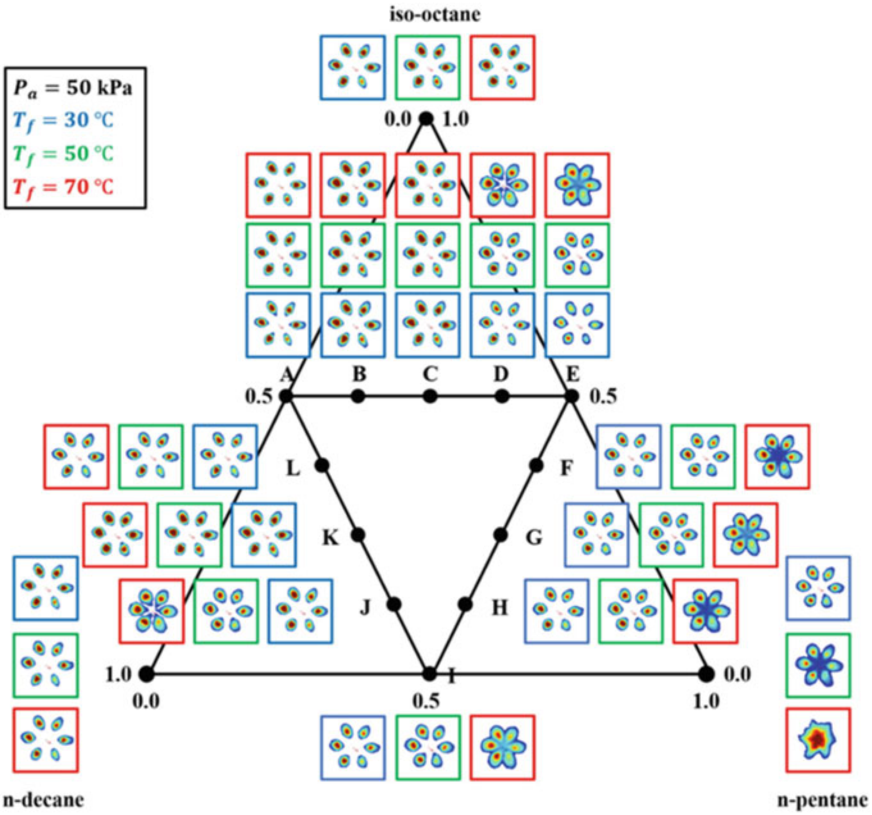


Fig. 11.7 Spray structures of different fuels in ternary plot at various fuel temperatures and 1.0 ms after the start of injection (Zhou et al. 2021)

The PDI instrument's receiver unit detects and analyses the refracted interference pattern caused by a droplet acting as a prism. The high-powered lasers enable measurements within a light-to-medium level of spray droplet density and enable the characterisation of points within spray pattern without losing accuracy due to droplets entering the laser beams outside the laser-intersection region. Extensive data processing is sometimes needed to turn the findings into usable data. Fdida et al. investigated the primary atomisation of cryogenic LOX/nitrogen and LOX/helium sprays and measures droplet size and velocity distributions near the injector (Fdida et al. 2019). Shadowgraphy is generally performed before PDI to visualise the droplet locations and helps to select the region of interest.

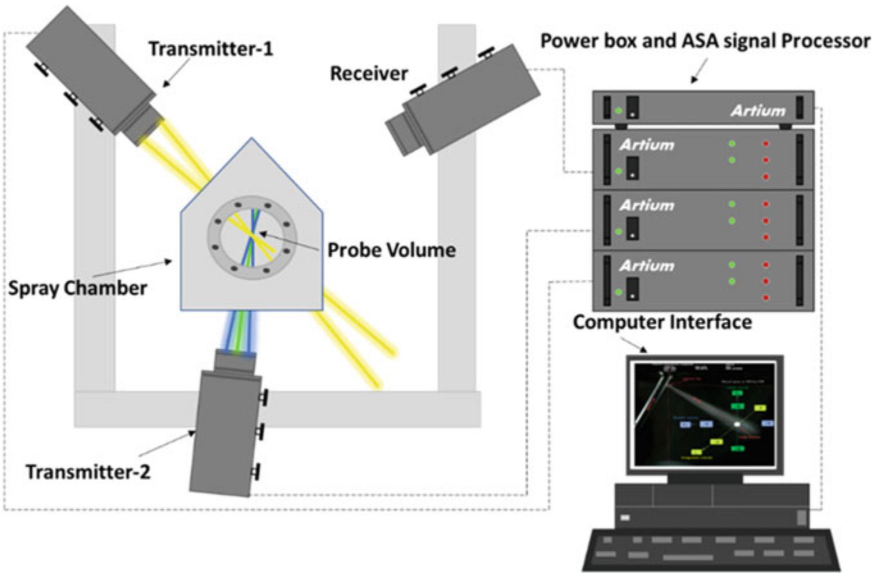


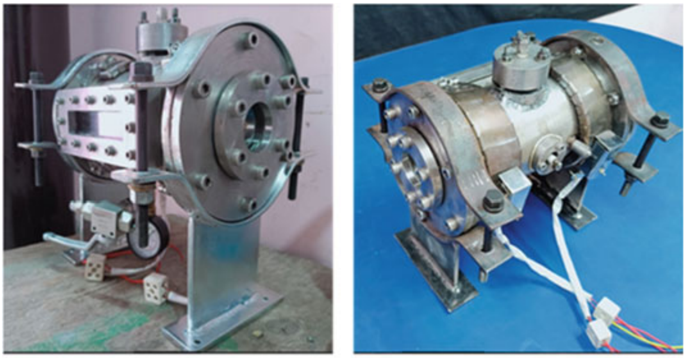
Fig. 11.8 A typical schematic of PDI setup for spray characterisation

11.3 Constant Volume Combustion/Spray Chamber Development

CVC for spray and combustion experiments in a DISI engine under simulated conditions was designed and instrumented at the Engine Research Laboratory (ERL) at IIT Kanpur. The following sections report various CVC's design, development and experimental activities.

