Chapter 6
Overview, Advancements and Challenges in Gasoline Direct Injection Engine Technology

Ankur Kalwar and Avinash Kumar Agarwal

Abstract Gasoline direct injection engines have become the popular powertrain for commercial cars in the market. The technology is known for its characteristics of high power output, thermal efficiency and fuel economy. Accurate metering of fuel injection with better fuel utilization makes the engine possible to run on lean mixtures and operation under higher compression ratio relatively makes it of greater potential than PFI engines. Due to its capability of being operated under dual combustion mode by varying fuel injection timing, it can be realized as a cornerstone for future engine technology. Under mode switching, the homogeneous mixture for higher power output at medium and high load-rpm conditions, and stratified mixture for greater fuel economy at low load-rpm conditions are achieved respectively. It can be considered as the technology having the benefits of both diesel engine of higher thermal efficiency and gasoline engine of higher specific power output. But, with the growing concerns towards the limited fuel reserves and the deteriorated environment conditions, strict norms for tail-pipe emissions have been regulated. And considering the higher particulate matter and particle number emissions as a major drawback for GDI engine, upgradation and improvement in designs is needed to meet the required norms of emissions. In the initial section, the chapter gives a brief idea of the overview of the GDI combustion system and its operating modes. Subsequently, the improvements and researches in various aspects like fuel injection parameters and strategies, dual fuel utilization, mixture formation, lean burn control and application of providing turbocharging and residual gas fraction, are elaborately discussed in the direction of optimizing the performance of the engine. Further, the following section explains the major challenges and overcoming of this technology. Review of the work done by various researchers is discussed, focussing on the effect of operating parameters on particulates emissions, injector deposits and knocking in GDI engine.

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Finally, the chapter presents the concluding ways for enhancing the performance, way forward for making it more efficient and reliable by overcoming the limitations of GDI engine technologies.

Keyword Gasoline direct injection technology · Homogenous charge · Lean-burn mixture · Fuel economy · PM emissions

Abbreviations

ATDC	After top dead centre
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTDC	Before top dead centre
CAD	Crank angle division
CFD	Computational fluid dynamics
CO	Carbon monoxide
CR	Compression ratio
DI	Direct injection
DISI	Direct injection spark ignition
DNA	Deoxyribonucleic Acid
EGR	Exhaust gas recirculation
GDI	Gasoline direct injection
GPF	Gasoline particulate filter
HC	Hydrocarbons
IC	Internal combustion
IMEP	Indicated mean effective pressure
ITE	Indicated thermal efficiency
MPFI	Multi-point fuel injection
NEDC	New European driving cycle
PFI	Port fuel injection
PM	Particulate matter
PN	Particulate number
RON	Research octane number
SI	Spark Ignition
TEM	Transmission electron microscope
THC	Total hydrocarbon
TRF	Toluene reference fuel
TWC	Three-way catalyst
VCR	Variable compression ratio
WLTC	Worldwide harmonized light vehicles test cycles

6.1 Introduction

Rising consumption of petroleum products and deteriorating condition of the environment has caused the implementation of the stringent emission standards globally and the development of notable engine technology. The research in engine technology focuses on meeting the objectives of minimizing the fuel consumption and engine emissions, and maximizing combustion efficiency and specific power output of the engine. All these parameters are directly or indirectly influenced by the process of mixture formation which can be either external, internal or both. Gasoline direct injection technology involves creating an air-fuel mixture inside the cylinder by injecting high pressure gasoline fuel directly into the air present in cylinder unlike port fuel injection and ignited with a spark plug. Thus, we get the combined advantages of both diesel and petrol engine i.e., brake specific fuel consumption approaches that of diesel engine and specific power output of petrol engine (Blair 1996). Formation of air-fuel mixture externally using carburetor and injection of fuel in low-pressure manifold has totally occupied 20th century for SI engine development. It has benefits of allowing larger time for mixture formation as it is independent of phase transformation inside the cylinder, thus leads to better fluid dynamic condition and control (Zhao et al. 1999). But still, it has disadvantages of throttling, inlet valve-wetting and charge loss due to valve overlap. GDI overcomes these limitations and its unthrottled operation during part-load conditions significantly improve fuel economy, cause fewer emissions and allow for leaner combustion. Early fuel injection for homogeneous condition results in charge cooling which certainly allows provision for higher compression ratio and lower octane rating fuels as comparison to that of PFI engines.

With the benefits of high thermal efficiency and substantially less HC and NO_x emissions, GDI engines are likely to dominate the powertrains of passenger cars. Although significant work in research and design is required for tackling the challenges of high particulate matter (PM) emissions and knocking tendency. Worldwide, countries have formulated strict legislations towards exhaust emissions from vehicles. In Europe, the target of approaching CO_2 emission of 95 g/km by 2020 for major light-vehicles has to be achieved. Average annual reductions in CO_2 emissions have to be 3.5 and 5% from 2017 to 2021 and 2022 to 2025 respectively, in the USA. India has decided to adopt Bharat stage 6 (BS-VI) from April 2020 directly from Bharat stage 4 (BS-IV) countrywide in order to curb the pollutant level. Euro 6 emission norms with 0.0045 g/km of particulate matter and the particulate number of 6×10^{11} particle number per km, are some of the examples showing stringent norms for emissions globally (China 2016). It requires more advancement in GDI technology, keeping in view of these regulations. Mazda SKYACTIV sets an example in this direction.[1] In Japan, industry-academia initiative of Research Association of Automotive Internal Combustion Engines aims at achieving the thermal efficiency up to 50% for GDI engine by 2020 (Aubernon 2014).

[1]Mazda Corporation, Skyactiv Technology. http://www.mazda.com/en/innovation/technology/skyactiv/.

Thus, examining the developments of GDI technology will be beneficial as the technology has significantly evolved and it has the potential of improvements in energy efficiency and emission reductions.

6.1.1 Evolution of Gasoline Induction Technologies

The strategies of mixture formation differentiate PFI from GDI engine as shown in Fig. 6.1. In PFI, fuel injection takes place over the back face of the inlet valve when it is in a closed state during exhaust stroke. Thus, it leads to the formation of liquid film on the back side of the inlet valve and on the walls of the intake port, causing wall-wetting phenomenon. These are the major concerns of the PFI engine which creates an error in metering and delay in fuel delivery. Injecting the fuel directly into the cylinder overcomes the problem of wall-wetting in the port; thus, much lesser time is required for fuel to transport. Also, better control of fuel to be injected helps the mixture burn leaner. Although, the port injection has the advantage of washing out the carbon deposits build up on the back of inlet valve due to positive crankcase ventilation and EGR. This trouble is mainly faced by GDI engines. Higher fuel injection pressure (4–15 MPa) in case of GDI enables the spray to atomize properly compared to PFI, where injection pressure is in range of 0.3–0.6 MPa. Better atomization of fuel results in a higher vaporization rate thus helps in tackling cold-start problems. Other advantages include fuel cut-off during deceleration and cooling effect by absorbing enthalpy of vaporization during phase change of liquid droplets. This increases the volumetric efficiency if fuel is injecting during the intake stroke (Chincholkar and Suryawanshi 2016).

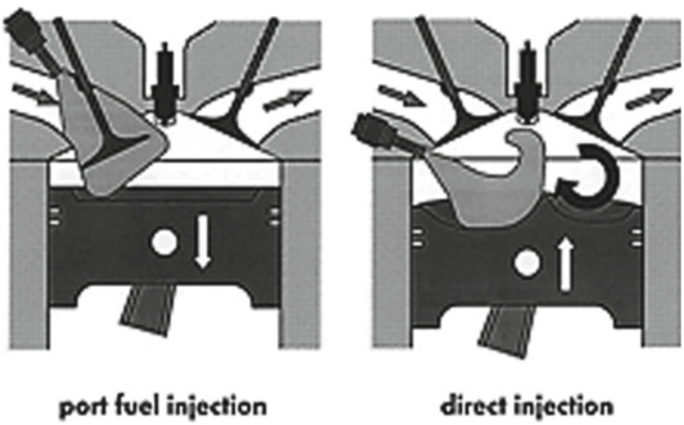


Fig. 6.1 PFI versus GDI engine configurations (Chincholkar and Suryawanshi 2016)

6.2 Overview of GDI Engine Technology

GDI technology allows the engine performance to vary according to the driving requirements. Its capability to operate in different modes according to user demand makes it efficient powertrain among SI engines. Broadly, there are two operating modes of GDI engines with three combustion system configurations.

6.2.1 GDI Operating Modes

The engine management system chooses the operating modes which are categorized by air-fuel ratio. Comparing the air-fuel ratio with the stoichiometric mixture of 14.7:1 for gasoline, the leaner mode can take the air-fuel ratio up to 65:1. Running the engine on the leaner composition of mixture helps in reduction of fuel consumption to a greater extent. There are two operating modes in the GDI engine.

(1) Stratified mode—It operates with overall leaner mixture and utilized during low load and low speed requirements. In this, fuel injection takes place late during the compression stroke, thus stratified layers of charge of different equivalence ratio are formed within the combustion chamber with the rich combustible mixture near the vicinity of spark plug and leaner mixture away from the spark plug. The toroidal or ovoidal cavity on the piston is used where combustion takes place as shown in Fig. 6.2. The location of the cavity on piston is according to the injector position and is used to create the swirl during the injection of fuel so that mixture having optimal air-fuel ratio gets located near spark plug when firing occurs. As a result, it can generate the flame and burn the overall lean mixture, hence gives better fuel economy (Nakashima et al. 2003). To a large extent, air and residual gases surround the stratified layers of charge, thus

Fig. 6.2 Piston showing swirl cavity (https://en.wikipedia.org/wiki/Gasoline_direct_injection)

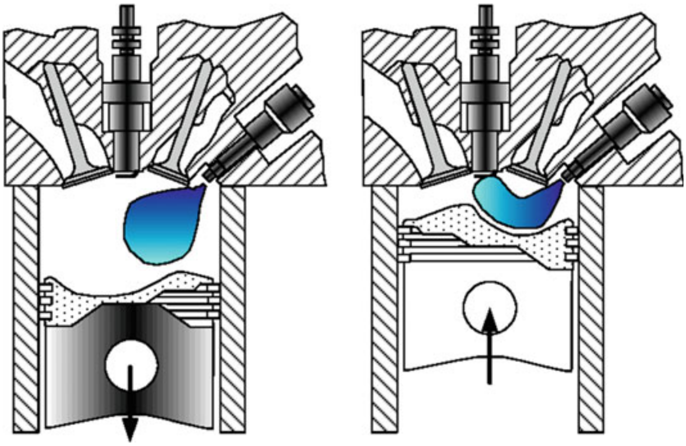


Fig. 6.3 Injection timing under homogeneous (left) and stratified (right) mode (Chincholkar and Suryawanshi 2016)

minimizes the heat loss during combustion by keeping the flames away from the walls and lower emissions due to less combustion temperature.

(2) Homogenous mode—This mode operates on stoichiometric composition at all loads and speeds. It involves the injection of fuel during suction stroke, thus gets sufficient time to form a homogeneous mixture and results in complete combustion and lesser emissions. Early injection cools the charge as the droplet absorbs heat of vaporisation from the air present inside the cylinder, thereby increasing the volumetric efficiency of the engine. Cooling of the charge allows for operating under higher compression ratio with greater knock tolerances.

Figure 6.3 shows the fuel injection timing for achieving homogeneous and stratified composition of air-fuel mixture. GDI engine with mixed operating mode has the best fuel economy. But mode switching in GDI is a very complex mechanism and a massive hurdle in the pathway of GDI development.

