Chapter 9
Fundamentals, Evolution, and Modeling of Ignition Systems for Spark Ignition Engines

Dhananjay Kumar and Avinash Kumar Agarwal

Abstract The advancement of technologies has led researchers to explore new ways to comply with stringent emission norms globally and fulfil the energy requirements. The trends in engine development favour computational studies for initial investigations due to lesser time demand and economy. In a spark ignition (SI) engine, ignition of the fuel–air mixture is achieved by the spark discharge across the spark plug electrodes. The discharge is of very high intensity for a very short interval, providing sufficient energy in the form of plasma kernel to initiate chemical reactions necessary to generate a self-sustaining flame. Direct injection SI combustion system is considered an upcoming next-generation technology capable of meeting stringent emission norms with improved engine performance. Conventional spark plug system undergoes various issues such as erosion of spark plug, heat losses at the electrodes, hindrance in working at high in-cylinder pressures, and fixed spark location. Therefore, the researchers explore alternate ignition concepts/ systems that provide greater flexibility than conventional ignition systems. These alternate ignition concepts/ systems include laser ignition, turbulent jet ignition, corona ignition, and microwave ignition. These all are also referred to as advanced ignition systems. Advanced ignition has emerged as an alternative way to ignite leaner fuel–air mixture owing to higher engine performance and lower emissions. These systems offer significant advantages; however, they are still under research, and many challenges need to be overcome before they are commercialized. In this chapter, the evolution of the spark ignition systems has been discussed. Modelling aspects of spark ignition engines using 1D and 3D simulation tools have been summarised. The working of these advanced ignition systems has been discussed in detail, and their challenges are also summarised.

Keywords Advance ignition system · Modelling · Spark ignition engine · Laser ignition · Turbulent jet ignition

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Abbreviations

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
bTDC	Before Top Dead Centre
BSFC	Brake Specific Fuel Consumption
CAD	Crank Angle Degree
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CPOA	Cylinder Pressure Only Analysis
CW	Continuous Wave
EGR	Exhaust Gas Recirculation
ECU	Electronic Control Unit
IC	Internal Combustion
SI	Spark Ignition
GDI	Gasoline Direct Injection
H_2	Hydrogen
HCNG	Hydrogen Enriched Compressed Natural Gas
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
LI	Laser Ignition
MFB	Mass Fraction Burned
NOx	Oxides of Nitrogen
TPA	Three Pressure Analysis
TKE	Turbulent Kinetic Energy
TJI	Turbulent Jet Ignition
R-L-C	Resistance-Inductance-Capacitance

9.1 Introduction

Future generation spark-ignition (SI) engines would have higher power output with lesser emissions to meet the emission norms adopted by various legislative bodies. The compression ratio of the SI engine is significantly lower than the compression ignition (CI) engine, resulting in lower temperature and pressure conditions in the combustion chamber at the end of the compression stroke. The self-ignition temperature of high-octane/ low-cetane fuel is high, which requires an ignition source to ignite the fuel–air mixture inside the combustion chamber. Close to the end of the compression stroke, electrical discharge produced between the two spark plug electrodes is responsible for initiating the SI engine's combustion process. Spark plug creates a high-temperature plasma kernel in the thin reaction sheet (between the central and ground electrodes). This plasma kernel develops into a self-sustaining flame front. The spark needs to be produced repeatedly over a range of speeds and loads at an appropriate crank angle of the engine cycle to ensure smooth engine running. The ignition process is a small-scale local phenomenon in a small zone inside the engine combustion chamber.

9.1.1 Importance and Challenges of Ignition System

In the SI engine, ignition of the fuel–air mixture is achieved by spark discharge across the spark plug electrodes. The discharge is of very high intensity for a very short interval, providing sufficient energy in the form of heat to initiate chemical reactions necessary to generate a self-sustaining flame. The heat released from the chemical reactions must be greater than the heat losses across the cylinder walls, spark plug electrodes, and unburnt gases. There is a need for higher power output with the existing engines with the same smoothness level at idle and part loads. With an ideal thermodynamic cycle for SI engines, three primary ways of improving engine efficiency are: (i) increasing the engine's compression ratio or (ii) burning the leaner mixture by adapting EGR or (iii) employing a superior ignition system. Both stratified and homogenous approaches are used to adapt to the burning of the leaner mixture. Moreover, they differ by the needs of engine demand for the burning processes. For the stratified mode of operation, spray formation provides favourable conditions at the location of the ignition.

Furthermore, spatial and temporal variations in charge distribution exist near the spark plug's tip (Scarcelli et al. 2016). Therefore, an appropriate ignition system preferably covers considerable space and multiple bursts to average the fluctuations due to each cycle's spatial and temporal charge variations. For the homogeneous mode operation, fuel injection starts early, and mixture gradients are quite small. Therefore lesser spatial variations of charge are present, resulting in a longer delay period. To have smoother and faster combustion, higher levels of turbulence and charge motion are generally desirable.

Moreover, higher turbulence also increases the heat loss near the cylinder wall. For the ignition process, the ability to adapt to turbulence is essential for efficient combustion. In tumble dominated SI engines, the tumble breaks down to reduce the TKE at the TDC. Resolving this breakdown (through finer meshes and correct turbulence models) is important for accurate spark modelling. In other words, the ignition system should cope with both leaner and richer mixtures with different turbulence levels. Lean combustion offers a considerable reduction in emissions and fuel consumption at part load operation. However, igniting the extended leaner mixture imposes several challenges to the conventional ignition systems. Another key challenge of critical consideration is the capability to adapt to the transient behaviour of the engine at different loads. The particle formation during combustion and probability of ignition components fouling is of significant importance under the

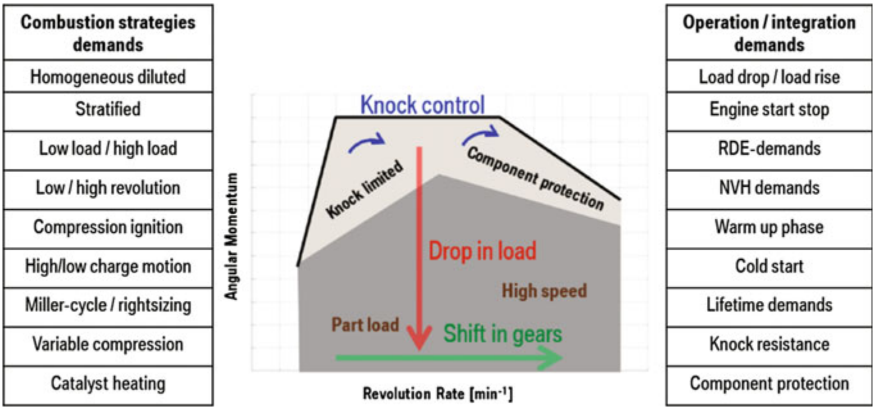


Fig. 9.1 Challenges and demands associated with modern SI combustion systems (Schenk et al. 2017)

dynamic engine operating conditions of the engine. Figure 9.1 summarises major challenges associated with the ignition systems at different engine loads (Schenk et al. 2017).

9.1.2 Evolution of Ignition System

An ignition system involves electrical/ electronic components to ignite the fuel–air mixtures in the engine cylinder. In 1860, Etienne Lenoir demonstrated the first internal combustion (IC) engine (gas engine) integrated with an electrical spark plug (History of the Ignition System 2021). Tesla (1898) patented the first spark plug. Bosch's (1902) invented the spark plug capable of producing high voltage and commercialized it as a part of the magneto ignition system for IC engine applications. After that, the basic magneto system was improved and integrated with a replaceable battery. Then the battery ignition systems came into the picture ~ 1910. The battery-operated coil, capacitors, contactor points, and distributer were integrated to achieve the breakdown voltage necessary to achieve electrical plasma ignition.

Nowadays, modern ignition systems are used in vehicles that employ electronic ignition instead of mechanical devices like contactor points. These systems are becoming more advanced with time and providing flexibility in controlling the ignition timing. A modern ignition system can be coupled to a computer interface for real-time observation, and also it can be programmed for optimizing the engine power/ torque output. With tightening emission legislations and higher power requirements, the ignition of extended lean burning of fuel–air mixture poses increasing challenges to these modern ignition systems. Conventional spark plug ignition systems face several challenges such as erosion of spark plug, heat losses at the electrodes, hindrance in working at high cylinder pressures, fixed spark location (Soldera et al.