11.3.1 General Design Considerations

For spray and combustion fundamental research investigations, constant volume chambers with optical access are preferred. The main objective of designing these chambers is to create environmental conditions similar to actual engines. For instance, the chambers should be capable of producing and withstanding the high pressure-temperature environment similar to engine running at TDC. Therefore, it is crucial to consider high pressure and temperature while designing a constant volume chamber (CVC). Depending on the experimental requirements, CVC might be spherical, cubical, pentagonal or cylindrical. Cylindrical chambers are further classified into horizontal and vertical, depending on orientation. The cylinder and fuel injector axes are parallel in vertical CVC instead of perpendicular in horizontal CVC. The chamber selection also depends on application and optical techniques employed



(a) Isometric view-1 (a) Isometric view-2

Fig. 11.9 Image of the constant volume chamber

for specific investigations. For spray and combustion study the chamber should be equipped with ignition sources, specifically if it simulates the stratified combustion of a DISI engine. The following sub-section will demonstrate the design of CVC capable of simulating stratified and homogeneous combustion of gasoline spray using laser and spark ignition.

11.3.2 Design of Horizontal CVC

CVC was designed to have a volume of 2.98 L, with an inner diameter of 130 mm and a length of 225 mm. It has three optical windows, one for laser ignition (providing access to the laser beam) and the other for visualising the flames. The clear aperture of an optical window is 50 mm, and its thickness is 25 mm. Figure 11.9 shows the image of the developed CVC. Toughened glass is used for optical access to CVC because of its mechanical and thermal strength and low cost. The CVC had four holes machined in its body for housing the pressure sensor, gas filling, spark plug and injector.

11.3.3 Material Selection and Structural Analysis of CVC

Stainless steel is used to manufacture the CVC due to its high corrosion resistance, rust resistance and low strain. Theoretically, spherical vessels are considered superior due to their uniformability to distribute fluid pressure. However, cylindrical vessels are chosen over spherical vessels because cylindrical vessels are easy to fabricate and are economical. A simulation was performed on the CVC model to test its strength under limiting conditions, which helped to determine the window material.

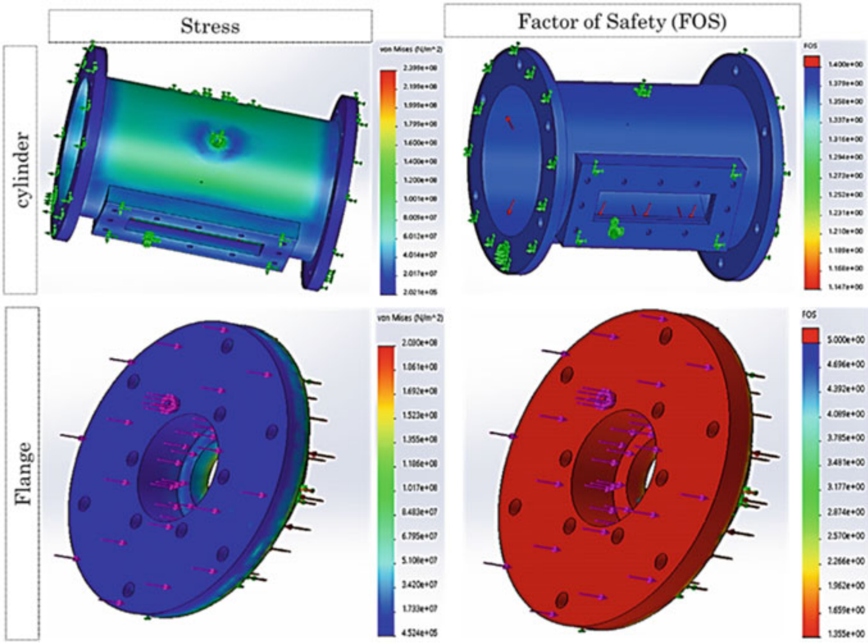


Fig. 11.10 Stress and FoS of main cylinder and associated flanges for side mounting of optical window

The minimum factor of safety (FoS) is set as the deciding parameter in choosing a suitable window material. The minimum FoS for the cylinder and the flange is chosen to be 1.2 and 1.45, respectively. Simulations determined that toughened glass has a reasonable FoS, close to quartz and sapphire, but at a significantly lower cost. Therefore, toughened glass windows are chosen because they offer good mechanical and thermal strength at a reasonable cost. Internal pressure, temperature and bolting stresses are incorporated in determining the structural limits of CVC components. Figure 11.10 shows the CVC component's stress analysis, depicting the points experiencing maximum stress.

11.3.4 Injector and Spark-Plug Assembly

For a spray-guided multi-hole DISI injector, an injector holder is designed, manufactured and installed on CVC. A pneumatic high-pressure pump (Maximator; HTPU-M1-450 SS) is used to inject gasoline at high fuel injection pressure (FIP). Figure 11.11 shows the injector holder and its installation on the CVC. The upper part acts as the common rail for DISI injector.

Fig. 11.11 Injector CAD drawing and installation in the CVC

It is necessary to generate a symmetric spray so that comparative effects of spark and laser ignition can be observed at an exact location within the fuel spray boundary. Spray experiments are conducted to determine the dimensions of injector's axis and optical window. Figure 11.12 shows Mie scattering images of spray in different orientations.

A slot was made in the upper rail to ensure symmetry in the fuel spray. Figure 11.13 shows injector orientation and optical view depicting symmetry w.r.t. laser and the spark plug. The spark plug mount is designed, manufactured and installed on the CVC.