6.2.2 GDI Combustion Systems

GDI combustion systems are classified into three types as air-guided, wall-guided and spray-guided. These configurations are used for operating in the homogeneous and stratified mode as shown in Fig. 6.4. These are differentiated on the basis of injector position and piston cavity for in-cylinder motion. In air guided and wall guided systems, injector position is away from the spark plug and mixture formation is created by well-defined in-cylinder motion or by spray interaction with the cavity. In spray-guided, the injector is placed near the spark plug so that rich combustible mixture can be formed in the proximity of the spark plug. Spray-guided system is of

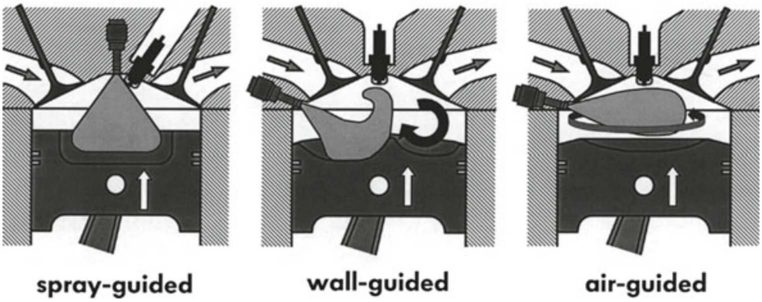


Fig. 6.4 Combustion systems of GDI (Chincholkar and Suryawanshi 2016)

second-generation type and has advantages of greater combustion efficiency which leads to improvement of the fuel economy. Wall-guided and spray-guided configurations are used for a stratified mode of mixture formation. Wall-guided system makes the use of piston bowl to guide the injected fuel to locate around the spark plug at the time of ignition while spray-guided make the use of its location to locate the spray near the spark plug.

6.3 Recent Progress in GDI Engine Technology

GDI technology has been evolved to a significant extent for the past two decades. Automotive engineers and researchers have been continuously improving the areas such as injection system optimization, mixture preparation, combustion system etc., in order to achieve good performance and lower emissions. Various areas of improvement are discussed below, along with the recent progress and work done in the area.

6.3.1 Injector Location

The wall guided configuration has limitations of fuel impingement and emissions of particulate and THC, thus is at least priority in recent engine production (Park et al. 2012). However, with a combination of air-guided system, the wall-guided system is still used to cut down cost in some systems (Yu et al. 2009). GDI combustion system employing a combination of air-guided and spray-guided have shown satisfactorily outcome in recent studies (Tang et al. 2018; Eichhorn et al. 2012). Spray-guided motion is used for stratified mode operation by incorporating late injections to reduce fuel impingement and also turbulence caused by in-cylinder air motion is considered to be significant while designing combustion system (Itabashi et al. 2017). In a spray-guided combustion system, the engine can be operated at a higher range of load and speed than that of wall-mounted combustion system as shown in Fig. 6.5.

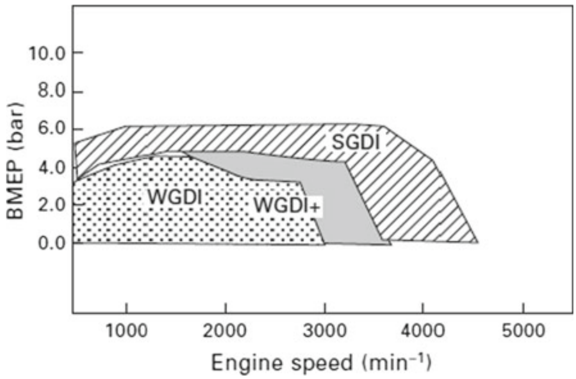


Fig. 6.5 Comparison of performance between wall-guided (WGDI) and spray-guided direct injection (SGDI) system (Zhao 2010)

In wall-guided and air-guided configurations, injectors are located on the side wall while, in spray-guided configuration, the injector is located centrally. Side-mounted injector results in enhanced tumble factor, reduction in thermal load, greater thermal efficiency and preignition suppression in comparison to central-mounted injector (Sevik et al. 2016). However, there are more chances of impingement which has its own drawbacks. Central injector offers greater flexibility and simplifies the design of the combustion chamber, while attempting to avoid wall-wetting in order to reduce emissions of PM/PN. It is situated centrally near the spark plug so as the spray easily reaches the vicinity of the spark plug in order to operate the engine in stratified mode. Also, piezoelectric injectors (Skogsberg et al. 2007) are centrally mounted for multi-injection operation in short intervals for obtaining a desired air-fuel composition for improved performance.

6.3.2 Dual Fuel Injection

Using gasoline blended with ethanol as a single fuel in fixed proportion limits the potential of ethanol to improve the engine performance under varying operating condition. For making flexible and efficient use of ethanol, a system having dual injection was introduced which covers the advantages of both port and direct injection. The dual fuel injection system is becoming an important trend in GDI combustion system by making the use of port fuel injection and direct injection as shown in Fig. 6.6.

Ikoma et al. (2006) initially proposed the use of dual injector which provides the advantages of achieving highest power output among similar displacement engines, better fuel economy and lowest emissions. They used dual fan-shaped spray DI injector to eliminate the limitation of a heterogeneous mixture in the absence of any devices for creating in-cylinder motion. Port fuel injector improved the homogeneity of the mixture during high load and low speed conditions.

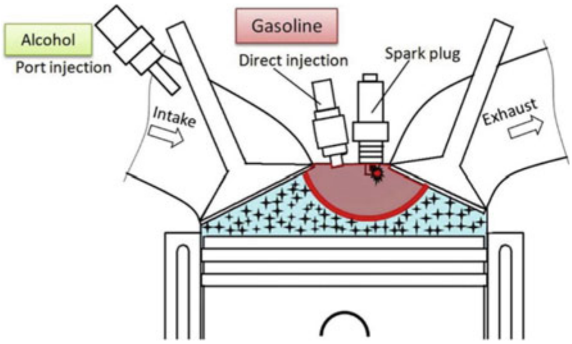


Fig. 6.6 Dual-injection system (PFI and DI) (Liu et al. 2015)

Many studies have employed the use of dual fuel combinations (mainly alcohol and gasoline) for port and direct injection application. Feng et al. (2018) evaluated the combustion performance using n-butanol as direct injection fuel and gasoline as port-fuel injection fuel. Different injection ratio of these two fuels was used by varying the mass fraction of gasoline in PFI from 100 to 0%. Dual fuel injection strategy using n-butanol with optimum spark timing benefitted in extending the engine load and higher IMEP with early rise in combustion pressure as compared to gasoline PFI and GDI. However, indicated specific energy consumption decrement showed better fuel energy conversion efficiency when fuelling with n-butanol dual injection. In contrast, despite cooling effects, knock propensity for smaller ratios of DI of n-butanol are increased as compared to butanol direct injection and GDI relatively due to low RON and increasing engine load. In an experimental study (Zhuang et al. 2017), the author found that ethanol direct injection with gasoline port injection is more effective than gasoline port injection and GDI in eliminating engine knock with more spark advance and thereby enhancing the thermal efficiency of small engines.

Authors have also experimented with port injection of alcohol and direct injection of gasoline. He et al. (2016) studied the combustion performance taking ethanol and n-butanol as the port injected fuel and gasoline as direct injected fuel. He found better efficiency and lesser emissions for the dual fuel strategy of port injection of n-butanol and direct injection of gasoline than gasoline direct injection only. Also, the highest thermal efficiency was observed for ethanol and gasoline combination as a port and direct injected fuel respectively.

These results were justified by the work of many researchers in a direct or indirect way. Qian et al. (2019) found the similar indicated thermal efficiency in the dual fuel system when 35% of ethanol is port injected and gasoline surrogates (TRF) of RON of 75 is direct injected, compared with direct injection of TRF of RON 95 under knock limited spark timing. Thus, the same combustion characteristics and efficiency can be obtained with fuel having less RON if operated with an optimal amount of ethanol in port injection, to that of operating solely on fuel having high RON. The results also accounted for longer flame development duration (about 2°CA) and rapid combustion duration (about 3°CA) and lesser emissions on increasing the ethanol injection ratio with direct injection of fuel of RON 90. Increasing the proportion of ethanol for the dual-fuel injection strategy (DI of gasoline and port injection of ethanol) could increase the compression ratio of the engine leading to rise in engine efficiency and could help in extending the knock-limit effectively (Liu et al. 2014) while reducing the particulate matter emissions (Liu et al. 2015).

Gasoline/alcohol blended fuels have also been tested for their combustion, performance and emissions characteristics and the results were positive in terms of efficiency and emissions (Turner et al. 2011). However, Storch et al. (2015) found the presence of diffusion flames during combustion in the gaseous phase and improper evaporation of droplets for gasoline blended with 20% ethanol by volume as compared to iso-octane. Also, there is more susceptibility of higher unregulated emissions for ethanol-gasoline blended fuels, especially carbonyls (Clairotte et al. 2013). Qian et al. (2019) investigated the combustion and emissions in a GDI engine for C3-C5 alcohol blended with TRF, resulting in the mixture of fixed RON of 95. He found the advancing of knock-limiting spark timing on blending with alcohols where ethanol/TRF and n-propanol/TRF showed more advancing than remaining one. Blend of n-butanol/TRF showed the highest ITE among other blends at the same blending ratio while n-propanol/TRF mixture showed the highest indicated thermal efficiency for the same oxygen content. Considering the combustion and emissions results, n-propanol and n-butanol are reported to be more suitable alternative fuels than ethanol and n-pentanol. Increasing the ethanol percentage lead to a significant rise in HC and NO_x emissions while the reduction in PM emissions (Costagliola et al. 2013).

From the previous studies and all the results discussed above, it can be justified that addition of ethanol as fuel can improve combustion efficiency of SI engine (Balki et al. 2014). Presence of inherent oxygen molecules can widen flammability limit which helps in lean burn combustion (Koç et al. 2009) and higher-octane rating of ethanol can improve the compression ratio. On the other hand, limitations like lower heating value of ethanol, higher latent heat of vaporization and lower saturated vapour pressure may result in cold-start issues.

6.3.3 Split Injection Strategy

In split injection strategy, primary injection is done during the intake stroke to give sufficient time for forming a lean homogeneous mixture; then the secondary injection is done while compression happens such that stratified mixture is formed. Thus, it is used for obtaining overall lean homogeneous stratified charge at the start of ignition (Song et al. 2015; Costa et al. 2016).

Many investigations have been done on split injection of GDI engine. In the researches carried out by Song et al. (2015), Kim et al. (2015), improvement in mixture quality and combustion characteristics were observed due to split injections, one is done at the middle of induction and other at the starting of compression. Retarding the injection timing for the second injection of gasoline results in the greater turbulence intensity inside the cylinder. This results in shorter combustion duration with higher in-cylinder pressure since turbulence created due to faster movement of spray increases the flame propagation speed. However, the local regions of rich-fuel mixture cause an increase in higher emissions. Clark et al. (2016, 2017) analyzed the combustion performance under the effect of different split injection timings using the optical engine. An increase in indicated mean effective pressure (imep) was observed on retarding the second gasoline injection or advancing first gasoline injection. The highest imep was obtained for the primary injection at 300 CAD BTDC (suction stroke) and secondary injection at 110 CAD BTDC (compression stroke), considering the starting of power stroke at 0 CAD at TDC. The eccentricity of flame boundary tends to increase on retarding second injection timing because of the decrease in homogeneity with regions having variable laminar burning speed. On the other hand, greater particle emissions, fuel film formation due to spray impact and incomplete evaporation were still to be the areas of study for GDI engines (2016).

Ji et al. (2018) performed the investigation for varying second gasoline direct injection timings in hydrogen-blended gasoline direct injection engine. Hydrogen is blended by hydrogen port injection system during intake. The blending of hydrogen results in minimizing the variations in the performance of engine caused by parameters affected by different second injection timing, when compared to operate with pure gasoline. Hydrogen blended mode leads to higher brake thermal efficiency and maximum pressure rise due to rapid combustion. Hydrogen addition had resulted in a significant reduction in HC, CO_2 emissions and particulate number while greater NO_x percentage was observed.

6.3.4 Fuel Injection Parameters

Fuel injection pressure and fuel injection timing are considered to be among the most influential parameters affecting the combustion performance of the engine. Huang et al. (2016) analyzed the impact of injection timing on the mixture formation and combustion results for a dual fuelled engine having direct injection of ethanol and port injection of gasoline. They justified the results with the help of CFD simulation studies. Retarding direct injection timing of ethanol proved effective in producing a greater cooling effect and mitigating knock tendency, however, combustion and emissions results of late injection were very degenerated. The results found that late direct injection of ethanol leads to form richer composition opposite spark plug and leaner mixture near spark plug which retards the combustion speed. Severe problem of fuel impingement on piston occurs due to reduced volume of the combustion chamber at the time of compression stroke and this causes slower in-cylinder motion and incomplete evaporation. Thus, higher HC and CO emissions resulting from incomplete combustion are major concerns though NO_x was in less percentage due to reduced volume of the combustion chamber.