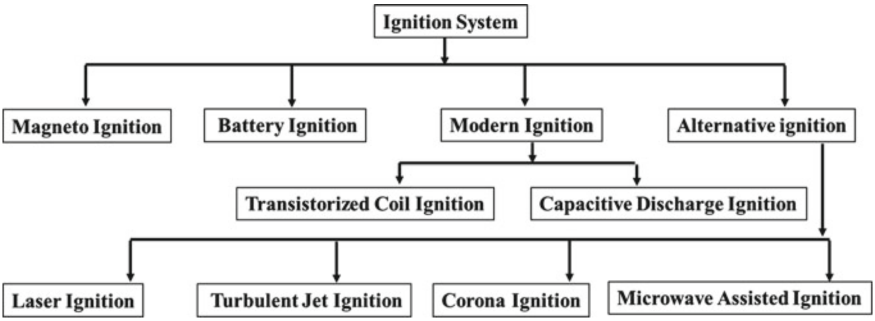


Fig. 9.2 Evolution of ignition system for IC engine applications

2004; Pischinger and Heywood 1990). Therefore, several researchers have explored alternate ignition systems that provide greater flexibility over conventional ignition systems. These alternate ignition systems include laser ignition (LI) (Vasile and Pavel 2021; Singh et al. 2020; Kumar and Agarwal 2020; Prasad and Agarwal 2021; Wermer et al. 2021; Prasad and Agarwal 2021), turbulent jet ignition (Attard et al. 2010; Gholamisheeri et al. 2017; Taskiran 2020; Distaso et al. 2020; Biswas and Ekoto 2019), corona ignition (Cimarello et al. 2017; Cruccolini et al. 2020; Vinogradov et al. 2008), and microwave ignition (Hwang et al. 2017, 2021; Chen et al. 2020). These are also referred to as advanced ignition systems. These systems offer significant advantages; however, these are still under development, and several technical challenges need to be addressed before being commercialized in practical vehicles. These advanced ignition systems have been discussed in detail in the following sections. Figure 9.2 categorizes different advanced ignition systems for IC engine applications and their evolution pathways.

9.2 Ignition Process

Four phases of spark generation were suggested by Maly (1984). These phases consisted of pre-breakdown, breakdown, arc, and glow discharge (Maly 1984). Pre-breakdown refers to the initial phase when the electric field between the electrodes increases continuously for few microseconds. The breakdown phase (~nanosecond range) occurs in the electrode gap when the electric field reaches the conductivity threshold of the air–fuel mixture present in the nearby volume. The required maximum voltage developed in the breakdown phase is referred to as the 'breakdown voltage.' Various parameters contribute to the breakdown voltage, including the fuel–air mixture strength, fuel type, engine load, electrode temperature, electrode orientation, etc. For instance, gaseous fuels such as H_2, CNG, HCNG, etc., require higher breakdown voltage than liquid fuels such as gasoline, methanol, etc. Also, for the leaner mixtures, the required breakdown voltage is much higher than the richer mixture since the leaner mixtures possess more air, which reduces the electrical conductivity in the electrode gaps.

The temperature in this phase reaches in the range of (50–60 × 10^3) K (Fernandes et al. 2016). This phase of spark generation is particularly important for combustion. After the breakdown for a particular cycle, a sharp drop in temperature (5000–6000 K) happens with the arc discharge phase lasting for a few microseconds. The arc discharge phase is responsible for damaging the electrode surfaces by erosion. Therefore it is necessary to understand the arc discharge phase. The transition from arc discharge to glow discharge is considered the fourth phase of spark generation. The glow discharge phase generally lasts for several milliseconds.

9.3 Modelling of Spark Ignition Systems for IC Engines

The trend in engine development favours computational study for initial investigations owing to lesser time and economy (Valera et al. 2020). Non-uniform fuel–air mixture distribution in the vicinity of spark electrodes can lead to unfavourable conditions for efficient combustion and cyclic fluctuations for port injection SI combustion and direct injection SI combustion (Drake et al. 2005). It is important to understand the underlying processes and mixture behaviour in the vicinity of the spark plug. Experimental studies require efforts to develop an experimental setup, which is time-consuming and expensive. On the other hand, computational studies offer flexibility in predicting the engine parameter variations with time economically and efficiently. Computational Fluid Dynamics (CFD) studies of engines use various assumptions for modelling the in-cylinder phenomenon. Computational studies have shown significant advantages in engine performance improvement and emission reduction in the past few decades. Computational studies use various techniques to solve complex combustion phenomena in the engine.

9.3.1 One Dimensional (1-D) Simulations

The prediction of a performance parameter of an engine uses a deterministic approach. The deterministic modelling approach can be of 0D, 1D, 2D, or 3D. Different approaches refer to the number of independent space variables and time variables. A model can be transient or steady. 0D modelling uses ordinary differential equations to model the variable parameters. It does not consider the spatial variations of the parameters and only solves for time variations. However, 1D, 2D, and 3D modelling approaches consider spatial and time variations together. 1D modelling is a simple approach for understanding an engine's performance, combustion, and emission characteristics. Many commercial codes, such as GT-Power, Ricardo Wave, AVL BOOST, etc., are available to perform a 1-D simulation. 1D modelling has a handicap in predicting emissions, especially HC and CO. The 1D model cannot predict spatial and temporal emissions variations, which can be done in 3-D simulations.

9.3.2 3-D CFD Simulations

The in-cylinder charge motion greatly influences the fuel–air mixing and combustion process in the engine. Studying turbulence flows characteristics and bulk flow patterns are essential since they significantly impact heat transfer. The intake process sets up the initial in-cylinder flow pattern and is subsequently modified during the compression and expansion processes. In the context of 3D, it felicitates understanding of the temporal and spatial variations of the in-cylinder phenomenon, which is not possible with 1D modelling (Kumar et al. 2021). It allows understanding the basic phenomenon occurring within the cylinder, such as fuel–air mixing, heat transfer, etc., and its effects on the global engine parameters. Many commercial codes, such as CONVERGE, KIVA, AVL-Fire, are available for simulating engine-like conditions.

9.3.3 1D Model Preparation Using GT Power

There are several commercial software capable of solving complex engine processes with fair accuracy. Commercially available software such as AVL BOOST, Ricardo Wave, GT Power are popular tools for 1D simulations. Figure 9.3 shows a simple setup for a 1D model of SI engine developed using GT Power. The flow model comprises Navier Stoke, continuity, and energy equations. In 1D modelling, this equation is solved in a single direction; variables in the other directions are averaged only in the flow direction. This method of solving the flow process reduces the simulation time. However, spatial variations are not possible with a 1D model, but this model is best suited for predicting overall performance with reduced simulation efforts. In Fig. 9.3, the intake system is shown using a blue box, and the red

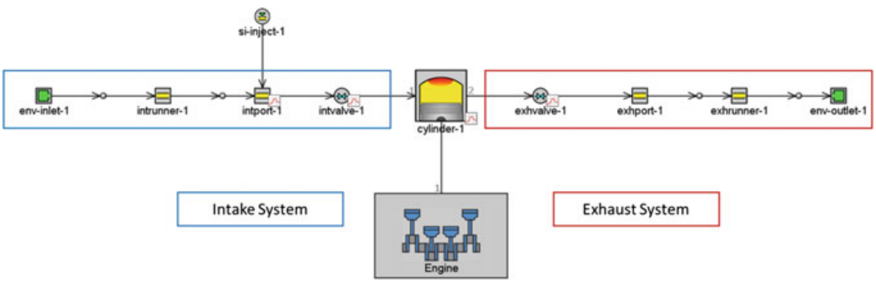


Fig. 9.3 A general outline of a 1D model for a single-cylinder spark-ignition engine

Table 9.1 Typical parameters required for 1D modelling of different components

Sub-system	Component name	Parameters required
Intake and exhaust system	Environment conditions	Temperature, pressure, air composition, humidity
	Runner pipe and inlet and outlet port dimensions	Diameter at inlet and outlet, Discretization length
	Intake and exhaust valve	Cam timing, valve lift with crank angle, the flow discharge coefficient
Injection system	Injector	Injector delivery rate, fuel ratio, fuel name, injection timing
Cylinder	Engine cylinder	Initial condition, wall temperature (head, piston, cylinder), heat transfer model, combustion timing, duration
Engine	Engine crank train	Engine type (4-stroke or 2-stroke), engine speed, cylinder geometry, firing order, inertia, the start of a cycle

box represents the exhaust system. The intake system comprises inlet environment conditions, runner pipe, port dimensions, and intake valve. While modelling, each component needs to be considered and, some critical parameters are required as input for a decent accuracy while predicting. Table 9.1 shows the required general parameters for 1D modelling of a SI engine.

9.3.3.1 Combustion Model Selection

There are three main combustion models: non-predictive combustion model, predictive combustion model, and semi-Predictive combustion model (Kumar 2021).