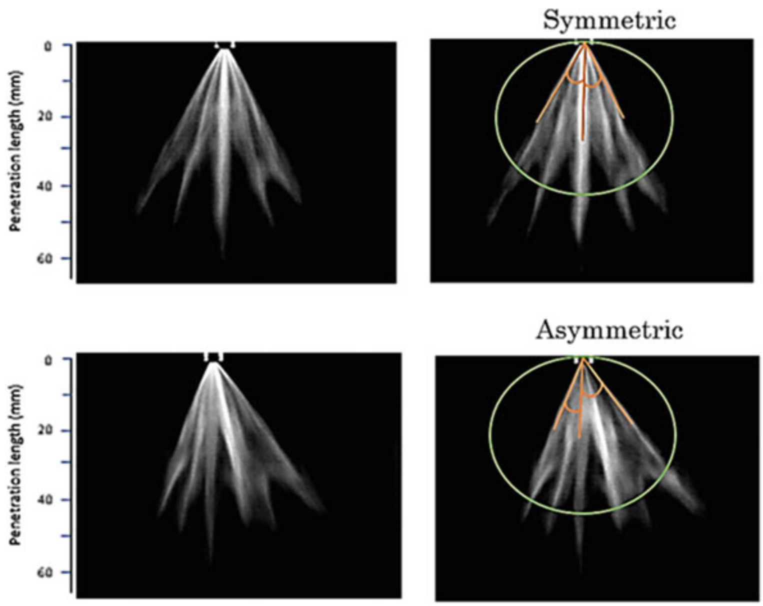


Fig. 11.12 Mie scattering imaging from the front (top row) and side view (bottom row)

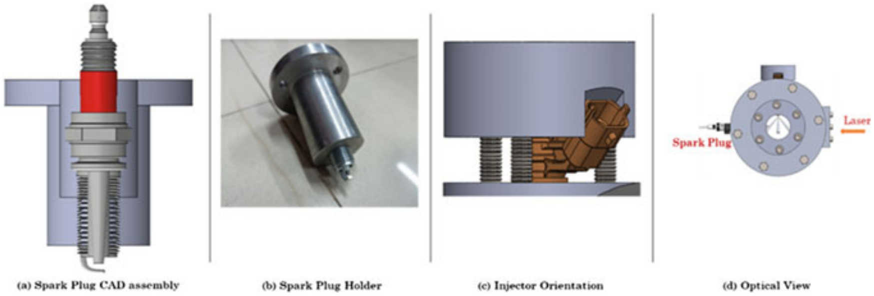


Fig. 11.13 Installation of injector and spark plug in CVC

11.3.5 Structural and Thermal Analyses of Optical Windows

Optical windows provide access to the laser beam and allows flame visualisation. High-pressure gasoline spray penetration length is the primary criterion for selecting the dimensions of optical windows. Figure 11.14 shows the structural analysis of optical windows incorporating clamping forces, internal pressure and chamber temperature.

11.3.6 Manufacturing, Assembly and Testing of CVC

Different sub-systems of CVC, such as injector, spark plug and optical window assembly, are designed, manufactured and assembled. Figure 11.15 shows different views of CAD assembly of CVC.

The CVC is tested at different operating pressures and temperatures. The CVC can be heated up to 200 °C using two-band heaters of 575 W rating. A thermocouple is mounted on CVC to measure the chamber temperature and control it with a precision of ±5 °C. Figure 11.16 shows the temperature measurement and control circuit schematic. CVC is tested to withstand up to 60 bar static pressure. A piezoelectric pressure transducer is mounted onto the CVC, transferring the signal to the high-speed data acquisition system via a charge amplifier.

11.4 Ignition Systems

One of the significant challenges for stratified combustion is to prepare a repeatable fuel–air mixture at the ignition location. This must be done to minimise partial burns or misfires while maximising the stratified combustion efficiency. Another critical factor is the ignition system.