Song et al. (2018) investigated the effect of injection pressure and coolant temperature for two fuel injection timings on THC and particle emissions. As higher injection pressure gives better atomization and reduces particulate emissions, while the increasing temperature of coolant during cold-start could effectively improve engine efficiency and reduce emissions. His results stated that for wall wetting condition (injection at 330° CAD bTDC), increasing injection pressure up to 50 MPa from 10 MPa can lead to the reduction of particulate emissions by 90% due to the formation of a thinner film. For non-wall wetting condition (injection at BTDC 270), an increase in injection pressure didn't have much effect on particulate emission. Also, minute reduction in THC was observed on increasing fuel injection pressure. However, the increment in coolant temperature from 40 to 80 °C during cold start reduced the soot and THC substantially along with better thermal efficiency.

6.3.5 Injector Design

Typical designs of different kind of injectors, namely, swirl, outward opening and multi-hole injectors are shown in Fig. 6.7. Multi-hole nozzle is more popular because jet orientation control can be easily achieved with this. Toyota made use of the slit

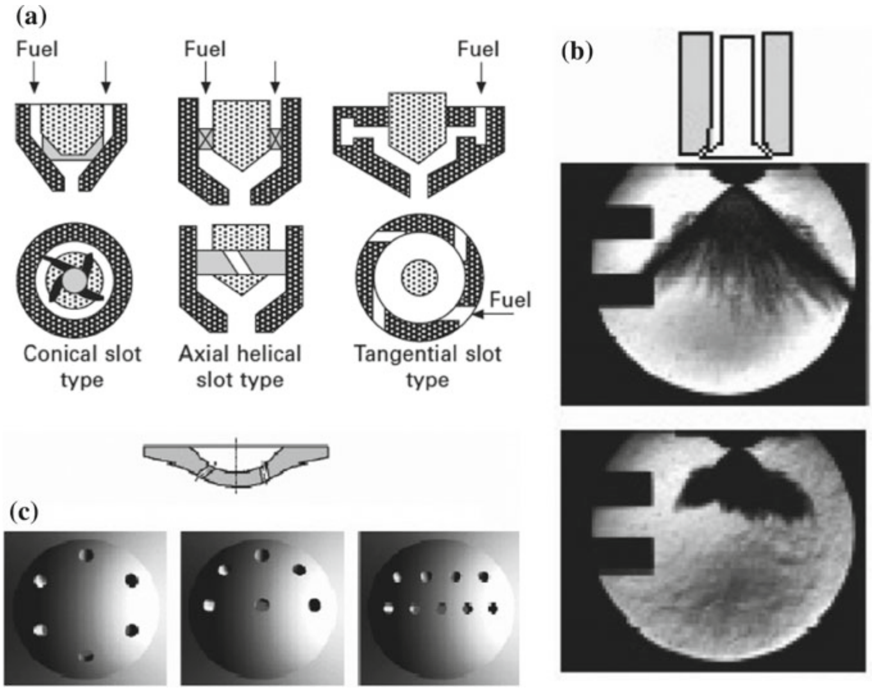


Fig. 6.7 **a** Swirl injector **b** outward opening injector **c** multi-hole injectors (Zhao 2010)

nozzle due to its fan-shaped spray which results in wider dispersion and proper atomization (Matsumura et al. 2013). Features like fast response time with better accuracy and control put the piezo-driven injector on the upper side as compared to solenoid-driven injectors (Dahlander et al. 2015), however, their applications are restricted due to high cost.

Recently, the utilization of outward-opening piezo driven injectors in stratified mode has been increased as it produces a spray of relatively shorter penetration length which eliminates the trouble of wall-wetting (Dahlander and Hemdal 2015; Stiehl et al. 2013). Additionally, it results in more ignition stability because of slower flow velocity in vortex than mainstream spray.

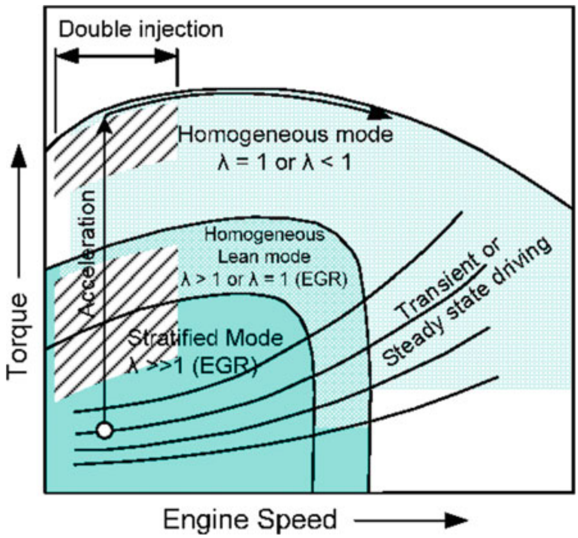
6.3.6 Application of Turbo-Boost, VCR and EGR in GDI Engine

For achieving higher thermal efficiency while developing GDI combustion system, larger compression ratio (CR) and minimal heat losses play a vital role in fulfilling the requirements. For natural aspirated GDI engine, the value of CR can lie in the range of 11–13 (Lee et al. 2017; Hwang et al. 2016) while for turbo boost engine, CR reduces to 9.5–11 (Wada et al. 2016; Yamazaki et al. 2018) as it is limited by knocking phenomenon. The highest CR of 15 is achieved in the development stage (Lee et al. 2017). Thus, naturally aspirated engines enjoy the advantage of better thermal efficiencies. But boosting helps in attaining higher mean effective pressure and higher power output with downsized engines.

Incorporating variable compression ratio (VCR) (Kojima et al. 2018) or variable valve timing (VVT) (Lee et al. 2017; Yamazaki et al. 2018) resulted in attaining CR above 13. Asthana et al. (2016) designed seven different configurations for VCR, but mostly lacking the adaptability for high speed, robustness and cost. The Nissan developed the world’s first production-ready VCR turbo engine in 2017 (Kojima et al. 2018). It covers the range of CR 8.0 to 14.0 with the help of multi-link rod crank and servo motor for continuous variation. Different design models have been adopted for VCR adaptability by AVL and FEV, where the variation of rod length was done (Wolfgang et al. 2017; Kleeberg et al. 2013). Honda utilizes dual piston system (Kadota et al. 2009). Studies suggested that the VCR system resulted in a rise in fuel economy by 8% (Wolfgang et al. 2017).

Applying exhaust gas recirculation (EGR) helps in minimizing combustion temperature by increasing the specific heat of gaseous mixture, thus reduces NO_x and also improves fuel economy. EGR contribution in improving thermal efficiency can be understood by the effect of two factors. Firstly, EGR minimizes the pumping loss due to availability of less oxygen in the cylinder; throttle needs to be opened more and second, it reduces the heat loss from the engine because of less combustion temperature. Thus, at higher loads, knock suppression and less heat loss due to EGR improves the thermal efficiency (Cairns et al. 2006; Potteau et al. 2007). As shown in Fig. 6.8,

Fig. 6.8 Different operating modes with EGR (Sharma et al. 2018)



stratified mode and lean homogeneous mode are applied for low load-rpm and part load-rpm conditions respectively, but the lean mixture combustion leads to high NO_x emissions. Thus, EGR addition is done to limit NO_x levels in the exhaust. In high load and low rpm conditions, stratification results in high soot formation due to availability of highly rich-mixture. And in high load and high rpm conditions, stratification of the charge cannot be maintained due to high turbulence. Thus, it is limited to low load and low rpm conditions, while homogeneous mode with the stoichiometric mixture is used for high load and rpm conditions. The double injection is used during accelerating conditions while taking the transition from stratified to homogeneous mode at low rpm conditions. It results in forming stratified with the overall lean homogeneous mixture. In high load and low rpm conditions, large combustion duration and high in-cylinder temperature increase the chances of knocking. It can be inhibited by the application of double injection strategy. However, applying high EGR rates worsen the combustion stability of the engine (Yu and Shahed 1981). Hydrogen can be used as an additive for gasoline fuel as it improves the combustion stability due to faster flame speed, brings homogeneity in mixture due to larger diffusion coefficient and reduces the chances of knocking due to higher ignition temperature (Kim et al. 2015). Hence, hydrogen can be used to enhance combustion stability at high EGR rates. In the study done by Kim et al. (2017), it was found that hydrogen exhibited an important role in improving the combustion and emission characteristics of turbo GDI engine with EGR. They found that the addition of hydrogen results in faster combustion with less cycle-to-cycle variations and provides stability in combustion performance. Thus, the engine can be operated under high EGR rates with improved thermal efficiency. Reduction in HC and CO emissions were observed, but NO_x was higher due to higher adiabatic flame temperature.

But these desired requirements can only be fulfilled by cooled EGR which not only reduces NO_x but also help in knock suppression, especially at higher loads. On the other hand, hot EGR reduces the volumetric efficiency of the engine but decreases HC emissions during cold-start and low load. The study suggested that hot EGR can greatly affect the combustion duration and efficiency of the engine as compared to cooled EGR (Toulson et al. 2007). It is reported (Wei et al. 2012) that, with cooled EGR there was a reduction up to 90% in NO_x and 50% in CO, and also lowers the brake specific fuel consumption by 11%. But the THC emissions shoot up significantly. Hot EGR can result in four times NO_x emissions than cooled EGR, while cooled EGR can produce 1.5 times THC emissions than hot EGR.

6.3.7 Lean-Burn Strategy

Several pieces of research have been done for lean combustion in GDI engine operating under stratified mode. Though the results proved effective in increasing fuel economy, high engine NO_x emissions and low exhaust temperature have always been an obstacle in emission control and after-treatment devices. Earlier, Toyota, Nissan and Volkswagen have proposed for first-generation lean-burn engines which were based on wall-guided combustion type having side mounted injector. Spray utilizes the shape of the piston cavity to deflect its movement such that spark plug get surrounded by the rich mixture. The mixture development is easier but depends on the in-cylinder flow which gets influenced by various operating conditions (Kim et al. 2009; Lee and Lee 2006). Thus, combustion of the stratified mixture is limited by a particular range of operating conditions, and also wall-wetting conditions lead to emissions of higher unburnt hydrocarbons. BMW and Daimler-Benz have manufactured commercial lean-burn GDI engine with spray-guided combustion system. Although, the high cost of injection system and after treatment devices has demolished the wider utilization of these engines. However, with an increase in cost of fuel and burden of CO_2 emission regulation, the lean-burn engine may find applications to a greater extent.

Park et al. (2014) evaluated the combustion and emissions characteristics along with visualization studies of ultra-lean gasoline DI engine operating under stratified mode. With spray-guided configuration, they were able to improve fuel economy up to 23% for excess air-ratio of 4. They optimized the event timing for injection delay and ignition advance taking the stoichiometric conditions as reference. Flame visualization was also carried out along with in-cylinder measurements. Under lean operating conditions, combustion phasing occurred earlier till BTDC 41 CAD with maximum pressure in the cylinder was attained at ATDC 2 CAD as shown in Figs. 6.9 and 6.10. Despite stable combustion at an excess ratio of 4, there were an increased amount of NO_x and HC emissions due to the presence of over-rich mixture near the spark plug and more fuel impingement on piston respectively. As shown in Figs. 6.9 and 6.10, the blue flame can be realized as a result of premixed combustion and are

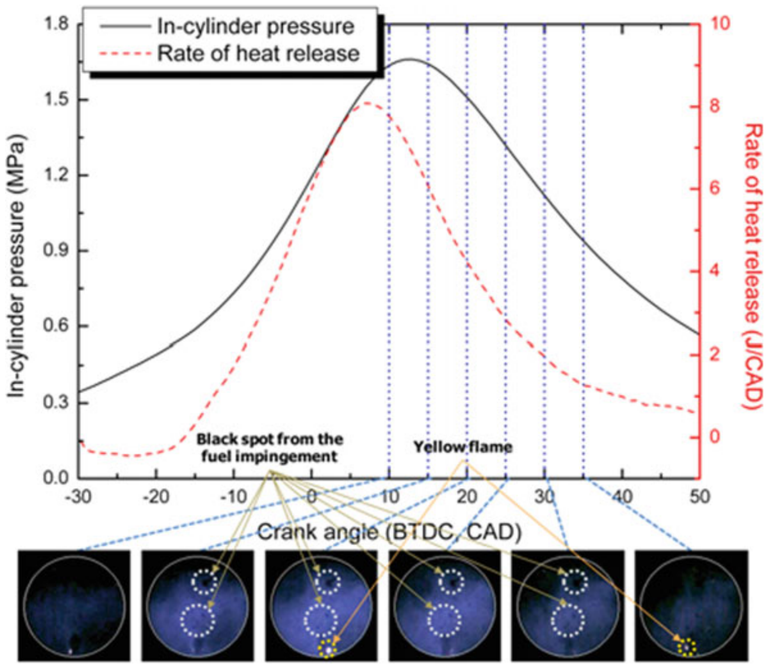


Fig. 6.9 Pressure and heat release curves with flame images for stoichiometric conditions having injection at BTDC 330 CAD and spark advance timing at BTDC 50 CAD (Park et al. 2014)

of less intensity. On the other hand, diffusion combustion near spark plug can result in higher luminosity due to residual fuel on electrodes while operating in stratified mode.