Non-Predictive Combustion Model

This type of combustion model requires an imposed burn rate as a function of crank angle degrees. Combustion would be controlled by the imposed burn rate, regardless of any other in-cylinder conditions. This model assumes that sufficient fuel is available in the combustion chamber to follow the imposed burn rate. Hence, the burn rate remains unaffected by other variables such as residual mass fraction, trapped mass, injection timing, etc. This model is helpful to study the effect of variable parameters, which do not affect the fuel burn rate. However, this model is not suitable for studying engine variables, which directly implies the burn rate. A predictive or semi-predictive combustion model is preferred to study these variables that directly correlate with the burn rate. For example, suppose someone wants to study the effect of injection profile and injection timing in a diesel engine. In that case, the predictive capability must have meaningful results since these parameters strongly affect the burn rate.

Semi-Predictive Combustion Model

The semi-predictive combustion model is weakly sensitive to the engine variables that substantially affect the burn rate. This model responds appropriately to these variables. However, this does not use any physical model to predict their implications. This model may be an appropriate choice for predictive modelling in some cases.

Predictive Combustion Model

This type of combustion model is preferable for different engine simulations. Predictive combustion models are an appropriate choice for all simulations. There are practical factors that make non-predictive combustion models preferable in certain situations. It requires calibration with measured data to provide accurate results. The model imposes a burn rate to predict the in-cylinder pressure. However, if the burn rate is not available, it can be obtained using experimental data generated under known test conditions.

Burn-rate prediction from the known in-cylinder pressure history is obtained using the reverse run method. In this method, inputs and outputs of the calculations are reversed from the typical engine combustion calculations. In the forward run, in-cylinder pressure comes out as an output, and the burn rate serves as an input, and the reverse run is vice-versa. Hence two-zone combustion approach has been followed to predict the burn rate. Two-zone generally considered are the burnt zone and the unburned zone. The reverse run uses the same set of equations as the forward run, including thermodynamics and combustion. In the reverse run method, the amount of fuel being transferred from the unburned zone to the burned zone is iterated for each time step until its in-cylinder pressure matches the measured in-cylinder pressure. Two approaches can be used to predict the apparent burn rate from the experimentally measured in-cylinder pressure trace. The first approach is based on closed volume analysis, also known as 'cylinder pressure only analysis' (CPOA), and the second approach is 'three pressure analysis' (TPA). Both methods follow the same basic functions to calculate the burn rate and produce similar results. However, these two approaches differ in the way they require necessary additional input data such as trapped air and fuel mass, heat transfer in addition to the measured in-cylinder pressure-crank angle history. GT-power uses different heat transfer models as per data availability, such as the WoshiniGT model is used to predict the heat transfer when swirl parameters are not available. There are several other heat transfer models, such as WoschiniHuber, WoshiniSwirl, where more accurate prediction is possible with the availability of required initial conditions. The details of these models have been explained in our previous publication (Valera et al. 2020). If spatial and temporal variations within the cylinder are required with high accuracy, using more complex 3D CFD modelling becomes essential. 3D computational modelling requires high computational resources.

9.3.4 3D Model Preparation Using CONVERGE CFD

In this section, 3D model preparation steps for the spark-ignition engine are discussed. For the model preparation, the computational boundary needs to be prepared. CONVERGE has two platforms, namely 'CONVERGE Studio' and 'Solver,' to set up the model and run simulations, respectively. CONVERGE studio is designed for case Preparation and setting up different boundaries. CAD models of different components such as cylinders, valves, ports, pistons need to be prepared and assembled. Initial geometry diagnosis may be required and taken up in CONVERGE studio, and boundary conditions need to be assigned, as mentioned in the 1D modelling section. Moving boundary conditions can also be specified by enabling transient boundary conditions.

Figure 9.4 shows an example model prepared for 3D simulations. Unlike 1D, 3D simulations solve the governing equations (mass, momentum, and energy) in all three directions. Thus, the spatial and temporal variations within the computational domain can be analyzed. It requires a complete reaction and transport mechanism for a particular fuel for solving involved transport phenomena. CONVERGE can generate run time mesh structure and assign the embedding region where more fine meshing is required with appropriate grid size. This is one of the essential features of this software since mesh generation was always challenging and time-consuming for complex geometry, especially near the wall region.

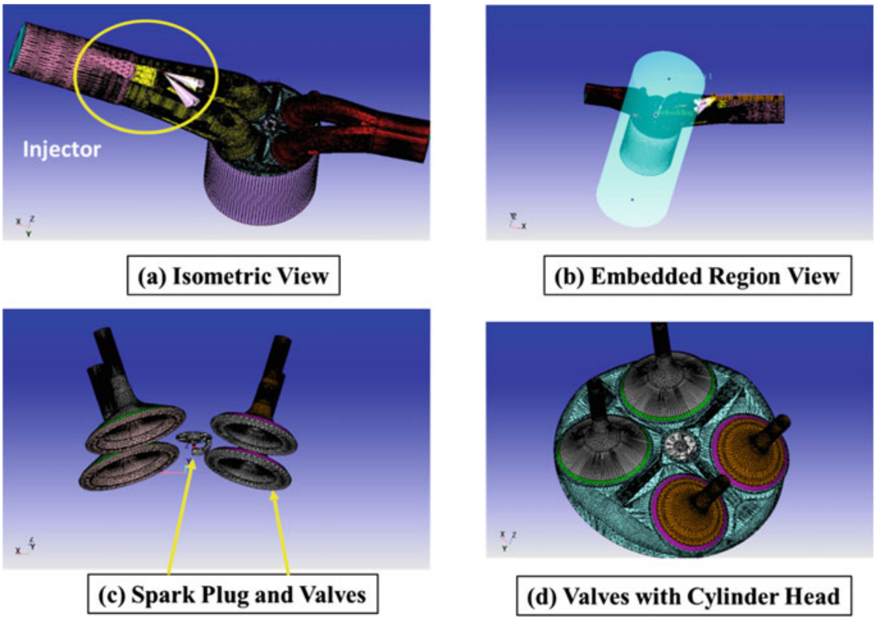


Fig. 9.4 Different views of port fuel injected (PFI) spark ignition engine

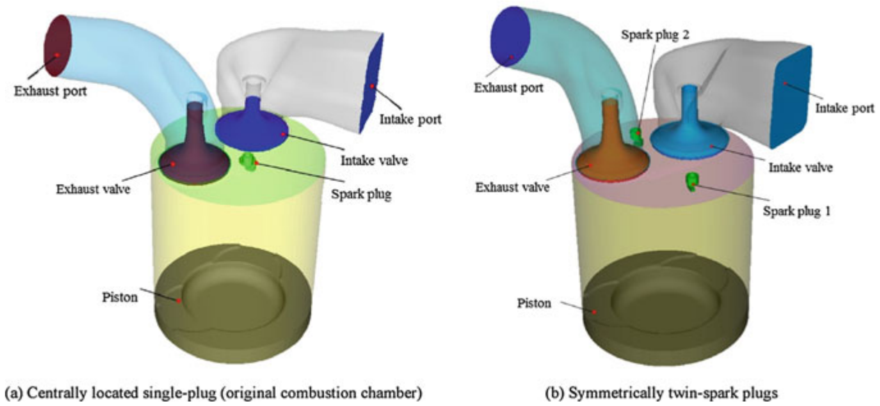


Fig. 9.5 Computational domain of the model, showing single and twin spark plug configurations (Duan et al. 2020)

Case Study: Effect of twin Spark Plug on Engine Performance and Emissions

Duan et al. analyzed the effect of the twin-spark plugs on the combustion and performance for the lean operation of a natural gas engine (Duan et al. 2020). They first validated the model with the experimental results using one centrally located spark plug for carrying out the investigations, as shown in Fig. 9.5a. Other boundaries such as exhaust and intake port, intake and exhaust valves, piston liner can also be observed in Fig. 9.5.

The location of the spark plasma has a strong impact on the initiation of combustion as it starts the initial flame kernel. After that, flame development occurs in the combustion chamber. Any deviation in the spark timing, spark location, and the number of sparks will severely affect the engine performance, combustion, and emission characteristics. The main advantage of multiple sparks is that they can extend the lean limit of the fuel–air mixture and contribute to lesser NOx emissions. In the present case, a physical model was developed using 3D CONVERGE CFD, which offers run time mesh generation and can solve complex chemical kinetics. The model validation using the experimental data was done for a single spark plug.