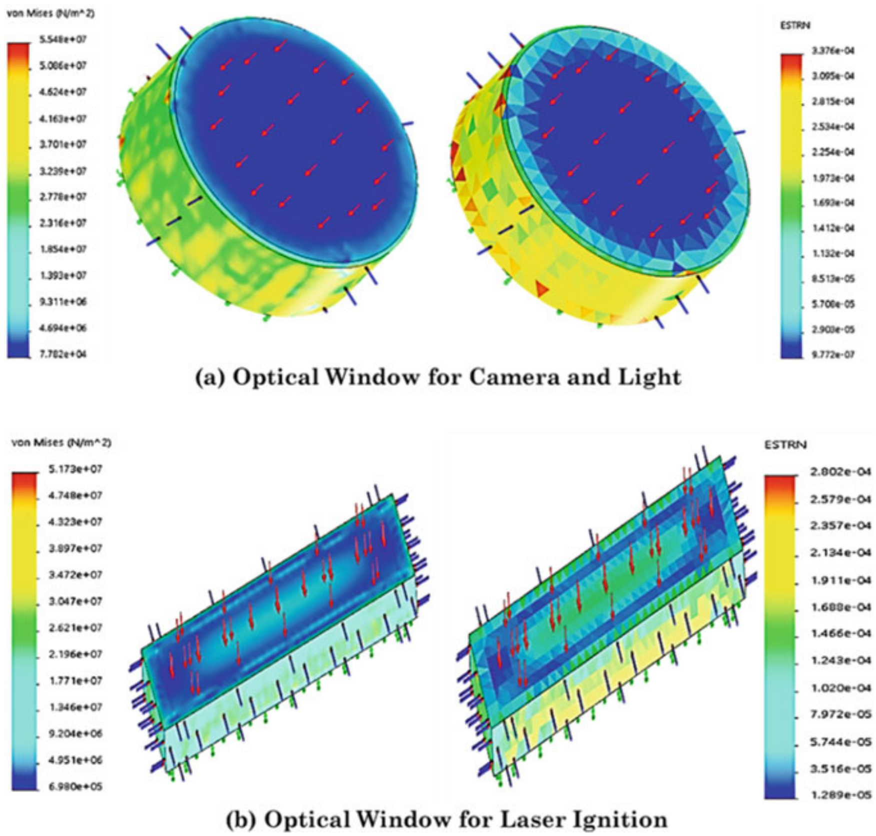


Fig. 11.14 Structural analysis of different windows used for this chamber

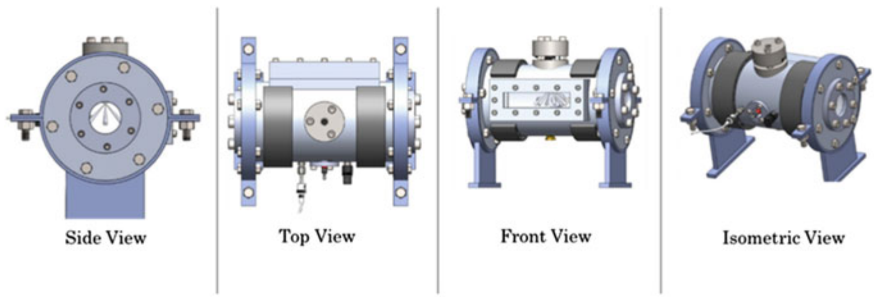


Fig. 11.15 CAD assembly of the CVC

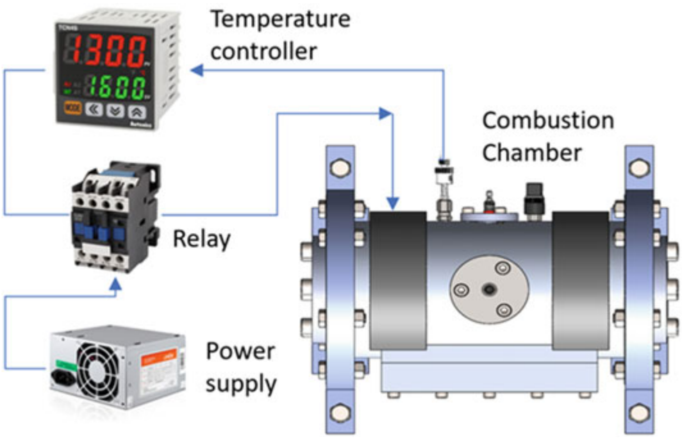


Fig. 11.16 Schematic of temperature measurement and control circuit

11.4.1 Limitations of Spark Ignition

The combustible charge is ionised between the spark plug electrodes in a conventional electric SI system. The spark electrode surface interacts with plasma and may face issues such as erosion of spark plug electrodes. Several factors contribute to the erosion of the spark plug electrodes. These factors include electrode gap, electrode shape and size, fuel type, electrode material, combustion temperature and spark energy. In DISI engines, EGR, globally lean air–fuel mixture, and boost are used to attain high combustion efficiency and low NO_x emissions (Kneifel et al. 2009). These conditions can cause misfiring and combustion instability in electric spark-ignition systems (Piock et al. 2010). In spray-guided combustion systems, the spray is in the proximity of the electrodes, velocity and equivalence ratio distribution gradients are higher at the spark gap and therefore charge can quickly go beyond the ignitability range (Drake et al. 2005; Dahms et al. 2009).

Furthermore, extended spark intervals up to 3 ms and high-velocity variations at the spark gap can cause the spark channel to grow wider (Dahms et al. 2011; Martin et al. 2010), thereby incorporating a wider range of velocity and equivalence ratios. This can cause an early flame development to have an asymmetric shape with substantial cycle-to-cycle variations (Matsumoto et al. 2010). Also, initial flame kernel development and convective motion of the spark channel have a significant role in the misfiring tendency. For successful flame propagation, movement of the flame kernel in the downward and outward direction from the spark plug is necessary (Peterson et al. 2011). The spark plug electrodes can further influence the primary kernel incidents, early flame quenching, upsetting in-chamber flows and promoting irregular flames (Febler et al. 2008; Orlandini et al. 2009). The electrodes are further dependent on spray wetting/choking and enhance the residue formation (Weinberg and Wilson 1971). Moreover, the spark-ignition systems are not very effective in igniting the lean mixture, which frequently occurs in stratified mode. Hence, alternative ignition systems are being extensively developed to improve the lean air–fuel mixtures' ignition and combustion stability.

11.4.2 Laser Ignition

This section discusses the fundamental advantages of laser ignition systems over conventional spark-ignition systems. A laser can ignite very lean mixtures, leading to low combustion temperatures and lower NO_x emissions. There is no issue of erosion of spark plug electrodes, leading to a prolonged lifespan of the laser ignition system. Unlike traditional spark ignition, the threshold for optical breakdown decreases with increasing ambient pressure (Bradley et al. 2004). Laser ignition supports ignition pressures as high as 35 bar, leading to improve the engine efficiency. There is flexibility in choosing the ignition location, which can be used to focus on the combustion location to reduce the maximum flame travel distance. This may lead to higher efficiency, specifically in very lean mixtures. A single laser source may be converted to a multipoint ignition system to enhance the combustion of a lean mixture with greater efficiency (Dale et al. 1978; Ryu et al. 2009; Phuoc 2000; Morsy and Chung 2003; Morsy et al. 2001). Ignition timing can be precisely controlled for high engine efficiency.