In many studies (Park et al. 2014; Matthias et al. 2014), it is reported that lean burn combustion can minimize BSFC to a great extent along with minimizing the coefficient of variance and knocking. Iida (2017) achieved the burning of the super lean mixture ($\lambda = 1.92$) by utilizing highly energized ignition system and complying large tumble ratio of 2.5, thereby getting an indicated thermal efficiency up-to 46% in single cylinder engine. However, large PM/PN emissions are the disadvantages of the stratified mode operation. It has been found that particle concentration from lean stratified combustion is much higher than the conventional stoichiometric and lean homogeneous combustion, whereas lean homogeneous condition produced minimum particulate number and soot (Bock et al. 2018). Figure 6.11 reports the similar results of higher PM emissions for the lean-burn case.

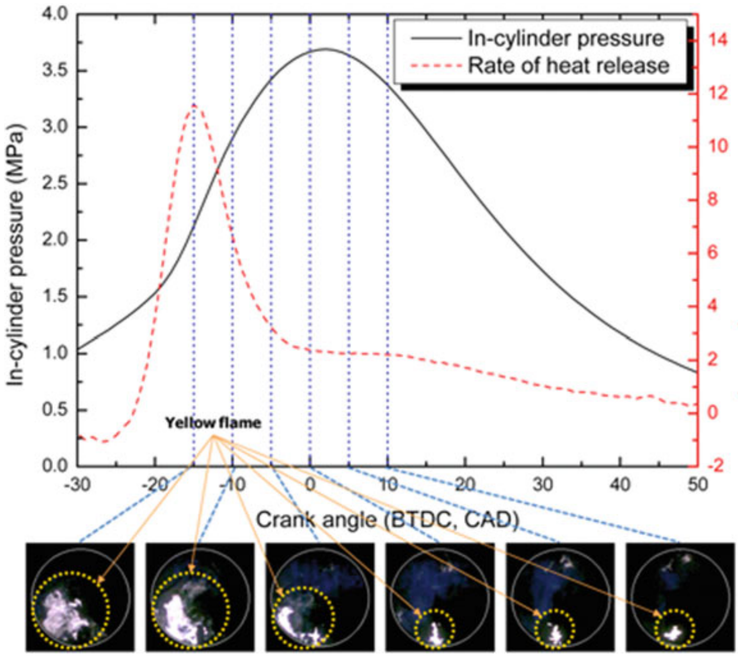


Fig. 6.10 Pressure and heat release curves with flame images for lean combustion conditions having injection at BTDC 31 CAD and spark advance timing at BTDC 35 CAD. (Park et al. 2014)

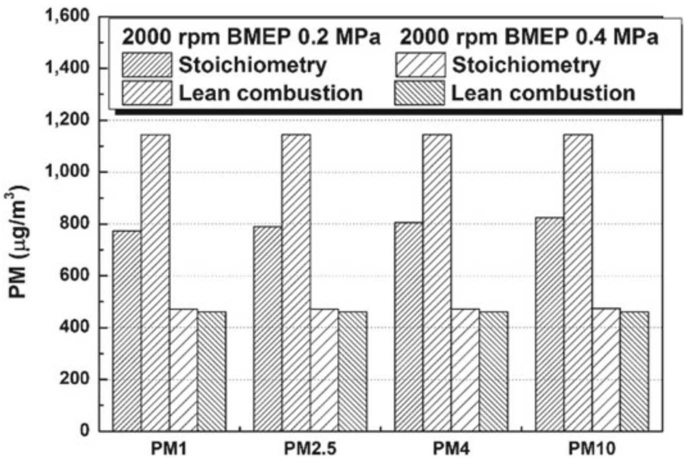


Fig. 6.11 Effects of engine load and combustion strategy on particulate matter (PM) mass concentration having excess air ratio of 3.6 and 2.1 for 0.2 MPa and 0.4 MPa respectively (Park et al. 2016)

6.4 Challenges in GDI Engine Technology

Despite having several best-in technology features, GDI engines are facing major challenges of high particulates emissions, injector fouling due to deposits and deto-knock. Injector deposits ultimately hinder the proper mixture formation, as a result, large PM emissions can be observed in the exhaust. Deto-knock occurs due to pre-ignition of charge and causes large pressure oscillation during combustion. It has a very damaging effect on engine components and performance. The factors responsible for these limitations of GDI engines along with the preventive measures are explained elaborately in the subsequent sections.

6.4.1 Particulates and Soot Formation in GDI Engine

6.4.1.1 Causes and Sources

Although GDI engines are very popular due to various advantages such as high thermal efficiency and lower BSFC, however large soot and particulate emissions is one of their major limitations. The process of soot formation is initiated by the soot precursors like C_2H_2 (ethylene) and PAH (polyaromatics hydrocarbons), then the growth of nucleates takes place by agglomerating particles and their coalescence, and finally followed by their oxidation (Tree and Svensson 2007). The gaseous and semi-volatile hydrocarbons from engine exhaust get adsorbed on these solid particles and coagulate into larger particles. Formation of soot in GDI engines can be attributed to mainly three sources, namely, pool fire due to fuel impingement (Velji et al. 2010), improper mixing in stratified combustion of the charge (Lucchini et al. 2014) and the diffusion combustion of fuel jet near injector (Berndorfer et al. 2013). In homogeneous mode, pool fire and diffusion combustion are dominant, while the presence of rich-mixture locally and pool fire are the major factors in stratified mode. The exhaust particles are classified based on their sizes and also divided into nucleation and accumulation mode as shown in Fig. 6.12 (Kittelson 1998).

In a report published in June 2014, the World Health Organisation (WHO) officially classified engine soot particles as carcinogenic. Research has established that material found in PM 2.5 is water soluble and can form droplets under certain conditions. PM 2.5 can penetrate the cardiovascular system of the human body which results in pulmonary diseases and can affect DNA (Short et al. 2015). Thus, institutional bodies across the world have set stringent emissions norms to curb the ill-effects of emissions on the environment. As per application of Euro 6 standards in Europe, particulate mass emission is restricted to 4.5 mg/km and particulate number emissions are limited to 6.0×10^{11} particles/km from 2017 (Euro 6c). The limiting values for particulate mass and number are shown in Fig. 6.13 for PFI and GDI engines with their current emission levels.

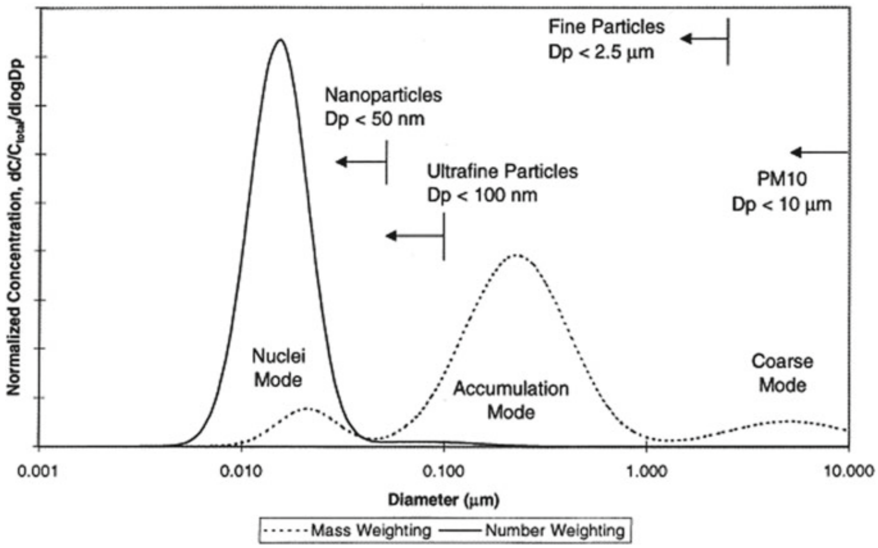


Fig. 6.12 Size distribution of engine exhaust particles on mass and number basis (Kittelson 1998)

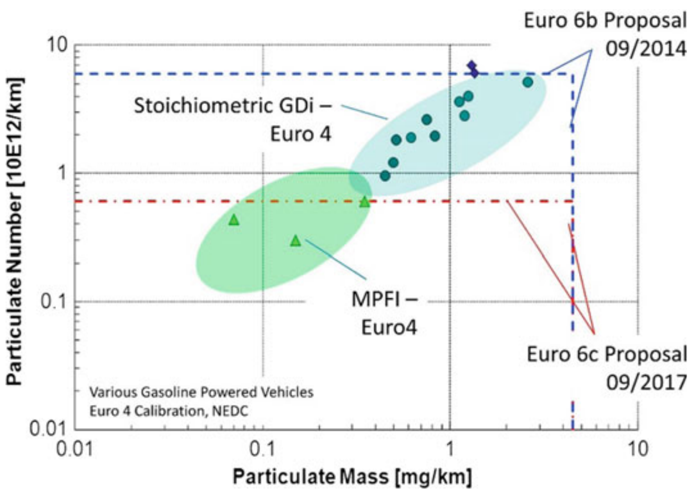


Fig. 6.13 Euro 6 standard for PM and PN emissions (Qian et al. 2019)

6.4.1.2 Responsible Operating Parameters and Controlling Measures

Researchers have been studying particle emissions under different combustion modes of an IC engine. Their formation, size and number distribution are largely dependent on the fuel composition, mixture preparation, ignition mechanisms and operating conditions of the engine. Many studies have been conducted to improve the atomization of fuel spray for proper mixing by increasing the injection pressure, which can greatly inhibit the formation of soot. Injection pressures up to 35 MPa have been used for refining the spray. Hoffmann et al. (2014) reported a decrease in Sauter mean diameter (SMD) i.e., D_{32} of spray droplets with increase in injection pressure. However, atomization can be largely influenced by injector design parameters; thus in-depth research is needed in this aspect.

It is stated that the New European Driving Cycle results in approximately ten times higher concentration of particle number for GDI engine than that of PFI, while particle mass emissions lie between that for PFI and diesel engines. Hence, it is very crucial for the GDI engine to limit their particulates emissions to meet the prescribed emissions standard. It can be done in two ways, either by using after-treatment systems like gasoline particulate filter (GPF) and three-way catalyst (TWC) or by reducing in-cylinder particle emission. Aftertreatment devices generate exhaust back pressure. Hence, optimizing the different factors responsible for in-cylinder particle generation will certainly limit the emission. For this, multiple injection strategy, injection parameters, fuel type and combustion mode are some of the factors to be optimized. Also, understanding soot particles characteristics, structure and morphology will help to get better insight for its controlling actions. Particles from GDI engine mostly contain soot as compared to organic particles than PFI engines as shown in Fig. 6.14. Figure 6.15 shows the TEM images of soot and organic particle from gasoline engine illustrates the chain and agglomerates structures of soot with darker regions of organic particles which are lighter and inhomogeneous (Xing et al. 2017).