Further, the twin spark plug location was chosen to be symmetrically opposite, as shown in Fig. 9.5b. The different percentages of EGR (5, 10, 15%) and their effects were compared for single and twin spark plug configurations. Figure 9.6 shows a comparative plot of the in-cylinder pressure and heat release rates for different conditions. Figure 9.6a shows that the peak in-cylinder pressure for the twin spark plug was significantly higher than the single spark plug with no EGR case. By introducing EGR (5 and 10%), the peak in-cylinder pressure was somewhat lower than a twin spark plug with no EGR case. However, the cylinder pressure was still significantly higher than a single spark plug engine case. Moreover, with 15% EGR and twin spark plug, the in-cylinder pressure was lowest among all cases. This trend was also supported by the heat release rate curve, as shown in Fig. 9.6b. The heat release rate

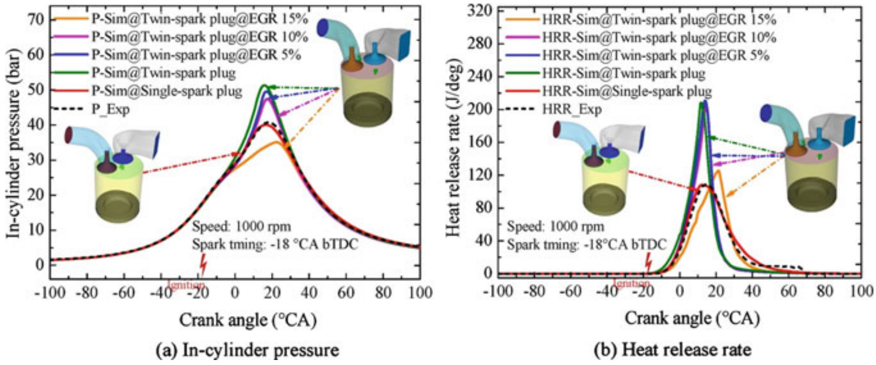


Fig. 9.6 In-cylinder pressure and heat release rate comparison of simulated and experimental results for different EGR % obtained for single and twin spark plug configurations (Duan et al. 2020)

of the twin spark plug (with and without EGR) was much higher than the single spark plug, except for a twin spark plug with a 15% EGR case. It can be concluded that an EGR of up to 10% was favourable with a twin spark plug configuration. The result obtained is from numerical analysis needs experimental validation. The authors also investigated spatial parameters such as flame development within the combustion chamber and used the 'SAGE' combustion model to predict the combustion. The total flame kernel volume of the initial spark was observed to be larger than a single spark, which was obvious. Flame propagation speed was faster for the twin spark plug.

9.4 Advance Ignition System for SI Engines

Conventional ignition systems have several limitations and shortcomings. The required voltage and energy are relatively higher for initiating dilute stoichiometric combustion with a conventional spark plug. Furthermore, higher voltage imposes reliability problems such as spark plug erosion, degradation of electrodes, and recurrent replacement of spark plugs (Bisetto et al. 2006). Some advanced ignition systems in the research phase can downsize the engines and ignite the leaner mixture. Several new spark plug systems include laser-induced ignition, corona ignition, and turbulent jet ignition systems. In the following sub-section, some of these alternative ignition systems have been discussed.

9.4.1 Laser-Induced Ignition

Laser-induced ignition is an innovative concept to ignite the fuel–air mixtures in an internal combustion engine. It uses a couple of optical elements to focus the laser beam at any location within the combustion chamber. It has the potential to overcome various problems common to conventional ignition systems. LI can be used for different engines such as IC engines, rocket engines (ramjets, scramjet), and gas turbines (Kumar and Agarwal 2020; Lorenz et al. 2016; Azarmanesh and Targhi 2021; Morsy 2012). A LI system for IC engine applications needs to overcome critical challenges faced by SI engines such as inappropriate combustion, lesser lean limit, higher NOx emissions, and lower efficiency.

9.4.1.1 Fundamentals of Laser Ignition

An intense laser beam is focused in the combustion chamber, where a subsequent breakdown of gaseous molecules initiates combustion. Figure 9.7 shows the basic principle of operation. An intense laser beam of a short pulse is focused into the combustion chamber with the help of suitable optical components, and a bright plasma is generated at the focal spot of the laser focusing lens (Azarmanesh and Targhi 2021).

There are four well-known modes by which laser beam can interact with the fuel–air mixture to initiate the combustion. These modes are (i) photochemical ignition, (ii) thermal ignition, (iii) resonant ignition, and (iv) non-resonant ignition (Kumar and Agarwal 2020; Morsy 2012).

In the photochemical mode of interaction, a laser source of resonant wavelength with absorbing medium is used. Target molecules get dissociated into atoms, and the chain branching mechanism generates highly reactive radical species. Also, there is no electrical breakdown. The local temperature rises due to the collision of produced radicals with nearby molecules, leading to ignition. However, due to collision, produced radicals may recombine with themselves or nearby molecules. Studies (Chou and Zukowski 1991; Lavid and Stevens 1985) suggest that full-scale

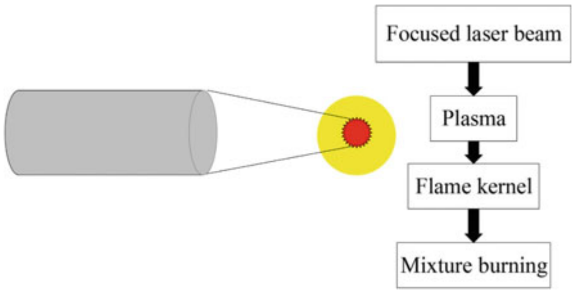


Fig. 9.7 Different stages of laser ignition of fuel–air mixture (Azarmanesh and Targhi 2021)

combustion starts when the production rate of radicals is higher than their recombination rate in photochemical ignition. Reported studies also concluded that radical concentration to initiate the combustion process should be in the range of 10^{17}–10^{18} atoms/cm^3. This is not favourable for IC engine applications due to disadvantages such as close match requirement of laser wavelength and absorbing molecules in the medium. However, fuel concentration varies from rich to lean in the engine, depending on the engine load and test conditions. In the thermal mode of interactions, ignition occurs without the electrical breakdown. The laser source is used to excite the gaseous molecule in translational, vibrational, or rotational modes. This leads to the generation of radicals of gaseous molecules, and indirect heating leads to the start of chemical reactions, consequently starting the ignition. A continuous-wave (CW) laser can achieve this ignition mode. However, this mode of LI is generally not preferred in IC engine applications since it takes longer to ignite the fuel mixture, requires a solid target to start the chemical reactions, and is difficult to ignite the leaner mixtures (Tanoff et al. 1995).

In the resonant mode of laser-induced ignition, the ignition process starts with non-resonant photodissociation of the molecules of the medium, followed by resonant photoionization of atoms created during the dissociation processes (Forch and Miziolek 1991). Both these events occur in a sequence, leading to the formation of seed electrons in the vicinity of the incident laser beam. After that, the seed's electrons gain energy by absorbing photons or from generated energy because of collisions. This phenomenon is also referred to as an 'inverse bremsstrahlung process. When these seed's electrons gain enough energy, they collide with nearby molecules, generating more free electrons. This way, a chain reaction starts, which increases the electron density in the vicinity of the focal region of the beam. This further leads to electron avalanche and the electrical breakdown of gaseous molecules. This mode of laser-induced ignition is exceptionally efficient over the others. However, it involves rigorous complexity. This mechanism requires tuning the laser to produce a laser beam of wavelength equivalent to the molecular length of the combustible mixture. Otherwise, two different lasers, one for the photodissociation process and the other for the ionization process, are used. Therefore, the resonant mode is not suitable for practical engine applications. In the non-resonant mode of laser-induced ignition, the process is somewhat similar to the resonant mode of ignition. However, it involves non-resonant multiphoton ionization of molecules. This laser-induced ignition does not require a close match of molecules and laser wavelengths, making it feasible for IC engine applications. Two different processes, multiphoton ionization breakdown and electron cascade ionization dominate the non-resonant laser-induced ignition, depending on fuel–air mixture composition and the laser parameters (Phuoc 2006; DeMichelis 1969). The former involves simultaneous absorption of photons required to achieve ionization potential. Electrons generated gain energy via the bremsstrahlung process. However, the cascade ionization is the reverse of the bremsstrahlung process. Electrons lose their energy to nearby molecules through collisions. Here ignition starts when the rate of energy absorption from photons overcomes the rate of losses. Table 9.2 summarizes the significant characteristics of different laser-induced ignitions.