Compared to the electric spark, a short ignition delay has been observed for laser ignition (Grob et al. 2009). There is a heat loss while transferring the spark energy through electrodes to the flame kernel. Laser ignition permits the maximum energy transfer to the flame region by eliminating the heat loss from the electrodes. Also, it was observed that flames produced by a laser source could travel up to 20 times faster than unstretched laminar flames (Bradley et al. 2004). Rapid flame growth and quicker ignition can reduce cyclic variations and combustion duration. Since the laser ignition system includes smaller components, it eliminates the need for extra space in the cylinder head, leading to the feasibility of having larger valves, hence contributing to even higher efficiency engine development. Laser ignition offers significant prospects for improving engine combustion (Dearden and Shenton 2013). Different aspects must be fully exploited to develop an optimised laser ignition system control, such as laser delivery to the focal point, optical sensing and the development of inexpensive high-energy lasers. The opportunity for feedback control and optical sensing makes laser ignition exciting in the following areas:

(a) Ignition passage through the cylinder head can be easily optimised for laser ignition since fewer critical components than in conventional spark-ignition systems. This may lead to increased intake and exhaust valve sizes. The laser beam's cylinder entry part could be smaller than a spark plug.
(b) By focussing the laser beam via optical elements to the appropriate point, the ignition location can be dynamically changed, allowing a deeper ignition location than a conventional spark plug. The condensed ceramic lasers can deliver

multipoint ignition at predetermined locations, and the provision that the pump energy variations in the laser array can control the pulse timing (Tsunekane et al. 2011). Using a single laser beam, diffused optical elements can form plasma at multiple locations in the combustion chamber. Evolving technologies, such as liquid lenses, can automatically change their focus when sufficient voltage is applied. The liquid lenses provide sharp images by changing the focal point in a fraction of a second. Further evolution of these techniques could change the focal position to incorporate various engine operating conditions. This could be beneficial in DISI engines where optimised ignition location can be chosen for stratified or homogenous engine operation.

(c) With recent progress in high-frequency lasers such as fibre lasers, laser ignition systems of the future have the potential to deliver multiple pulses during a combustion cycle. Likewise, multiple spark discharges have been extensively researched for stratified and homogenous combustion. A high-frequency laser system precisely handles several pulses and pulse timings, and delivers quick sparks as required.

(d) The laser ignition system potentially offers an optical route in and out of the combustion chamber because of its self-cleaning nature. This visual pathway will monitor the light produced from the combustion event and analyse different combustion parameters through pattern recognition, signal processing and optical sensing methods. LIF and LII are being explored, but their complexity and high costs are significant factors for slower progress. In theory, all these methods can be used for real-time, online feedback control of the combustion using laser ignition in IC engines.

Despite numerous advantages, laser ignition has several challenges and drawbacks. The lasers have a high upfront cost. Mass production and the evolution of inexpensive lasers can make laser delivery systems cheaper. Therefore, it could be used commercially in practical engines. The robustness of the optical windows via which the beam is directed into the chamber is essential (Dearden and Shenton 2013; Ranner et al. 2007). The optical windows should sustain high pressure and temperature (Phuoc 2005). Transmittivity of the laser beam reduces due to carbon residue formation on the optical surfaces, which might lead to engine misfires.

11.5 Spray and CVCC Studies

Successful stratified engine operation depends heavily on the injection and ignition systems. It is challenging to produce a repeatable charge cloud at the ignition point. This section focuses on improving ignition systems for a successful stratified operation. Spark energy can be increased to ensure successful ignition, but surroundings in the vicinity of spark plug pose many challenges, such as high air velocities and wet electrodes. These lead to flames getting extinguished. The residual energy in a single coil ignition system is low, due to which this system cannot re-ignite the extinguished flames.

11.5.1 Spark-Ignited Direct-Injected Gasoline Spray

Spark breakdown occurs within the spark plug electrodes, which triggers the combustion. The high voltage generated between the spark plug electrodes creates an electric field that produces a highly conductive thin plasma after the breakdown. This conductive film allows free electrons to move and collide with air molecules in the spark plug gap. Thus, ionising them and generating more free electrons lead to an exponential growth of electrons, called an avalanche. Then localised charge strength controls the laminar burning speed that defines flame kernel evolution. This localised charge composition governs the premixed combustion, whereas the remaining fuel-lean charge supports the flame growth. Several challenges exist in the spark-ignited DI, preventing the success of stratified combustion (Peterson et al. 2011). Airflow motion has a severe impact on the ignition breakdown.

11.5.2 Laser-Ignited Direct-Injected Gasoline Spray

It is challenging to ignite stratified charge successfully using a laser in DISI engines. When moving to spray-guided operation, Grob et al. (2009) and Febler et al. (2008) discovered similar combustion stability and ignition delay for laser and spark plug-induced ignition, even slightly quicker ignition and flame development with laser. The similarities of these ignition systems emerge as plasma in each case combines with rich charge where the ignition delay is short. Furthermore, intermittent misfire is reported with LI, whereas no misfire observed in spark ignition. The rationale behind these occasional misfires is unknown, although they thought it to be caused by the dynamics of laser-driven ignition compared to turbulence-stratified fuel spray mixing. A high-energy Q-switched laser pulse will be ~10 ns and concentrated into a diameter of a few microns to attain the plasma breakdown. In contrast, an electric spark discharge can persist up to 2–3 ms (Dahms et al. 2009; Sick et al. 2010), with the spark channel spanning up to 10 mm in a turbulent flow. Air–fuel equivalence ratio and velocity distribution near the spark-ignition point will likely be outside the ignitability range.