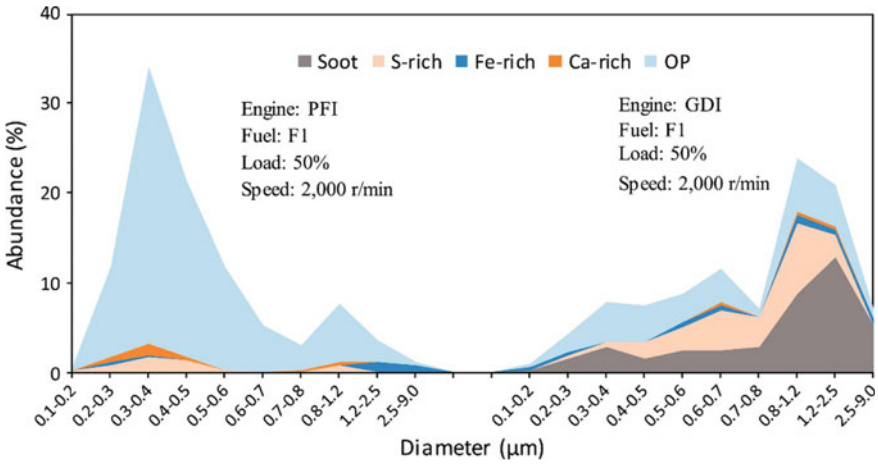


Fig. 6.14 Number size distribution of different particles types in PFI and GDI engines (Xing et al. 2017)

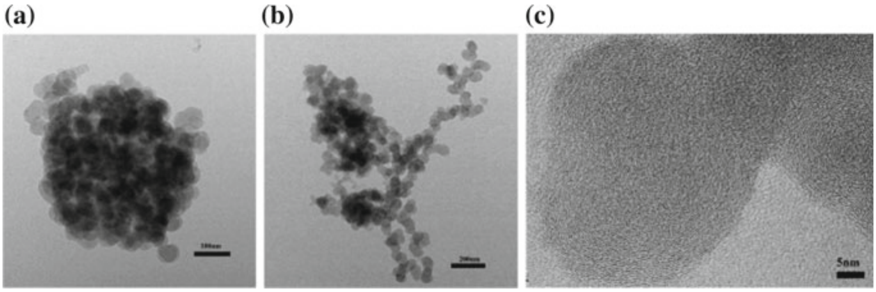


Fig. 6.15 Soot particles images from TEM **a** Cluster-like soot, **b** chain-like soot **c** high-resolution TEM image of soot (Xing et al. 2017)

It is reported that the injection timing of fuel has a significant effect on particulate emissions characteristics. Ketterer and Cheng (2014) found that more fuel impingement occurs when fuel is injected either at the early induction or at the late compression, which certainly leads to more PM emissions. If injection happens early in the compression stroke, droplets get more time to evaporate and film formation occurs in much less quantity. Hence, particle number and size reduce than at late injections. Moreover, fuel impingement characteristics are found to be directly influenced by injection timing (Beavis et al. 2017). The film formation location has also been noticed to be different for different fuels by many studies which can be stated as a probable reason for higher particulates for heavier fuels.

Based on the endoscopy studies done on a single cylinder engine, Berndorfer et al. (2013) concluded that diffusion combustion of fuel jet near injector is a major cause of particulate formation. As early injection was done during suction stroke, the blue flame radiation above piston indicates the well-mixed homogeneous mixture. However, the diffusion flame resulting from the injector tip can be observed as highly luminous, indicating rich mixture condition. The results showed a clear correlation of injector diffusive flame and PN with soot mass emissions.

In a report given by the Japan Petroleum Energy Centre with other agencies, particulate emissions from different engines with the varying after-treatment system were collected and analyzed. It can be inferred that particle number size distribution from DISI engine is unimodal having peak concentration of particle size of around 85 nm. Local availability of rich-fuel mixture in lean-burn DISI engine resulted in 10 times higher emissions compared to stoichiometric DISI engines. Overall the PN distribution for both cases of DISI engine lies much higher than that of MPFI gasoline and diesel particulate filter (DPF) vehicles.

Location of injector also plays a vital role in mixture preparation as there are fewer chances of spray impingement on the wall for spray-guided arrangement than wall-guided arrangement. Consequently, diffuse combustion seldom occurs during combustion. Thus, particulate matter is emitted in less quantity in spray-guided DI engine than that of wall-guided (Price et al. 2006).

As port fuel injection systems are believed to emit fewer particulates, thus several automobile companies turned for dual injection systems (port and direct injection) (Trimbake and Malkhede 2016). Toyota bought PFI and GDI dual injection system in 2005, to improve mixture quality and reduce emissions, and similar strategies later followed by Nissan, Suzuki and Honda. Audi bought the similar strategy recently, reducing particulate emissions and meeting the standards of Euro 6 without using gasoline particulate filter. Daniel et al. (2013) investigated the PM emissions using dual injection strategy. And found to have higher in-cylinder temperature due to dual injection which enhances the burning of fuel droplets and eliminates soot formation to a good scale. The PFI also provides more time for mixture preparation than solely DI, thereby reducing the problem of wall-wetting. In dual injection mode, the average size of PM is comparably smaller than DI mode and the accumulation mode particles are negligible.

Additionally, two fuels can be used in a dual injection system for better control of engine performance and emissions by varying the mixture properties. In the study done by Liu et al. (2015), it was reported that as compared to alcohol-gasoline duel fuel SI mode, gasoline-alcohol duel fuel SI mode was more efficient in fuel economy due to the utilization of the higher latent heat of vaporization of alcohol. With the increase in alcohol percentage, a significant reduction in PN was observed under all combustion strategies.

Various physical and chemical properties of the fuel like viscosity, boiling point, surface tension, distillation curve, vapour pressure, molecular structure (length of carbon chain, branching, unsaturated bonds, rings, etc.) largely affect the particulate emissions (Chapman et al. 2016). Jiang et al. (2018) discovered that three surrogates fuels of the same RON have lower particulates number than gasoline due to the presence of heavier molecules in gasoline.

The engine operating conditions like load, equivalence ratio, injection parameters, charge boosting, EGR, ignition timing etc. certainly influence the particulate emissions as justified by several studies. Bonatesta et al. (2014) observed higher soot mass emissions under high load-low speed and medium load-medium speed condition as a result of high nucleation rates, in the homogeneous stoichiometric mode of combustion. According to a study (Pei et al. 2014), the air-fuel ratio is likely to affect the particle number concentration and causes decrement in particle number on increasing the air-fuel ratio for a rich mixture. It is also believed that lean burn gasoline DI engines emit a larger amount of ultra-fine particulates than a conventional engine. Further increase in air ratio beyond 2 leads to increment in particulate number and PM emissions, which could be likely due to increased air pressure and a decrease in combustion temperature. High ambient pressure results in lower penetration of spray, forming local rich-mixture in the cylinder.

High fuel injection pressure leads to finer droplets, high spray velocity i.e., more penetration length, and shorter duration of injection. All these parameters enhance proper combustion by restricting the formation of locally rich mixture composition and wall-wetting trouble (Chung et al. 2016).

De Boer et al. (2013) varied fuel temperature and studied its effects on mixture formation and particulate emissions. They operated the engine with injection pressure in the range of 150–300 bar and fuel temperature of 320 °C which is above the supercritical condition of gasoline (45 bar and 280 °C). The results showed a significant reduction in particulate number, ranging from 47 to 98%. It dictates the potential of fuels in the supercritical state for PN reduction than liquid fuels.

Few studies have been done which quantify the EGR on PM emissions from SI engines. It is believed that EGR can affect the engine combustion and emissions by (a) heating intake charge (b) increasing heat capacity (c) diluting the charge and (d) changing chemical aspects (Zhao et al. 2001). Hedge et al. (2011) concluded from their study on light-duty GDI engine that cooled EGR can bring down the particle mass by 65% and particle number by 40% in most of the conditions. Wide EGR range can result in a decrease in combustion temperature and can lead to a higher number of accumulation mode particles, while nucleation mode particles showed a decreasing trend (Lattimore et al. 2016).

Turbocharging results in improved performance of the vehicle, higher thermal efficiency, reduced fuel consumption and exhaust emissions, thus are widely used in GDI engines. Although Cucchi and Samuel (2015) observed that there was a clear difference in particle concentration before and after the turbocharger. The centrifugal motion of the exhaust gas particles enhanced the nucleation of particles and agglomeration, which are fragmented into micro-scale particles. Thus, the particles size was seemed to be larger after the passing through the turbine. Whelan et al. (2013) studied the particulate emissions from wall-guided turbo-charged DI engine running in transient conditions of cold-start and warm-up. Total particle count was found to decrease during cold start transient and was tend to increase with higher coolant and oil temperature of the engine.

Jiang et al. (2017) studied the variation in spray and emission due to injector deposits. Deposits on the injector tip increased the penetration length and mean droplet size of spray, which was mainly responsible for a larger amount of PM emissions. The deposits accumulation on injector can deteriorate the particulate emissions by these possible sources (a) fuel impingement due to larger penetration length (b) incomplete combustion due to large size droplets (c) leaking of fuel due to imperfect closing and (d) adsorption of fuel on the deposits tends to increase diffusion combustion.

Pirjola et al. (2015) studied the effect of using different lubricating oil with low sulphur gasoline on the particulates emissions and found that the results were affected during cold-start and warm-up phase. The emissions were increased during acceleration and steady-state than deceleration condition. Lubricating oil having metal content are found to emit more PM emissions.

The blended fuel may have different physical and chemical properties, depending on the amount of blending done. These properties affect the injection characteristics, mixture composition and overall combustion process, thus cause variation in soot formation and particulate emissions. Hence, it cannot be directly concluded that alcohol blended gasoline fuels result in the increase or decrease in PM emissions as the parameters for injection strategy of ethanol/gasoline blends are not optimized for the overall operating range of engine (Storch et al. 2015).

PM emissions are also very sensitive to driving cycle on which vehicle is running. As tested under the NEDC cycle, particle concentration during cold start was very high and decreased during warm-up conditions (up to 300 s) for PFI engine. However, particulate concentration for GDI engine was high in warm-up conditions too and during the transition from one operating condition to other (Chen et al. 2017).

Hence, the gasoline particulate filter optimization is of uttermost need due to large particulate emissions from GDI and strict emission limit of WLTC cycle. Considering after-treatment technologies for PM reduction in GDI engines for meeting the limit of exhaust particles in Euro 6, gasoline particulate filter (GPF) and three-way catalyst (TWC) are unavoidable. Figure 6.16 shows various arrangements for location of GPF coupled with TWC or GPF in the underfloor position (AECC Technical Summary 2017). For underfloor position, bare GPFs are used while coated GPFs are usually placed in close-coupled position after TWC. GPF with the underfloor position was found to have 15% more filtration efficiency than that when placed in close-coupled position, due to reduced exhaust gas temperature resulting in the decrease in the volumetric flow rate of gas.

GPF with coating positioned at the under-floor location is capable of converting the exhaust gases by catalytic activity along with increased filtration efficiency of particulate number (Inoda et al. 2017). A system of coated GPF (CGPF) with TWC was demonstrated using two GDI vehicles and found to have improved tailpipe emissions, particularly the NO_x emissions (Richter et al. 2012). However, CGPF cannot replace the application of TWC as CGPF requires comparatively more time to light-off in cold starting than conventional TWC (Opitz et al. 2014).

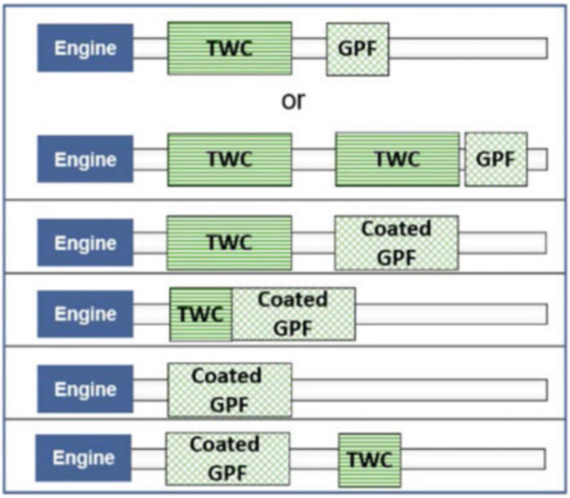


Fig. 6.16 Possible layouts of a GPF and TWC (AECC Technical Summary 2017)

6.4.2 *Injector Deposits*

6.4.2.1 Causes of Formation

The deposits on injector were considered to be majorly dependent upon the temperature of the nozzle tip and the rate of deposits build-up increased when the temperature of the tip goes beyond 150 °C (Kinoshita et al. 1999). In the study, the mechanism behind the rapid accumulation of deposits after reaching 150 °C was described as thermal condensation and cracking reaction kinetics of gasoline. Although this growth was only limited to a range of temperature, as on exceeding a specific higher temperature (dependent on fuel and deposit composition), the self-cleaning phenomenon started (Stępień 2015). Kinoshita et al. (1999) formulated the relation between the temperature of the injector tip and T90 temperature of the fuel (temperature at 90% volume distillation) for GDI injector deposition. And concluded that when injector tip temperature is less than T90 temperature of the fuel, fuel present on the tip remains in the liquid state and washes away the deposit's precursors by next injection. On the other hand, if the tip temperature is more than T90 temperature, liquid fuel will be in the vapour state, which makes the deposits precursor adhere and will form agglomeration near the nozzle wall. EGR and intake-air cooling have a certain influence on injector deposits as they determine the in-cylinder charge temperature (Zhao et al. 1999). Carbon deposition can be routed from two factors, namely, high-temperature decomposition of hydrocarbons and generation of poly-aromatic hydrocarbons (PAHs), which latter nucleate and grow to form carbonaceous deposits.