Table 9.2 Summary of characteristics associated with different types of laser-induced ignitions

Ignition types	Characteristics
Photo chemical ignition	Minimum radical concentration to initiate the combustion process should be in the range of 10^{17}–10^{18} atoms/cm^3 Require close match between laser wavelength and absorbing medium molecules Not favourable for IC engine applications
Thermal ignition	A laser source is used to excite the gaseous molecules A continuous-wave laser can achieve it It takes a long time to ignite the fuel–air mixtures Require solid target to start the chemical reactions Difficult to ignite lean mixtures Not Suitable for IC engine applications
Resonant Ignition	Extremely efficient ignition Require tunable laser to achieve ignition Complex and expensive Not favourable for IC engine applications
Non-resonant ignition	Different types of lasers can be used A tunable laser is not required Can ignite different types of fuels (gaseous or liquid) Any particular wavelength is not necessary to initiate the combustion Can ignite leaner fuel–air mixtures Favourable for practical engine applications

9.4.1.2 Laser-Induced Multi-point Ignition

One of the primary advantages offered by the LI system is to direct the laser beam to several spots in the combustion chamber that eventually allow the ignition of the fuel–air mixture at several locations simultaneously. This technique of achieving laser-induced ignition, called multi-point ignition, increases the engine's combustion efficiency and overall performance. Laser-induced multi-point ignition offers many advantages over single-point ignition. It improves the in-cylinder combustion characteristics by shortening the flame propagation distance, resulting in a shorter combustion duration (Lavid and Stevens 1985). Some researchers (Dale et al. 1997; Saito et al. 2017; Kuang et al. 2017; Grzeszik 2017) explored various aspects of the multi-point technique and highlighted its advantages over the conventional spark plug and single-point LI techniques. Evaluation of multi-point ignition is still in its infancy and needs further experimental investigations and development. Grzeszik et al. experimented with three-point ignition for gasoline engines and found an increase in operational lean limit, lower fuel consumption, and lower NOx emissions (Grzeszik 2017). Vasile and Pavel demonstrated that the multi-point ignition of the methane-air mixture using a fibre-coupled laser diode-pumped, passively Q-switched Nd: YAG/Cr^{4+}:YAG compact laser with four-output laser beams in a constant volume combustion chamber (CVCC) (Vasile and Pavel 2021). Four laser beam outputs were used with beam pulse energy of 3.8 mJ at 0.9 ns pulse duration. Sapphire windows were installed in the periphery of the CVCC for the incoming laser beam, and several inlets and outlets port were made for facilitating the gas exchange process. They used four fibres of 600 μm diameter with a numerical aperture, NA = 0.22, to pump the laser beam. They performed several primary investigations to ensure the four-beam output of the same energy. Beam quality factor (M^2) of 4.8 was reported for all four-beam output from the laser. The schematic of the laser and optical breakdown of the air is shown in Fig. 9.8.

Figure 9.9 shows the excess pressure variations with time for different λ under single and multi-point ignition in a CVCC. They concluded that the multi-point LI showed increased excess pressure than the baseline single-point ignition. It was reported that the multi-point technique widened the flammability limit of ignition up to λ = 0.91–1.77 for the rich and lean mixtures. For all values of λ, the excess pressure was somewhat higher for the multi-point ignition technique than for the single-point ignition.

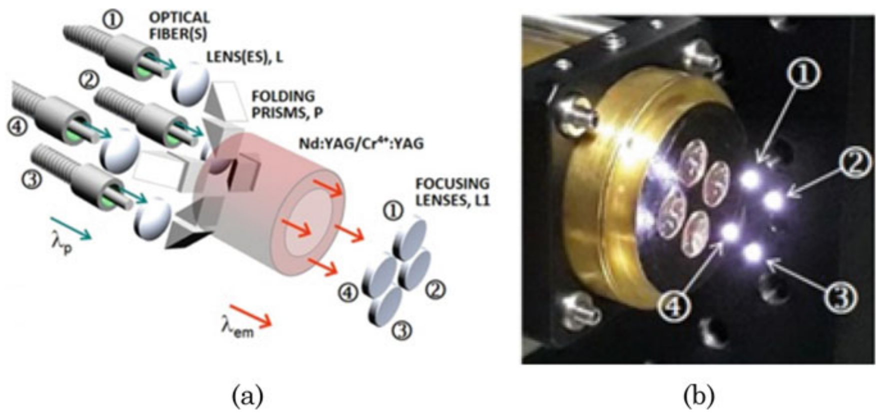
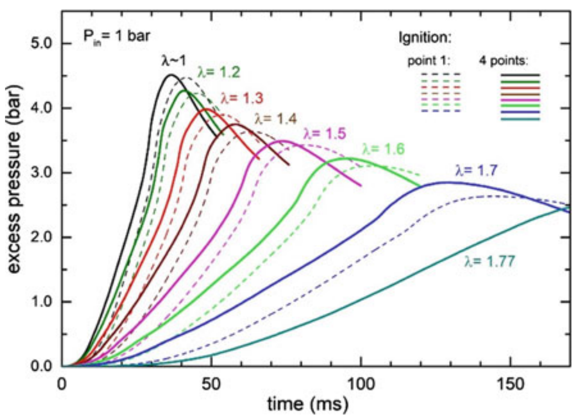


Fig. 9.8 **a** Schematic of multi-point laser ignition with four focused beams, and **b** multi-point air breakdown by each beam (Vasile and Pavel 2021)

Fig. 9.9 Variations of the excess pressure with time at 1 bar initial CVCC pressure for different methane-air mixture proportions (Vasile and Pavel 2021)



9.4.1.3 Laser-Induced Engine Characteristics

IC engines with conventional spark ignition can be retrofitted with a laser-induced ignition system. An engine's performance and combustion characteristics with LI are superior to conventional ignition. Azarmanesh and Targi compared the laser and conventional spark plugs by modelling the thermodynamic combustion of methane-air mixtures (Azarmanesh and Targhi 2021 Feb). They reported an 8% improvement in thermal efficiency for the lean methane-air mixture ($\lambda = 1.42$) and 10% higher maximum pressure for LI. Also, after extending the lean limit about ($\lambda = 1.66$), the unburnt mixture proportion was relatively higher within the cylinder, resulting in inferior efficiency when ignited using the conventional spark plug; however, after implementing a LI system, the combustion quality improved, and efficiency increased by ~ 21%. Several other studies reported an increased peak pressure, rate of pressure rise, and HRR with LI (Pal and Agarwal 2015; Srivastava and Agarwal 2014).

Birtas et al. (2019) developed a LI system mounted directly to the cylinder head, shown in Fig. 9.10. A similar approach was also reported (Pavel et al. 2017; Birtas et al. 2017) for analyzing the potential of the LI system. They used optical fibres (0.6 mm diameter, the numerical aperture NA = 0.22) to transfer the pump light to the active medium. This system delivered energy of ~ 4 mJ with 0.8 ns pulse duration. The engine used for the study was a 4-cylinder Renault engine. The laser system was triggered by ECU installed with the engine. By optimizing the spark timing for the air–fuel mixtures, they concluded that only minor engine performance improvements could be achieved using the LI system for the stoichiometric mixture. However, for lean mixture operation, LI improved the engine performance significantly. With a leaner mixture, combustion duration was lower, and combustion stability was better.

Lied et al. investigated the effect of plasma location using different converging lenses in the GDI engine cylinder and concluded that the optimum location of the laser-plasma was the center of the combustion chamber. At this location, the lowest BSFC was observed (Liedl et al. 2005).

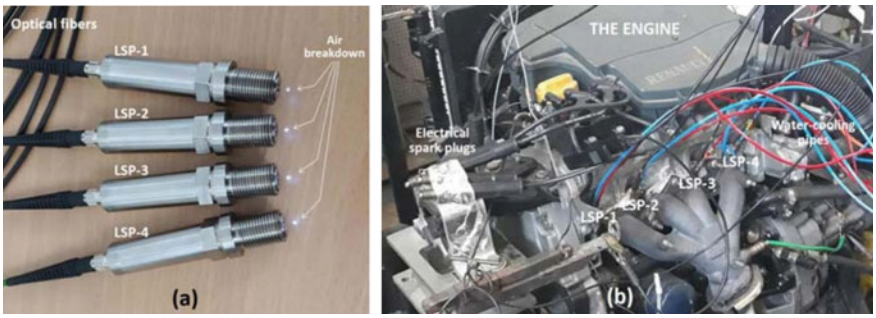


Fig. 9.10 **a** Laser ignition system with four laser spark plugs showing plasma formation in the air, **b** experimental setup installed with the laser ignition system (Birtas et al. 2019)

Prasad et al. (2021) experimented with the laser ignited hydrogen-enriched compressed natural gas (HCNG) fueled boosted single-cylinder engine. They concluded that brake-specific fuel consumption (BSFC) in LI mode was lower than conventional spark ignition (SI) mode. A recent study adopted a computational approach to predict the LI for methane-air mixture in IC engines (Azarmanesh and Targhi 2021). They modelled the combustion in four different stages, as shown in Fig. 9.11a. This multi-zone methodology (Mahabadipour et al. 2019) validated the in-cylinder pressure, as shown in Fig. 9.11b. For simulating LI conditions, it was assumed that the mixture would absorb the energy ~ 150 mJ.