This is because of the superimposition of stratified flow's turbulence and the condensed space–time scales. Although condensed space–time scales have hampered laser ignition in stratified operated engines, these parameters only helped to understand the conditions affecting successful combustion. The spark channel can last up to 24 CAD for a spark time interval of 2 ms at 2000 rpm. Localised airflow conditions are bound to change dramatically throughout this time, making it difficult to comprehend the impact of localised equivalence ratio, turbulence and air motion in the combustion processes. Soot and NO_x emissions can be improved along with the accurate monitoring of ignition timing. This provides precise charge formation, improving combustion. Due to its short spark duration, Grob et al. (2009) found incorporating laser ignition in DISI engines challenging. This is because the spark kernel generated by the laser is generally located in either too-rich or too-lean mixture regions outside the ignition range. Optimal laser spark location and injection parameters significantly enhance the ignition. Laser-induced ignition is currently not a viable alternative to traditional electrical ignition because of its short spark duration. Due to its proximity to the spray, mixture enrichment at the spark location has a negative impact on the heat release. Grob et al. (2009) investigated that laser spark position significantly affected combustion. Ignition timings vary according to variations in ignition location to achieve successful stratified combustion. Since the spark interval is short, cycle-to-cycle variations cannot be controlled even in a conventional SI system. A computation model showed that even high laser energy could not reduce the possibility of a misfire beyond a specific limit. The strain rate in the in-cylinder air flow affecting the LI might be the reason. Other laser variations, such as using a double spark, should be investigated to improve the possibility of laser ignition in DISI engines. Several optical approaches could explore the feasibility of combustion using the laser. This will entail researching the laser spark's lifespan and initial stages of flame kernel growth. A computer model is developed to understand the transport mechanisms and chemical reactions involved in laser-induced combustion. The model helps us understand the flame front growth of self-sustaining reactions produced by laser-induced plasma. The ignitability range could be calculated as a function of various characteristics using parametric analyses. The calculated ignition maps demonstrated that laser-induced ignition is extremely sensitive to the equivalence ratio and the degree of heat dissipative effects that transfer the particles out of the hot laser plasma. Ignition failure is more likely in lean mixtures than in rich ones. Some studies observed random misfires, even in homogenous charge operation, attributed to localised velocity fluctuations. Calculating ignition limits for turbulent flow will be one of the next steps in the research. The impact of kernel shape on subsequent flame development will also be examined. This job will need two-dimensional calculations, allowing for a more detailed examination of the effect of non-homogeneous flow fields around the hot kernel. Genzale et al. (2011) studied laser ignition at various timings of stratified gasoline spray (Genzale et al. 2011). Experiments were conducted in a cubical CVC under replicated DISI engine conditions. A Bosch automotive DISI injector is used for high injection spray.

Figure 11.17 shows the laser ignition at 340 μs AEOI at an injection duration of 1.2 ms. The green and white curves represent the liquid and axial vapour boundaries. The liquid droplets move downstream of the ignition location at nearly 300 μs, suggesting that vaporised air–fuel mixture is present at the ignition location. The laser plasma becomes visible at 340 μs, and the flame propagates away from the injector tip towards a rich charge. They summarised that laser ignition is impossible until 250 μs AEOI. Before 250 μs, the plasma gets formed and extinguishes quickly. The rationale behind this is the presence of a rich mixture that leads to unwanted flame evolution. Ignition is possible when the charge becomes leaner AEOI, and the

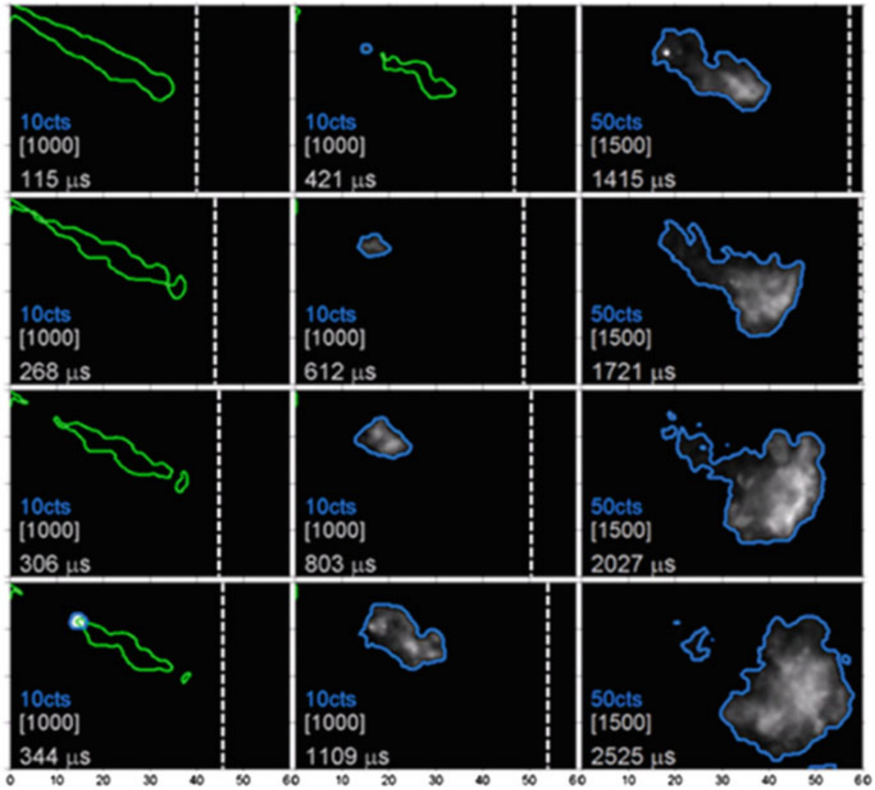


Fig. 11.17 Flame kernel images of gasoline spray with laser ignition (Genzale et al. 2011)

fuel droplets evaporate. However, a reduction in combustion efficiency is observed with more delay in the laser timings. The main charge gets away from the ignition location, and the charge becomes leaner at the ignition location, which might be a reason for the reduction in combustion efficiency.