6.4.2.2 Examining Techniques and Consequences of Deposits

Scanning Electron Microscope (SEM) (Imoehl et al. 2012; Jiang et al. 2017) has been used as an effective tool by many researchers for investigating the deposits around GDI injector, as shown in Fig. 6.17. Song et al. (2016) examined the deposits at the orifice of the choked injector with the help of photographs of SEM. There were loose deposits at the outer surfaces which were easy to remove, while deposits formed inside the holes were thick and distributed axially at the aperture with more density along a particular side of the hole. However, the depositions were radially distributed at an external aperture. Dearn et al. (2014) conducted the investigation of deposits distribution and composition at injector tip by mechanically cracking the injector. The deposits were formed at different levels over the injector with the proportion of its constituents varying with location. Their elemental study revealed that C, O, S and Ca were the elements with the largest proportion in the deposit. Moreover, there was a reduction in the amount of S and Ca, while increment in C in the deposits as location approaches towards the combustion chamber.

Deposits are most likely to form near the regions of metering of the fuel and where atomization takes place due to the constricted passage of the nozzle. It can distort the fuel injection spray by altering its shape and penetration length. It also results in

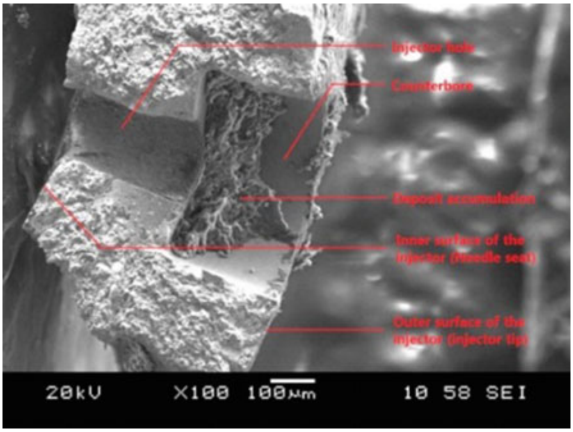


Fig. 6.17 SEM image of injector deposits (Jiang et al. 2017)

the reduction of fuel to be injected per pulse width. These modifications can affect the mixture formation and combustion characteristics adversely. Anbari et al. (2015) analyzed the spray structure of choked multi-hole injector using high-speed camera imaging and concluded that spray penetration length of spray plume increased and cone angle decreased due to choking effect. Also, the effect of choking was not same on all the plumes emerging from the injector. Similar results were derived from the work of Yiqiang et al. (2015), due to poor atomization of fuel by the choked injector. In contrast to this, Song et al. (2016) conducted the study on GDI injector and stated that penetration length and droplet size decreased while cone angle of spray increased. Thus, it can be inferred that spray characteristics would behave differently from different injectors due to deposits. Wang et al. (2014) compared the performance of fouled injector against that of clean injector in spray-guided DISI engine and came with results of higher emissions produced by fouled injector continuously, reaching the peak at maximum engine load condition of 8.5 bar IMEP. The PM emissions were 200% higher and PN emissions were 58% higher in the case of fouled injector. Badawy et al. (2018) investigated the effect of choking GDI injector on spray structures and engine performance of multi-cylinder engine. The choking process of injector was achieved in a consistent way by undergoing the fouling cycle. The spray characteristics like penetration length, cone angle, droplet diameters and velocity distribution were obtained using high-speed imaging and Phase Doppler Particle Analyser (PDPA). With higher penetration length of spray from choked injector as compared to the clean injector, the rear plume accounted for higher penetration as compared to ignition and side plume, and greater penetration observed with higher injection pressure among all plumes. Similarly, among smaller plume angles of choked injector, rear and side jets reported for maximum reduction in plume angle. Deposition distribution was studied using SEM and X-ray 3D microtomography as shown in Fig. 6.18. For visual scanning and composition analysis, Energy Dispersive X-ray Spectroscopy (EDS) was employed. Flame propagation characteristics revealed the occurrence of diffusion flame near the injector

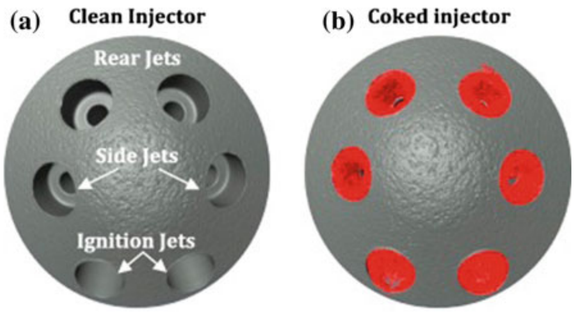


Fig. 6.18 X-ray microtomography of **a** clean and **b** choked injector (Badawy et al. 2018)

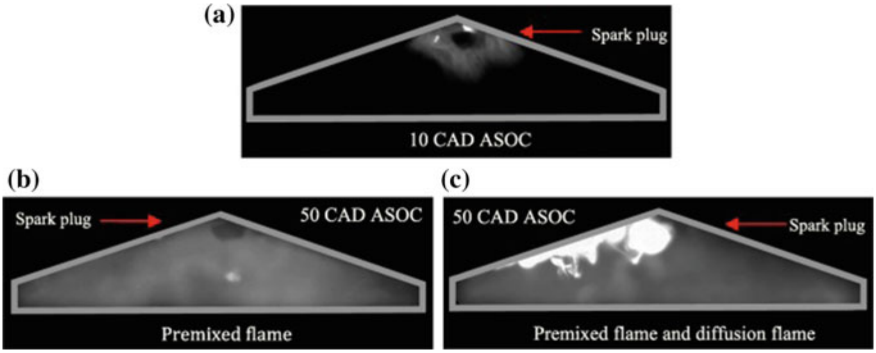


Fig. 6.19 Flame development with increasing crank angles, **a** early flame development of both clean and coked injectors, **b** clean injector and **c** coked injector, using gasoline (Badawy et al. 2018)

tip as shown in Fig. 6.19. In addition, with lower in-cylinder pressure and poorer combustion stability, choking in injector proved to be a crucial factor in affecting the engine performance. Inhomogeneity of charge and poor-repeatability of the mixture, lower load observation, higher unburnt HC emissions and particulates concentration are the major consequences of injector choking in GDI engine (Badawy et al. 2018).

6.4.2.3 Preventive Measures

The studies involving the methods for minimizing the formation of deposits include: (1) fuel detergents (Aradi et al. 2000), (2) coating of the injector with lower thermal conductivity material to reduce the injector tip temperature (Green et al. 2001) and (3) injection of fuel with high pressure (Von Bacho et al. 2009). These practices reduced the deposits formation in an efficient manner. Outward opening piezo-driven injector having a smooth surface, sharp inlet of the nozzle and counterbore design was proved significant in controlling deposit formation (Xu et al. 2015).

6.4.3 Pre-ignition and Deto-Knock

6.4.3.1 Causes

Several approaches like downsizing, high intake-boosting and direct injection have resulted in enhancing the fuel economy and power output of the engine. Although, higher boosting results in the engine knock condition which leads to an increment of developed pressure by one order magnitude as compared to the conventional knocking (Shuai et al. 2018). It is also termed as a super knock, mega knock or low-speed pre-ignition (LSPI) and is usually triggered at low-speed high-load conditions with the occurrence of pre-ignition prior to spark in the combustion chamber. The turbo-boosting in GDI engines is mainly restricted by deto-knock. As pressure and temperature of the charge attain the values of the deto-curve regime, the pre-ignition takes place at any hot spot inside the charge. The combustion flame front and wave propagated due to pre-ignition induce the ignition of the unburnt charge, resulting in high-pressure pulse with oscillating magnitude. It can cause severe damage to the liner and piston ring, and lead to the melting of exhaust valves.

Although pre-ignition induces the deto-knock, it is rare that pre-ignition will always lead to deto-knock as it occurs randomly with natural combustion and extinct naturally (Dahnz and Spicher 2010). It is measured by the number of its occurrences during certain completion of cycles, with a typical frequency of less than one in a thousand (Wang et al. 2017). Thus, investigation for the mechanism becomes difficult.

In the study, Wang et al. (2015) analysed the process involving the phenomenon of pre-ignition due to local hot-spot. This causes the rise in pressure and temperature of the charge, subsequently leading to deflagration of charge. This further induces the secondary hot spot at near-wall end-charge, causing a substantial increase in pressure trace with oscillating magnitude as shown in Fig. 6.20. This whole process is examined by synchronizing with high speed camera along with rapid compression machine (RCM) for pressure traces. It was concluded that the second hot spot situated in unburned charge was responsible for the detonation, which was induced by the deflagration (pre-ignition) due to primary hot spot.

Lubricating oil is considered to be a major source for pre-ignition that can lead to deto-knock condition due to higher tendency of auto-ignition (Amann and Alger 2012). The Dahnz and Spicher (2010) stated that wall-wetting due to spray and dilution of charge with oil present on the liner wall cause the oil droplets deposition in piston crevices. During deceleration of piston while moving towards TDC (top dead centre), less viscous diluted oil droplets enters the combustion chamber by virtue of inertia forces. In the optical study done by Lauer et al. (2014), oil droplets were found to be the initiator of pre-ignition. The pressure oscillations during auto-ignition release the deposits from the combustion chamber wall into the charge which act as ignition sources and subsequently leading to deto-knock. The diluted oil droplets and deposits require considerable time to accumulate, thus causing the event of deto-knock occasionally.

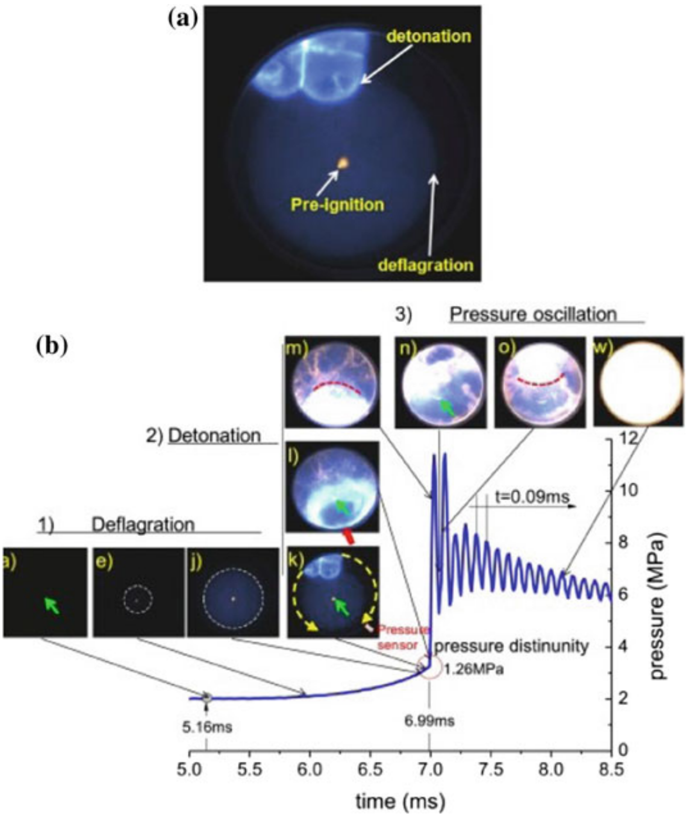


Fig. 6.20 Process showing the detonation induced by pre-ignition (Wang et al. 2015) **a** luminosity image showing pre-ignition, deflagration and detonation **b** synchronous pressure traces

6.4.3.2 Preventive Measures

The main approach for eliminating the trouble of deto-knock is to suppress pre-ignition. Various factors can be considered to diminish the chances of pre-ignition like oil and fuel properties, design and operational parameters of engines.