Figure 9.12a shows that peak in-cylinder pressure for LI was higher than the conventional spark plug for stoichiometric conditions. Also, combustion duration was reduced (~3 ms) for LI. After diluting the fuel–air mixture, LI became more promising and showed a significant increase in the in-cylinder pressure at $\lambda = 1.66$,

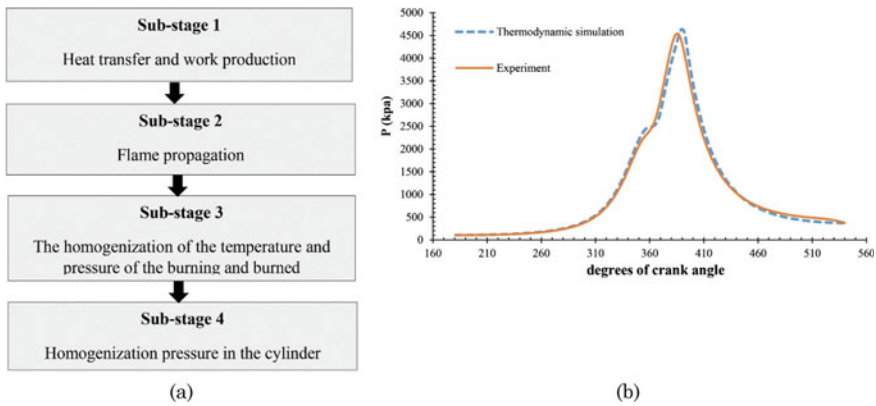


Fig. 9.11 **a** Flow chart of stages involved in combustion, **b** validation of experimental in-cylinder pressure (Azarmanesh and Targhi 2021)

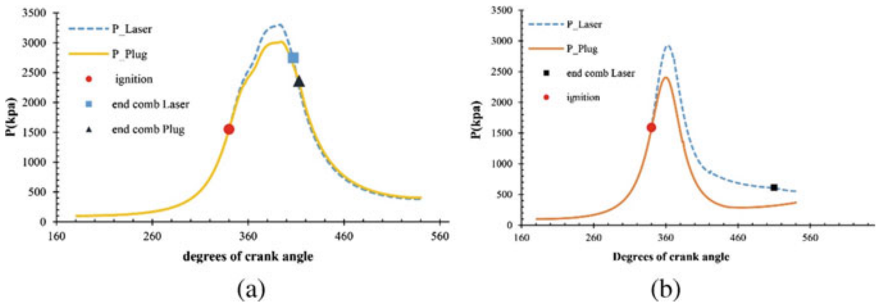


Fig. 9.12 Comparison of the in-cylinder pressure vs crank angle degree curves for the laser and spark plug ignitions at different stoichiometric conditions **a** $\lambda = 1$, and **b** $\lambda = 1.66$ (Azarmanesh and Targhi 2021)

as shown in Fig. 9.12b. They also reported that the rate of burning of the methane-air mixture was higher for the LI.

9.4.1.4 Advantages, Limitations and Future Prospects of Laser Ignition

From the literature discussed in the previous section, it can be concluded that the LI system has a significant advantage over the conventional ignition systems. It improves the combustion process by allowing the ignition of extended lean fuel–air mixtures. LI system provides the flexibility to choose an ignition location within the combustion chamber. Location change of ignition point can be changed by employing converging lenses of different focal lengths or by translating the converging lens in the plug along the direction of the laser beam (Grzeszik 2017). There is no intrusion, unlike conventional spark plug, and hence there is no quenching effect to the flame kernel in the combustion chamber. Several challenges, including the delivery of laser beam to the combustion chamber, powering the laser from the small-sized vehicle battery and making compact laser need to be addressed for realizing the LI system adaptation for practical engine applications. The open beam path approach is suitable only for laboratory-scale experiments and is unsuitable for practical engine applications. The open beam path approach uses several optical components and suffers from alignment issues and high-power transmissivity losses in the optics (lenses and mirrors). For multi-cylinder engine applications, closed path fibre delivers the laser beam, providing flexibility and resolving the alignment issues. The fibre delivery approach can also be used with a multiplexing system to ignite the multi-cylinder engine using a single laser source. However, the fibre used for transmitting the laser beams involves higher losses. A multiplexing system is a desirable alternative by which one laser may be used to ignite multiple cylinders. For successful implementation, engines should be optimized for laser beam multiplexing. This approach may overcome high-cost issues associated with a single laser per cylinder for multi-cylinder engine applications. Some other technical aspects must be considered and resolved to realize the LI system for production-grade engines. Optical windows for passing the laser beams should be more robust to sustain harsh conditions at different engine loads with minimum transmission losses. The size of the laser spark plug should be optimized to fit in the existing engine, and mass production of laser ignition systems should be undertaken to make them economical. A close-loop ignition control coupled with ECU may help trigger the laser at the right time for different cylinders. Multi-location plasma would help reduce the combustion duration with faster flame propagation to improve gaseous and liquid fuel combustion. Underlying physics at optimizing the plasma locations is still in the research phase. A computational study may help to understand the molecular characteristics at the ignition location. LI for the GDI engine application seems promising for different engine operation modes, particularly in the stratified mode.

9.4.2 Corona Ignition

This ignition system utilizes a series of circuits with a coil and capacitor. Series of circuits produce a high voltage at the tip of the igniter to generate corona. When a very high electrical field is enforced to a sharply curved and blunt surface, the voltage reaches a state that can break down the gas molecule in the vicinity. This local breakdown is in the form of a glow discharge, usually referred to as corona or electric wind, and hence the term corona ignition has been conceptualized. The magnitude of local voltage required here is lesser than the voltage generated in the conventional spark plug ignition for the same gap length. Corona ignition does not contain any ground electrode. Corona ignition covers a large combustion chamber volume and can ignite leaner mixtures that may not be ignitable by the conventional spark ignition.

9.4.2.1 Fundamentals of Corona Ignition

Corona ignition system uses series of resonant resistance-inductance-capacitance (R-L-C) circuits. The basic layout of the circuit is shown in Fig. 9.13a (Cruccolini et al. 2020). This electronic system is integrated with an igniter assembly, which is responsible for delivering high-frequency power to the igniter as per the feedback received from the ECU. The combination of resistance and inductor is connected in series, and this system amplifies the low to high voltage. Capacitors are installed at the firing end of the igniter plug installed in the cylinder head, as shown in Fig. 9.13b.

When a high voltage is applied to the igniter, the free electrons are accelerated because of the developed electromotive force and collide with the available gas molecules in the vicinity of the igniter plug. The ionization of gas molecules starts when the kinetic energy of electrons reaches the threshold limit of the ionization energy of the fuel–air mixture (gas molecules). This results in electron avalanche,

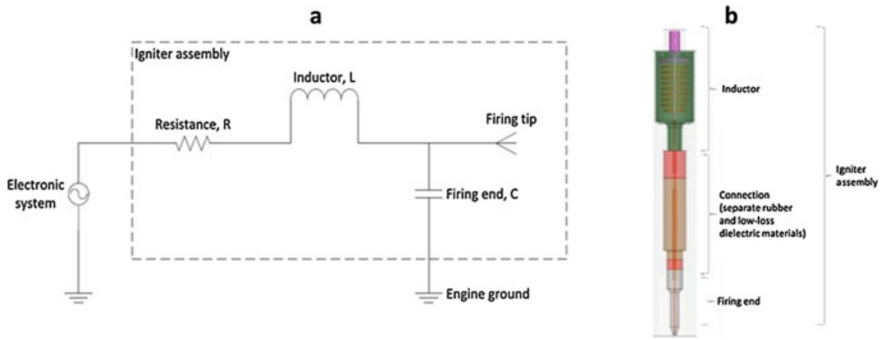


Fig. 9.13 **a** Electric circuit for corona ignition, and **b** schematic of corona igniter assembly (Cruccolini et al. 2020)

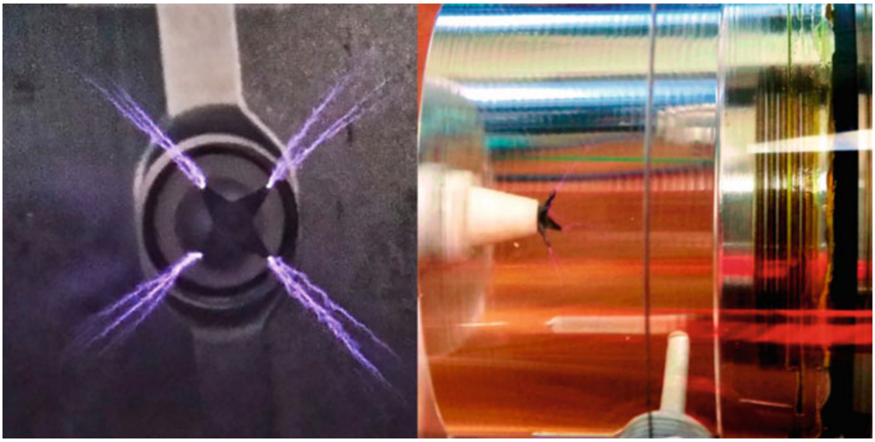


Fig. 9.14 **a** Corona igniter, **b** corona igniter installed in the combustion chamber (Discepoli et al. 2018)

and branch chain reaction leads to the breakdown of gas molecules. Discepoli et al. analyzed the energy required for the primary circuit of single and multi-point spark ignition and then compared it with the corona ignition (Fig. 9.14) (Discepoli et al. 2018). They reported that with increasing chamber pressure, the required energy for a primary circuit remains approximately constant, while for multiple spark cases, it decreases slightly. The required energy for corona ignition is independent of the chamber pressure.