11.6 Conclusions and Future Directions

With the advancements in engine technology, several methodologies are being adopted by the research community to fulfill the energy demand with reduced emissions. DISI technology has proven to improve engine performance with fuel economy. Stratified and homogeneous modes are the two basic operating modes of DISI engine. In the stratified mode operating DISI engine, laser ignition can extend the lean limit further. Fuel is delivered early in the intake stroke in homogeneous charge mode. Early fuel injection allows appropriate fuel–air mixing, resulting in the formation of a homogeneous charge. This mode is employed when the engine runs at high speeds and loads. Fuel is injected later in the compression stroke when the engine is in stratified mode to provide an ignitable charge close to the spark plug. Less fuel is fed into the engine in the stratified mode compared to the homogeneous mode since it is employed at lower loads and speeds. However, since fuel is injected directly, it requires adequate fuel–air mixing, which dictates the combustion characteristics. Hence, spray characterisation is required to assess the potential of laser ignition in the stratified mode operation. Various optical techniques are discussed for the fundamental spray and combustion investigations. It was recommended that for assessing the charge distribution using microscopic characteristics, the shadowgraphy technique is quite useful, requiring very few optical components. However, the Schlieren imaging technique is preferable for capturing the blue flames and minor density gradients. Different types of CVCs are discussed. A case study of a horizontal cylinder CVC design is also included. By enabling the ignition of prolonged lean fuel–air combinations, combustion gets enhanced. The choice of an ignition site within the CVC remains flexible using an LI system. By using converge lenses of various focal lengths or moving the converge lens within the plug in direction of laser beam, the location of ignition point may be adjusted. Laser ignition coupled with the stratified mode of operation certainly can increase the combustion efficiency by enabling multipoint laser ignition. However, several challenges associated with optics and laser beam delivery must be considered.

References

Baumgarten C (2006) Mixture formation in internal combustion engines. Springer Science & Business Media. https://doi.org/10.1007/3-540-30836-9_6

Bradley D, Sheppard CGW, Suardjaja IM, Woolley R (2004) Fundamentals of high-energy spark ignition with lasers. Combust Flame. https://doi.org/10.1016/J.COMBUSTFLAME.2004.04.002

Chang M, Lee Z, Park S, Park S (2020) Characteristics of flash boiling and its effects on spray behaviour in gasoline direct injection injectors: a review. Fuel. https://doi.org/10.1016/j.fuel.2020.117600

Dahms R, Fansler TD, Drake MC, Kuo TW, Lippert AM, Peters N (2009) Modeling ignition phenomena in spray-guided spark-ignited engines. Proc Combust Inst. https://doi.org/10.1016/J.PROCI.2008.05.052

Dahms RN, Drake MC, Fansler TD, Kuo TW, Peters N (2011) Understanding ignition processes in spray-guided gasoline engines using high-speed imaging and the extended spark-ignition model SparkCIMM. Part A: Spark channel processes and the turbulent flame front propagation. Combust Flame. https://doi.org/10.1016/j.combustflame.2011.03.012

Dale JD, Smy PR, Clements RM (1978) Laser ignited internal combustion engine—An experimental study. SAE Technical Papers. https://doi.org/10.4271/780329

Dearden G, Shenton T (2013) Laser ignited engines: progress, challenges and prospects. Opt Express. https://doi.org/10.1364/OE.21.0A1113

Drake MC, Fansler TD, Lippert AM (2005) Stratified-charge combustion: modelling and imaging of a spray-guided direct-injection spark-ignition engine. Proc Combust Inst. https://doi.org/10.1016/J.PROCI.2004.07.028

Duronio F, De Vita A, Allocca L, Anatone M (2020) Gasoline direct injection engines–A review of latest technologies and trends. Part 1: Spray breakup process. Fuel. https://doi.org/10.1016/j.fuel.2019.116947

Farron C, Matthias N, Foster D, Andrie M, Krieger R, Najt P et al (2011) Particulate characteristics for varying engine operation in a gasoline spark ignited, direct injection engine. In: SAE world congress and exhibition. https://doi.org/10.4271/2011-01-1220

Fdida N, Mauriot Y, Vingert L, Ristori A, Theron M (2019) Characterising primary atomisation of cryogenic LOX/Nitrogen and LOX/Helium sprays by visualisations coupled to Phase Doppler Interferometry. Acta Astronaut. https://doi.org/10.1016/j.actaastro.2018.12.029

Febler M, Wetzel M, Schenk M, Rottengruber H, Huhn W (2008) Determination of thermodynamic potentials for alternative ignition systems in spray-guided combustion. In: Proceedings of the 8th international symposium on internal combustion engine diagnostics

Feng L, Sun X, Pan X, Yi W, Cui Y, Wang Y, Wen M, Ming Z, Liu H, Yao M (2021) Gasoline spray characteristics using a high-pressure common rail diesel injection system by the method of laser-induced exciplex fluorescence. Fuel. https://doi.org/10.1016/j.fuel.2021.121174

Laser Induced Fluorescence (Lavision). https://www.smart-piv.com/en/techniques/lif-plif/#:~:text=Planar%20Laser%20Induced%20Fluorescence%20(PLIF,processes%2C%20sprays%20and%20combustion%20systems. Accessed 10th Nov 2022

Genzale CL, Pickett LM, Hoops AA, Headrick JM (2011) Laser ignition of multi-injection gasoline sprays. SAE World Congress and Exhibition. https://doi.org/10.4271/2011-01-0659