It has been established that oils with base stock having less reactivity and longer ignition delay, have less tendency towards auto-ignition (Welling et al. 2014). The metal elements used as additives in engine oil also influence the pre-ignition tendency of the charge. Calcium (Ca) based oil additives are found to enhance the phenomenon of pre-ignition (Kassai et al. 2016), whereas Zinc (Zn) and Molybdenum (Mo) based additives are reported to decrease the chances of pre-ignition. Similarly, fuel properties like lower aromatic content (Amann et al. 2011) and high volatility (Chapman et al. 2014) have led to decrease the frequency of pre-ignition. Designing and operating the engine with parameters such that it inhibits the wall-wetting and oil-diluted fuel deposition in crevices, can limit the chances of pre-ignition. As liner wetting is more prone to pre-ignition than piston wetting (Zahdeh et al. 2011), in-cylinder motion of mixture can help to reduce the liner wetting issues by limiting the penetration length of spray and washing deposited droplets off the liner (Palaveev et al. 2013). Moreover, split-injection strategy by optimizing the timing has shown an effective reduction in pre-ignition frequency (Wang et al. 2014). Avoiding the condition of auto-ignition of the mixture by controlling the pressure, temperature and composition of the charge is a good approach for reducing the reactivity of mixture. With the aid of EGR, a significant reduction in pre-ignition can be observed because of lower in-cylinder temperature (Zaccardi and Escudié 2015) without compromising the BMEP.

Thus, many factors are helpful in reducing the phenomenon of pre-ignition. However, the phenomenon is specific to the particular engine configuration, and so are the parameters for controlling it. Thus, these factors should be considered on the engine-to-engine basis.

6.5 Conclusions

A thorough analysis of the work done in the area of gasoline direct injection technology reveals that the technology has evolved in large proportions. The automotive engineers are trying to make it more reliable and efficient, along with solving critical issues related to DISI engines. We have discussed various works in the direction of improving the performance and fulfilling the required objectives of this notable technology.

The fuel injection system is the heart of the GDI technology which prepares the required mixture according to load and rpm conditions. From the research conducted, it can be concluded that spray-guided combustion system is best suited for running the engine on ultra-lean charge as well as stoichiometric charge. For this, injection timing, parameters and in-cylinder motion need to be optimized for avoiding the spray-impingement problem and obtaining proper mixture preparation and charge cooling benefits. Utilizing alcohol in port injection and gasoline in direct injection (dual fuel injection) has resulted in achieving better thermal efficiency and reducing emissions. Also, it decreases the tendency of knocking with the provision of greater spark advance timing. This strategy is helpful in utilizing alcohol as alternate fuel along with performance benefits. The characteristics of different injector designs are also discussed; out of which piezo-driven outward opening injectors are best suited for stratified operating mode due to lower spray penetration length. By optimizing the fuel injection timing for split-injection, successful operation of the overall lean homogeneous mixture has been observed in GDI engine. Further, higher injection pressure for better atomization, with lower coolant temperature during cold-start conditions have efficiently reduced the HC and PM emissions from the GDI engine. All these strategies are to be considered for optimizing the injection system of the GDI engine.

Additionally, with the advantages of downsizing the engine, boosting help in improving the power output of the engine, though it limits the operating compression ratio of the engine. Thus, the provision of variable compression ratio accommodates the engine operation according to the required load and rpm condition. Further, addition of EGR helps to reduce the NO_x emissions, minimize the heat loss and improve thermal efficiency of the engine.

We also discussed the particulate matter characteristics of GDI engine and its dependence on various operational factors. Improving atomization and eliminating fuel-film formation issues by running the engine with optimized fuel injection parameter helps to reduce high PM emissions. Likewise, supplying cooled EGR has reported a significant reduction in PM emissions. The issue of injector deposits is also seen as major concerns in GDI engine operation. Avoiding injector deposits by adopting the aforementioned measures and using suitable additives with engine oil can bring down the levels of particulate emission. Furthermore, the role of after-treatment devices such as TWC and GPF are discussed for limiting the tail-pipe emissions.

Finally, the occurrence of deto-knock due to pre-ignition of charge is discussed. The causes of pre-ignition like presence of oil-diluted fuel droplets and operating conditions like temperature, pressure and mixture composition leading to auto-ignition of charge, should be avoided in order to eliminate the chances of deto-knock. Here also, inhibiting wall-wetting conditions, utilizing split-injection strategy, enabling EGR and controlling operational parameters has proved beneficial for reducing the menace of deto-knock in engines.

Although GDI engines operating on homogeneous mode are available in the market, the stratified mode is still in the development phase. Studies of optical diagnostics and CFD simulation have literally helped to optimize the operating parameters for achieving stratified mode operation to some extents, but not completely. Hence, a full-fledged GDI system with mode-switching technology remains a promising field for the research community.

References

AECC technical summary (2017) Gasoline particulate filter (GPF), How can the GPF cut emissions of ultrafine particles from gasoline engines

Amann M, Alger T (2012) Lubricant reactivity effects on gasoline spark ignition engine knock. SAE Int J Fuels Lubric 5(2):760–771

Amann M, Mehta D, Alger T (2011) Engine operating condition and gasoline fuel composition effects on low-speed pre-ignition in high-performance spark ignited gasoline engines. SAE Int J Engines 4(1):274–285

Anbari AM, Badawy T, Xu H (2015) Optical investigation of influence of injector nozzle deposit on particulate matter emissions drift. IMechE, London, Internal Combustion Engines

Aradi AA, Colucci WJ, Scull HM, Openshaw MJ (2000) A study of fuel additives for direct injection gasoline (DIG) injector deposit control. SAE technical paper, 19 June 2000

Asthana S, Bansal S, Jaggi S, Kumar N. A comparative study of recent advancements in the field of variable compression ratio engine technology. SAE Technical Paper; 2016 Apr 5

Aubernon C (2014) Japanese automakers form alliance to develop next-gen fuel-efficient engines. http://www.thetruthaboutcars.com/2014/05/japanese-automakers-formalliance-to-develop-next-gen-fuel-efficient-engines/#more-826666.%202014
Badawy T, Attar MA, Hutchins P, Xu H, Venus JK, Cracknell R (2018a) Investigation of injector coking effects on spray characteristic and engine performance in gasoline direct injection engines. Appl Energy 15(220):375–394
Badawy T, Attar MA, Xu H, Ghafourian A (2018b) Assessment of gasoline direct injector fouling effects on fuel injection, engine performance and emissions. Appl Energy 15(220):351–374
Balki MK, Sayin C, Canakci M (2014) The effect of different alcohol fuels on the performance, emission and combustion characteristics of a gasoline engine. Fuel 1(115):901–906
Beavis NJ, Ibrahim SS, Malalasekera W (2017) Impingement characteristics of an early injection gasoline direct injection engine: A numerical study. Int J Engine Res 18(4):378–393
Berndorfer A, Breuer S, Piock W, Von Bacho P (2013) Diffusion combustion phenomena in GDI engines caused by injection process. SAE technical paper, 8 Apr 2013
Blair GP (1996) Design and simulation of two-stroke engines. Society of Automotive Engineers, Warrendale, PA
Bock N, Jeon J, Kittelson D, Northrop WF (2018) Solid particle number and mass emissions from lean and stoichiometric gasoline direct injection engine operation. SAE technical paper, 3 Apr 2018
Bonatesta F, Chiappetta E, La Rocca A (2014) Part-load particulate matter from a GDI engine and the connection with combustion characteristics. Appl Energy 1(124):366–376
Cairns A, Blaxill H, Irlam G (2006) Exhaust gas recirculation for improved part and full load fuel economy in a turbocharged gasoline engine. SAE technical paper, 3 Apr 2006
Chapman E, Davis R, Studzinski W, Geng P (2014) Fuel octane and volatility effects on the stochastic pre-ignition behavior of a 2.0 L gasoline turbocharged DI engine. SAE Int J Fuels Lubric 7(2):379–389
Chapman E, Winston-Galant M, Geng P, Konzack A (2016) Global market gasoline range fuel review using fuel particulate emission correlation indices. SAE technical paper, 17 Oct 2016
Chen L, Liang Z, Zhang X, Shuai S (2017) Characterizing particulate matter emissions from GDI and PFI vehicles under transient and cold start conditions. Fuel 1(189):131–140
China (2016) Limits and measurement methods for emissions from light duty vehicles (CHINA 6)
Chincholkar SP, Suryawanshi JG (2016) Gasoline direct injection: an efficient technology. Energy Procedia 1(90):666–672
Chung J, Kim N, Choi H, Min K (2016) Study on the effect of injection strategies on particulate emission characteristics under cold start using in-cylinder visualization. SAE technical paper, 5 Apr 2016
Clairotte M, Adam TW, Zardini AA, Manfredi U, Martini G, Krasenbrink A, Vicet A, Tournié E, Astorga C (2013) Effects of low temperature on the cold start gaseous emissions from light duty vehicles fuelled by ethanol-blended gasoline. Appl Energy 1(102):44–54
Clark LG, Kook S, Chan QN, Hawkes ER (2016) Multiple injection strategy investigation for well-mixed operation in an optical Wall-Guided Spark-Ignition Direct-Injection (WG-SIDI) engine through flame shape analysis. SAE technical paper, 17 Oct 2016
Clark LG, Kook S, Chan QN, Hawkes ER (2017) Influence of injection timing for split-injection strategies on well-mixed high-load combustion performance in an optically accessible Spark-Ignition Direct-Injection (SIDI) engine. SAE technical paper, 28 Mar 2017
Costa M, Sorge U, Merola S, Irimescu A, La Villetta M, Rocco V (2016) Split injection in a homogeneous stratified gasoline direct injection engine for high combustion efficiency and low pollutants emission. Energy 15(117):405–415
Costagliola MA, De Simio L, Iannaccone S, Prati MV (2013) Combustion efficiency and engine out emissions of a SI engine fueled with alcohol/gasoline blends. Appl Energy 1(111):1162–1171
Cucchi M, Samuel S (2015) Influence of the exhaust gas turbocharger on nano-scale particulate matter emissions from a GDI spark ignition engine. Appl Therm Eng 5(76):167–174