9.4.2.2 Corona Ignition Engine Characteristics

Cimarello et al. investigated the effect of corona ignition using an optical engine for gasoline-air mixture and compared it with the conventional spark-ignition engine (Cimarello et al. 2017). Their study focused on flame development, stability, and lean limit operations. ECU was used to trigger the circuit at the right timing. They concluded that corona ignition showed four times faster flame propagation compared to conventional spark ignition. They claimed ~ 88% NOx reduction by adopting the corona ignition system. NOx reduction was observed primarily because corona could ignite leaner mixture at multi-spots simultaneously. At low load and speeds, corona ignition allowed the extension of lean operation by 0.25 λ. Cruccolini et al. also experimented with the corona ignition in optical engines using gaseous fuels (H_2 and Methane) (Cruccolini et al. 2020). They reported that when corona ignition was employed for methane fuelled engine, there was a guaranteed extension of 0.15 λ for the lean working limit at different engine loads. By hydrogen enrichment of the mixture, a further extension of 0.25 λ was achieved in the lean limits.

A sharp transition between stable and unstable conditions was observed for conventional spark ignition for different HCNG mixtures. However, this transition

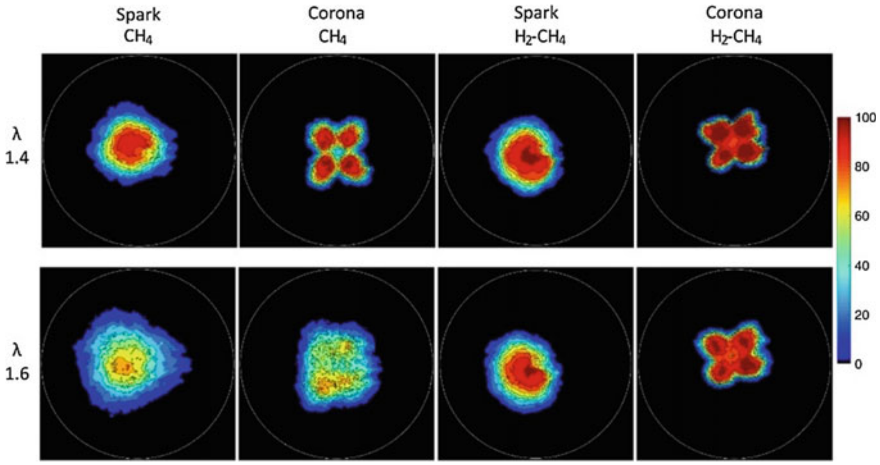


Fig. 9.15 Comparison of flame probability during 1% MFB for $\lambda = 1.4$ and $\lambda = 1.6$ for methane and hydrogen (Cruccolini et al. 2020)

was rather smoother in corona ignition. Hydrogen enrichment reduced cyclic variability with corona ignition; however, adding hydrogen increased the NOx emissions at stoichiometric conditions. Figure 9.15 shows the probability of flames at 9 mm of average equivalent radius (equivalent to 1% of MFB) for CNG and HCNG mixtures. Dark red contour represents 100% probability of the burned area while black represents the background. The figure shows that the corona ignition exhibited more dark areas than the spark ignition for both fuels and lambda conditions.

Ignition phenomena were captured using a high-speed camera. The shape of flame propagation was somewhat circular for spark. However, for corona ignition, a four-leaf flame structure was observed. Also, the flame presence probability increased upon adding hydrogen than the methane-fueled engine in corona ignition. The four-leaf flame structure was absent for lean mixtures of $\lambda = 1.4$–1.6 in methane fuelled engine. Marko et al. reported an increased EGR compatibility from 27% in spark ignition to 32% in corona ignition (Marko et al. 2017). Lower cyclic variations, stable combustion, and improved efficiency were observed with the corona ignition. Improved combustion characteristics of corona ignition are attributed to the faster flame propagation and leaner mixture operation. Mariani et al. experimented with the corona ignition in a spark-ignition engine and compared its efficiency and emissions (Mariani et al. 2013). They reported reduced combustion duration and increased engine efficiency in the range of 2–5%. There was a slight reduction in HC and CO emissions reported under some operating conditions. However, the NOx emission was considerably higher in corona ignition because of higher in-cylinder temperatures due to faster combustion.

9.4.2.3 Advantages, Limitations, and Future Prospects of Corona Ignition

Corona ignition covers a larger combustion chamber volume, resulting in faster flame propagation and smoother combustion. Corona can ignite leaner mixtures, which may not be ignitable by the conventional spark plugs otherwise. Also, the corona ignition system requires no separate ground electrode, which minimizes the heat loss associated with electrodes. However, there are associated challenges in the formation of the corona arc. When a metal surface is placed near the streamers (corona discharge), an arc is formed. However, it is essential to control the duration of the arc for the ignition of fuel–air mixtures, and further arcing may lead to excessive wear of sharp tips. The required input energy is higher in the corona ignition compared to the conventional spark ignition. Ignition events near the tip may be analyzed using optical diagnostic tools since corona ignition can ignite relatively leaner gaseous mixtures in the direct injection SI engines.

9.4.3 Turbulent Jet Ignition

Turbulent Jet Ignition (TJI) was first adopted in the two-stroke Ricardo Dolphin engines in the early twentieth century (Toulson et al. 2010). It uses a separate chamber where ignition starts with the help of a spark plug. Therefore it was also referred to as a pre-chamber spark ignition system. This ignition system facilitated to ignite leaner fuel–air mixtures, which are not easy to ignite using conventional spark plugs. However, this approach of igniting was not used widely in commercial engines because of associated complexity and the increased cost of the additional chamber in the cylinder head. In the recent past, the interest in lean combustion has increased. Hence TJI is being revisited by researchers from the automotive community.

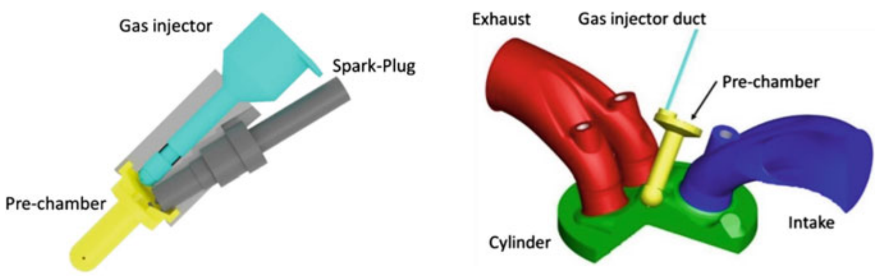
9.4.3.1 Turbulent Jet Ignition Fundamental

TJI system consists of two chambers; the first one is known as prechamber, where the rich fuel–air mixture is made available for ignition with the help of a spark plug, and the second one is known as the main chamber where a lean fuel–air mixture is inducted. Here combustion is initiated in the prechamber, and due to increased chamber pressure, the flames and partially unburnt charge are forced to the main chamber via nozzle holes. The burning charge comes from the prechamber in the form of hot gas jets via a nozzle responsible for igniting the lean fuel–air mixture available in the main chamber. TJI is further referred to as stratified or homogeneous, depending on the mixture strength of the prechamber. In the stratified TJI system, a secondary injector injects the fuel into the prechamber, creating a rich mixture. The leaner mixture is inducted into the main chamber via the intake port. However, in the homogenous TJI, no separate injector is required for the prechamber, and fuel is injected only to the main chamber (either directly or via the port). Here the fuel–air mixture of the main chamber enters the prechamber via nozzle holes, and then ignition starts using a spark plug. Generally, in both modes of operation, the volume of the prechamber is kept very small (~3% or less than the clearance volume), and it does not affect the overall fuel consumption (Toulson et al. 2010).