Grob V, Kubach H, Spicher U, Schiebl R, Maas U (2009) Influence of laser-induced ignition on spray-guided combustion—Experimental results and numerical simulation of ignition processes. SAE Technical Papers. https://doi.org/10.4271/2009-01-2623

Huegel P, Kubach H, Koch T, Velji A (2015) Investigations on the heat transfer in a single cylinder research SI engine with gasoline direct injection. SAE Int J Engines. https://doi.org/10.4271/2015-01-0782

Kneifel A, Buri S, Velji A, Spicher U, Pape J, Sens M (2009) Investigations on supercharging stratified part load in a spray-guided DI SI engine. SAE Int J Engines. https://doi.org/10.4271/2008-01-0143

Kosaka H, Won YH, Kamimoto T (1992) A study of the structure of diesel sprays using 2-D imaging techniques. SAE Trans. https://doi.org/10.4271/920107

Kumar TS, Ashok B (2021) Critical review on combustion phenomena of low carbon alcohols in SI engine with its challenges and future directions. Renew Sustain Energy Rev. https://doi.org/10.1016/j.rser.2021.111702

Kumar D, Agarwal AK (2022) Fundamentals, evolution, and modeling of ignition systems for spark ignition engines. In: Agarwal AK, Kumar D, Sharma N, Sonawane U (eds) Engine modeling and simulation. energy, environment, and sustainability. Springer, Singapore. https://doi.org/10.1007/978-981-16-8618-4_9

Kumar D, Sonawane U, Chandra K, Agarwal AK (2022) Experimental investigations of methanol fumigation via port fuel injection in preheated intake air in a single-cylinder dual-fuel diesel engine. Fuel. https://doi.org/10.1016/j.fuel.2022.124340

Lee S, Kim G, Bae C (2021) Behavior of hydrogen hollow-cone spray depending on the ambient pressure. Int J Hydrog Energy. https://doi.org/10.1016/j.ijhydene.2020.11.001

Manente V, Tunestal P, Johansson B, Cannella WJ (2010) Effects of ethanol and different type of gasoline fuels on partially premixed combustion from low to high load. In: SAE World Congress and Exhibition. 10.4271/2010-01-0871

Martin H, Helmut T, Tobias B, Frank A, Harald W (2010) Influence of a multi-spark ignition system on the inflammation in a spray-guided combustion process. SAE Int J Fuels Lubr. https://doi.org/10.4271/2009-24-0117

Matsumoto A, Zheng Y, Xie X bin, Lai MC, Moore W (2010) Characterization of multi-hole spray and mixing of ethanol and gasoline fuels under di engine conditions. SAE Technical Papers. https://doi.org/10.4271/2010-01-2151

Morsy MH, Chung SH (2003) Laser-induced multipoint ignition with a single-shot laser using two conical cavities for hydrogen/air mixture. Exp Thermal Fluid Sci. https://doi.org/10.1016/S0894-1777(02)00252-2

Morsy MH, Ko YS, Chung SH, Cho P (2001) Laser-induced two-point ignition of premixture with a single-shot laser. Combust Flame. https://doi.org/10.1016/S0010-2180(00)00218-2

Orlandini I, Gartung K, Schlerfer J (2009) Application of 3D-CFD simulations in the development of spark plugs. SAE Technical Papers. https://doi.org/10.4271/2009-01-0706

Peterson B, Reuss DL, Sick V (2011) High-speed imaging analysis of misfires in a spray-guided direct injection engine. Proc Combust Inst. https://doi.org/10.1016/J.PROCI.2010.07.079

Phuoc TX (2000) Single point versus multipoint laser ignition: experimental measurements of combustion times and pressures. Combust Flame. https://doi.org/10.1016/S0010-2180(00)00137-1

Phuoc TX (2005) A comparative study of the photon pressure force, the photophoretic force, and the adhesion van der Waals force. Optics Commun. https://doi.org/10.1016/J.OPTCOM.2004.10.047

Piock WF, Weyand P, Wolf E, Heise V (2010) Ignition systems for spray-guided stratified combustion. SAE Int J Engines. https://doi.org/10.4271/2010-01-0598

Ranner H, Tewari PK, Kofler H, Lackner M, Wintner E, Agarwal AK et al (2007) Laser cleaning of optical windows in internal combustion engines. https://doi.org/10.1117/1.2793704

Ryu SK, Won SH, Chung SH (2009) Laser-induced multipoint ignition with single-shot laser using conical cavities and prechamber with jet holes. Proc Combust Inst. https://doi.org/10.1016/J.PROCI.2008.05.080

Settles GS (2001) Shadowgraph techniques. In: Schlieren and shadowgraph techniques. Experimental fluid mechanics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-56640-0_6.

Sick V, Drake MC, Fansler TD (2010) High-speed imaging for direct-injection gasoline engine research and development. Exp Fluids. https://doi.org/10.1007/S00348-010-0891-3/FIGURES/15

Tsunekane M, Pavel N, Taira T (2011) Composite, all-ceramics, high-peak power Nd:YAG/Cr4+:YAG monolithic micro-laser with multiple-beam output for engine ignition. Opt Express. https://doi.org/10.1364/OE.19.009378

Weinberg FJ, Wilson JR (1971) A preliminary investigation of the use of focused laser beams for minimum ignition energy studies. Proc R Soc London. Math Phys Sci. https://doi.org/10.1098/RSPA.1971.0012

Whitaker P, Kapus P, Ogris M, Hollerer P (2011) Measures to reduce particulate emissions from gasoline DI engines. SAE Int J Engines. https://doi.org/10.4271/2011-01-1219

Zhou X, Zhai Q, Hung DL, Li X, Xu M (2021) Study of component proportion effects on flash boiling atomisation with ternary-alkane fuel mixtures. Fuel. https://doi.org/10.1016/j.fuel.2021.120798