9.4.3.2 Turbulent Jet Ignition Engine Characteristics

For the engine application of TJI, a compact prechamber is made in the vicinity of the spark plug in the cylinder head. Distaso et al. performed a numerical study to analyze a methane fuelled engine (Distaso et al. 2020). 3D CFD study is essential to understand the mixture characteristics and in-cylinder combustion behaviour. CFD study provides insights into physical and chemical phenomena in the prechamber, which is challenging to observe experimentally. Initially, they validated the CFD model against the experimental data. The model was developed using commercial software CONVERGE, and the prepared computational domain is shown in Fig. 9.16.

Figure 9.17a–f represents the simulated results of TKE and the streamline pattern. For differentiating the stream traces, combustion event was categorised as filling and scavenging (150–134 CAD bTDC), mixing (134–22 CAD bTDC), flame propagation (22–7 CAD bTDC), ejection (14.4–4 CAD bTDC), re-burning (4–16 CAD bTDC), and expulsion and Extraction (16–172 CAD bTDC) (Distaso et al. 2020). Figure 9.17a shows the fuel injection in the prechamber, where the scavenging happens to expel some trapped residual gas. In the mixing phase, the rich mixture in the prechamber gets diluted by a leaner charge. Flow entering the prechamber increases the turbulence slightly; however, the TKE value remains low (Fig. 9.17b). In a conventional SI engine, high turbulence levels negatively affect the flame kernel growth. However, the TJI system overcomes this issue because the kernel is developed in the upper part of the prechamber, where turbulence intensity is lower than the main chamber (cylinder). At -22 CAD, the spark is triggered, and the flame



(a) (b)

Fig. 9.16 **a** Proposed TJI configuration, **b** computational domain near TDC (Distaso et al. 2020)

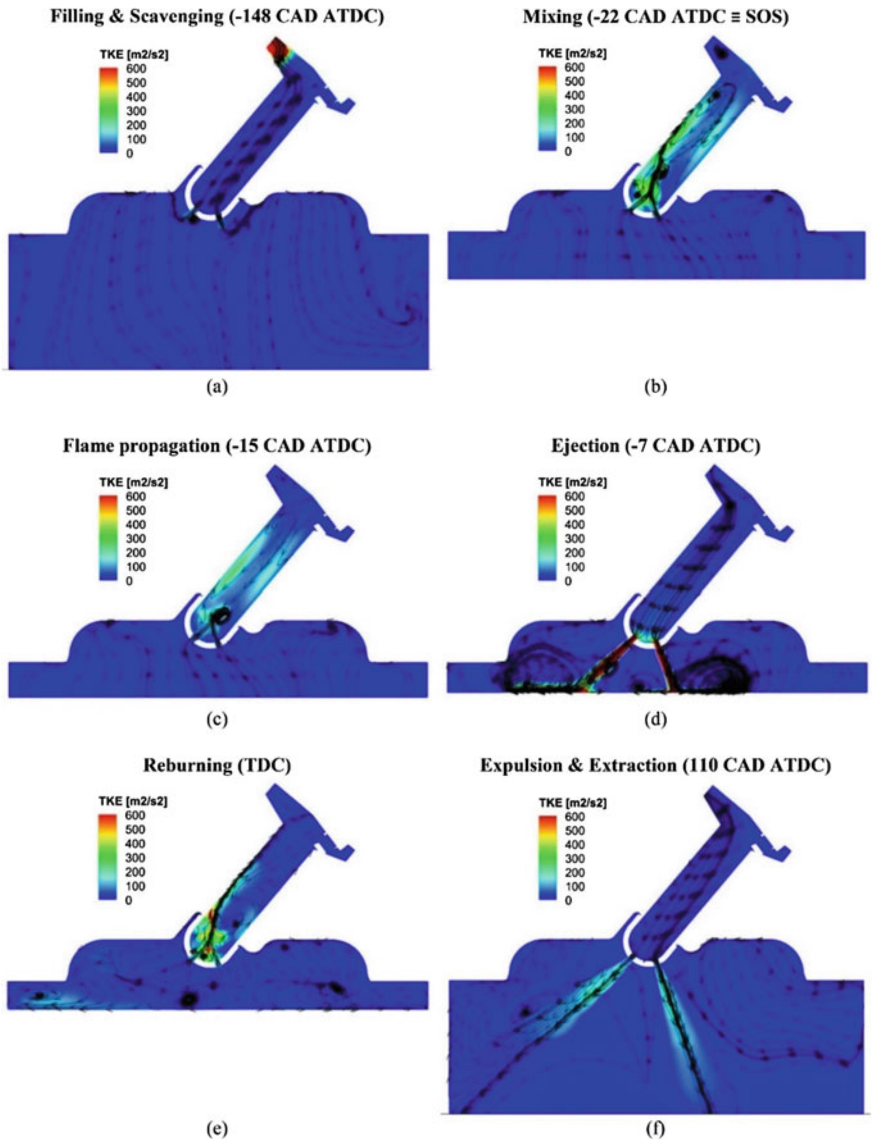


Fig. 9.17 Streamline traces and contour of TKE in a longitudinal plane for different events (methane, $\lambda = 1.3$) (Distaso et al. 2020)

propagation phase is initiated. In the ejection phase, multiple flame fronts are generated. Flow direction is inverted in the main chamber after the combustion events are initiated. This can be observed in Fig. 9.17e. The contour plot study showed that prechamber geometry and fuel injection strategy played the main role in mixing and combustion characterization. At the start of the spark, obtaining an optimized equivalence ratio distribution is important for improved performance and lower emissions. A higher in-cylinder pressure was reported with the TJI system compare to the conventional ignition system. Since a prechamber dominated the initiation of combustion, it promoted superior mixing and minimized the flame quenching in the main combustion chamber.

TJI system showed superior combustion stability, and its ignition energy requirement was lower for the lambda ranging from $\lambda = 1\text{–}1.8$. This may allow compact ignition coil and spark plug use, resulting in lower engine operating costs and compact packaging (Attard et al. 2010). The compression ratio of the engine can be increased without the possibility of knocking in the leaner mixture. It was predicted that an engine with a TJI system might achieve the indicated efficiency of up to 45%, which is more than the peak thermal efficiency achieved by the HCCI engines (Attard and Parsons 2010). Many researchers concluded that reduced NOx emissions would be possible for the TJI engine because of the lower temperature developed in the main chamber (Toulson et al. 2010; Alvarez et al. 2018 Jan). Furthermore, higher HC and CO emissions were reported with the TJI system. However, there is a scope to design an optimized prechamber that can promote even greater mixing and enhancing combustion parameters leading to lesser emissions and improved thermal efficiency.

9.4.3.3 Advantages, Limitations, and Future Prospects of Turbulent Jet Ignition

With increasing demands for an efficient engine with high power output and reduced emissions, the TJI engine has a significant role in a new generation engine with advanced technology. Engine with TJI system can offer several advantages over conventional ignition systems. The extension of lean limit operation is possible with the TJI system. Since it employs two combustion chambers (pre and main chamber), it offers greater control on the ignition events. TJI engine produces multiple and distributed sites in the main chamber, which provide a fast-burning rate in the main chamber with nominal cyclic variations. Also, the TJI system may work with a higher compression ratio since the tendency to knock is reduced by faster flame propagation. TJI provides flexibility to work in all ranges of engine loads without complex hardware systems. However, TJI involves challenges in handling fuel injection in the first chamber (prechamber). Therefore, research and development activities on injectors have to be taken up to inject the fuel effectively in the prechamber without any associated surface losses. An extensive computational study is also required to understand the underlying physics of mixing and flame growth from the prechamber to the main chamber. Higher improved combustion stability led to superior engine performance. However, HC emissions were also higher for the TJI system due to the additional surface area of the prechamber.

9.5 Concluding Remarks

Higher energy demand and stricter emission norms can be met by comprehensively analyzing the combustion events and parameters influencing them. The ignition system is responsible for igniting the fuel–air mixture in a SI engine. Ignition of the mixture has a significant effect on the flame evolution, growth, and propagation, consequently affecting the combustion. This chapter covers the importance of newer ignition systems and their evolution for IC engine applications. 1D and 3D modelling for SI engines have been included. The effect of the twin spark plug system promises a faster burn rate, leading to reduced combustion duration and improved combustion characteristics. Igniting leaner fuel–air mixture may not be possible with a conventional ignition system. Ignition of the lean mixture can be achieved by using advanced ignition systems such as laser-induced ignition, turbulent jet ignition (TJI), corona ignition. Laser-induced ignition is an electrodeless ignition system that gives the freedom to choose the ignition location anywhere in the combustion chamber, leading to improved combustion control. With laser-induced ignition and turbulent jet ignition, multi-point ignition is possible inside the engine combustion chamber. Therefore, considerable improvement in the flame propagation rate leading to lower combustion duration and improved combustion is possible. However, the practical application of advanced ignition systems faces several challenges that need to be resolved. In this chapter, the associated challenges and prospects are discussed.

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