Dahlander P, Hemdal S (2015) High-speed photography of stratified combustion in an optical GDI engine for different triple injection strategies. SAE technical paper, 14 Apr 2015
Dahlander P, Iemmolo D, Tong Y (2015) Measurements of time-resolved mass injection rates for a multi-hole and an outward opening piezo GDI injector. SAE technical paper, 14 Apr 2015
Dahnz C, Spicher U (2010) Irregular combustion in supercharged spark ignition engines–pre-ignition and other phenomena. Int J Engine Res 11(6):485–498
Daniel R, Xu H, Wang C, Richardson D, Shuai S (2013) Gaseous and particulate matter emissions of biofuel blends in dual-injection compared to direct-injection and port injection. Appl Energy 1(105):252–261
De Boer C, Bonar G, Sasaki S, Shetty S (2013) Application of supercritical gasoline injection to a direct injection spark ignition engine for particulate reduction. SAE technical paper, 8 Apr 2013
Dearn K, Xu J, Ding H, Xu H, Weall A, Kirkby P, Cooper B, Edington I, Krueger-Venus J (2014) An investigation into the characteristics of DISI injector deposits using advanced analytical methods. SAE Int J Fuels Lubric 7(3):771–782
Eichhorn A, Lejsek D, Kulzer A, Kufferath A, Wizgall E, Centmayer R (2012) Design of a boosted 2-cylinder SI-engine with gasoline direct injection to define the needs of future powertrains. SAE technical paper, 16 Apr 2012
Feng D, Wei H, Pan M, Zhou L, Hua J (2018) Combustion performance of dual-injection using n-butanol direct-injection and gasoline port fuel-injection in a SI engine. Energy 1(160):573–581
Green AC, DAVID M, Lambert MDD, Nandy M (2001) Injection nozzle. Delphi Technologies Inc. Patent EP1081374 A2 patent application, 2001. https://patents.google.com/patent/EP1081374A2/en
He BQ, Chen X, Lin CL, Zhao H (2016) Combustion characteristics of a gasoline engine with independent intake port injection and direct injection systems for n-butanol and gasoline. Energy Convers Manag 15(124):556–565
Hedge M, Weber P, Gingrich J, Alger T, Khalek I (2011) Effect of EGR on particle emissions from a GDI engine. SAE Int J Engines 4(1):650–666
Hoffmann G, Befrui B, Berndorfer A, Piock WF, Varble DL (2014) Fuel system pressure increase for enhanced performance of GDi multi-hole injection systems. SAE Int J Engines 7(1):519–527
Huang Y, Hong G, Huang R (2016) Effect of injection timing on mixture formation and combustion in an ethanol direct injection plus gasoline port injection (EDI + GPI) engine. Energy 15(111):92–103
Hwang K, Hwang I, Lee H, Park H, Choi H, Lee K, Kim W, Kim H, Han B, Lee J, Shin B (2016) Development of new high-efficiency Kappa 1.6 L GDI engine. SAE technical paper, 5 Apr 2016
Iida N (2017) Research and development of super-lean burn for high efficiency SI engine. In: The proceedings of the international symposium on diagnostics and modeling of combustion in internal combustion engines 2017.9, The Japan Society of Mechanical Engineers, pp PL-1
Ikoma T, Abe S, Sonoda Y, Suzuki H, Suzuki Y, Basaki M (2006) Development of V-6 3.5-liter engine adopting new direct injection system. SAE technical paper, 3 Apr 2006
Imoehl W, Gestri L, Maragliulo M, Del-Frate L, Klepatsch M, Wildeson R (2012) A DOE approach to engine deposit testing used to optimize the design of a gasoline direct injector seat and orifice. SAE Int J Fuels Lubric 5(3):1078–1095
Inoda S, Nomura Y, Ori H, Yabuzaki Y (2017) Development of new coating technology optimized for each function of coated GPF. SAE technical paper, 28 Mar 2017
Itabashi S, Murase E, Tanaka H, Yamaguchi M, Muraguchi T (2017) New combustion and powertrain control technologies for fun-to-drive dynamic performance and better fuel economy. SAE technical paper, 28 Mar 2017
Ji C, Cong X, Wang S, Shi L, Su T, Wang D (2018) Performance of a hydrogen-blended gasoline direct injection engine under various second gasoline direct injection timings. Energy Convers Manag 1(171):1704–1711
Jiang C, Xu H, Srivastava D, Ma X, Dearn K, Cracknell R, Krueger-Venus J (2017) Effect of fuel injector deposit on spray characteristics, gaseous emissions and particulate matter in a gasoline direct injection engine. Appl Energy 1(203):390–402

Jiang C, Li Z, Qian Y, Wang X, Zhang Y, Lu X (2018) Influences of fuel injection strategies on combustion performance and regular/irregular emissions in a turbocharged gasoline direct injection engine: commercial gasoline versus multi-components gasoline surrogates. Energy 15(157):173–187

Kadota M, Ishikawa S, Yamamoto K, Kato M, Kawajiri S (2009) Advanced control system of variable compression ratio (VCR) engine with dual piston mechanism. SAE Int J Engine 2(1):1009–1018

Kassai M, Shiraishi T, Noda T, Hirabe M, Wakabayashi Y, Kusaka J, Daisho Y (2016) An investigation on the ignition characteristics of lubricant component containing fuel droplets using rapid compression and expansion machine. SAE Int J Fuels Lubric 9(3):469–480

Ketterer JE, Cheng WK (2014) On the nature of particulate emissions from DISI engines at cold-fast-idle. SAE Int J Engines 7(2):986–994

Kim S, Nouri JM, Yan Y, Arcoumanis C (2009) Effects of intake flow on the spray structure of a multi-hole injector in a DISI engine. Int J Automot Technol 10(3):277–284

Kim T, Song J, Park S (2015a) Effects of turbulence enhancement on combustion process using a double injection strategy in direct-injection spark-ignition (DISI) gasoline engines. Int J Heat Fluid Flow 1(56):124–136

Kim J, Chun KM, Song S, Baek HK, Lee SW (2015) Effect of hydrogen as an additive on lean limit and emissions of a turbo gasoline direct injection engine. SAE technical paper, 1 Sept 2015

Kim J, Chun KM, Song S, Baek HK, Lee SW (2017) The effects of hydrogen on the combustion, performance and emissions of a turbo gasoline direct-injection engine with exhaust gas recirculation. Int J Hydrogen Energy 42(39):25074–25087

Kinoshita M, Saito A, Matsushita S, Shibata H, Niwa Y (1999) A method for suppressing formation of deposits on fuel injector for direct injection gasoline engine. SAE Trans 1:2177–2184

Kittelson DB (1998) Engines and nanoparticles: a review. J Aerosol Sci 29(5–6):575–588

Kleeberg H, Tomazic D, Dohmen J, Wittek K, Balazs A (2013) Increasing efficiency in gasoline powertrains with a two-stage variable compression ratio (VCR) system. SAE technical paper, 8 Apr 2013

Koç M, Sekmen Y, Topgül T, Yücesu HS (2009) The effects of ethanol–unleaded gasoline blends on engine performance and exhaust emissions in a spark-ignition engine. Renew Energy 34(10):2101–2106

Kojima S, Kiga S, Moteki K, Takahashi E, Matsuoka K (2018) Development of a new 2L gasoline VC-Turbo engine with the world's first variable compression ratio technology. SAE technical paper, 3 Apr 2018

Lattimore T, Wang C, Xu H, Wyszynski ML, Shuai S (2016) Investigation of EGR effect on combustion and PM emissions in a DISI engine. Appl Energy 1(161):256–267

Lauer T, Heiss M, Bobicic N, Holly W, Pritze S (2014) A comprehensive simulation approach to irregular combustion. SAE technical paper, 1 Apr 2014

Lee CH, Lee KH (2006) Experimental study on the stratified combustion characteristics according to compression ratio and intake temperature in a DIG engine. Int J Automot Technol 7(6):675–680

Lee B, Oh H, Han S, Woo S, Son J (2017) Development of high efficiency gasoline engine with thermal efficiency over 42%. SAE technical paper, 8 Oct 2017

Liu H, Wang Z, Wang J (2014) Methanol-gasoline DFSI (dual-fuel spark ignition) combustion with dual-injection for engine knock suppression. Energy 14(73):686–693

Liu H, Wang Z, Long Y, Wang J (2015a) Dual-Fuel Spark Ignition (DFSI) combustion fuelled with different alcohols and gasoline for fuel efficiency. Fuel 1(157):255–260

Liu H, Wang Z, Long Y, Xiang S, Wang J, Wagnon SW (2015b) Methanol-gasoline Dual-fuel Spark Ignition (DFSI) combustion with dual-injection for engine particle number (PN) reduction and fuel economy improvement. Energy 1(89):1010–1017

Liu H, Wang Z, Long Y, Xiang S, Wang J, Fatouraie M (2015c) Comparative study on alcohol—gasoline and gasoline–alcohol Dual-Fuel Spark Ignition (DFSI) combustion for engine particle number (PN) reduction. Fuel 1(159):250–258

Lucchini T, D'Errico G, Onorati A, Bonandrini G, Venturoli L, Di Gioia R (2014) Development and application of a computational fluid dynamics methodology to predict fuel–air mixing and sources of soot formation in gasoline direct injection engines. Int J Engine Res 15(5):581–596
Matsumura E, Kanda M, Hattori F, Nomura H, Hashimoto S, Yoshimaru K (2013) Development of DISI engine utilizing a fan-shaped spray jet. SAE technical paper, 8 Apr 2013
Matthias N, Wallner T, Scarcelli R (2014) Analysis of cyclic variability and the effect of dilute combustion in a gasoline direct injection engine. SAE Int J Engines 7(2):633–641
Nakashima T, Basaki M, Saito K, Furuno S (2003) New concept of a direct injection SI gasoline engine: a study of stratified charge combustion characteristics by radical luminescence measurement. JSAE Rev 24(1):17–23
Opitz B, Drochner A, Vogel H, Votsmeier M (2014) An experimental and simulation study on the cold start behaviour of particulate filters with wall integrated three way catalyst. Appl Catal B 1(144):203–215
Palaveev S, Magar M, Kubach H, Schiessl R, Spicher U, Maas U (2013) Premature flame initiation in a turbocharged DISI engine-numerical and experimental investigations. SAE Int J Engines 6(1):54–66
Park C, Kim S, Kim H, Moriyoshi Y (2012) Stratified lean combustion characteristics of a spray-guided combustion system in a gasoline direct injection engine. Energy 41(1):401–407
Park CW, Oh HC, Kim SD, Kim HS, Lee SY, Bae CS (2014) Evaluation and visualization of stratified ultra-lean combustion characteristics in a spray-guided type gasoline direct-injection engine. Int J Automot Technol 15(4):525–533
Park C, Lee S, Yi U (2016) Effects of engine operating conditions on particle emissions of lean-burn gasoline direct-injection engine. Energy 15(115):1148–1155
Pei YQ, Qin J, Pan SZ (2014) Experimental study on the particulate matter emission characteristics for a direct-injection gasoline engine. Proc Inst Mech Eng, Part D-J Automob Eng 228:604–616
Pirjola L, Karjalainen P, Heikkilä J, Saari S, Tzamkiozis T, Ntziachristos L, Kulmala K, Keskinen J, Rönkkö T (2015) Effects of fresh lubricant oils on particle emissions emitted by a modern gasoline direct injection passenger car. Environ Sci Technol 49(6):3644–3652
Potteau S, Lutz P, Leroux S, Moroz S, Tomas E (2007) Cooled EGR for a turbo SI engine to reduce knocking and fuel consumption. SAE technical paper, 29 Oct 2007
Price P, Stone R, Collier T, Davies M (2006) Particulate matter and hydrocarbon emissions measurements: comparing first and second generation DISI with PFI in single cylinder optical engines. SAE technical paper, 3 Apr 2006
Qian Y, Liu G, Guo J, Zhang Y, Zhu L, Lu X (2019a) Engine performance and octane on demand studies of a dual fuel spark ignition engine with ethanol/gasoline surrogates as fuel. Energy Convers Manag 1(183):296–306
Qian Y, Chen F, Zhang Y, Tao W, Han D, Lu X (2019) Combustion and regulated/unregulated emissions of a direct injection spark ignition engine fueled with C3-C5 alcohol/gasoline surrogate blends. Energy, 5 Mar 2019
Qian Y, Li Z, Yu L, Wang X, Lu X (2019c) Review of the state-of-the-art of particulate matter emissions from modern gasoline fueled engines. Appl Energy 15(238):1269–1298
Richter JM, Klingmann R, Spiess S, Wong KF (2012) Application of catalyzed gasoline particulate filters to GDI vehicles. SAE Int J Engines 5(3):1361–1370
Sevik J, Pamminger M, Wallner T, Scarcelli R, Boyer B, Wooldridge S, Hall C, Miers S (2016) Influence of injector location on part-load performance characteristics of natural gas direct-injection in a spark ignition engine. SAE Int J Eng 9(4):2262–2271
Sharma N, Agarwal AK. Gasoline direct injection engines and particulate emissions. In: Air pollution and control 2018. Springer, Singapore, pp 87–105
Short D, Vu D, Durbin TD, Karavalakis G, Asa-Awuku A (2015) Particle speciation of emissions from iso-butanol and ethanol blended gasoline in light-duty vehicles. J Aerosol Sci 1(84):39–52
Shuai S, Ma X, Li Y, Qi Y, Xu H (2018) Recent Progress in Automotive Gasoline Direct Injection Engine Technology. Automot Innovation. 1(2):95–113

Skogsberg M, Dahlander P, Denbratt I (2007) Spray shape and atomization quality of an outward-opening piezo gasoline DI injector. SAE technical paper, 16 Apr 2007
Song J, Kim T, Jang J, Park S (2015) Effects of the injection strategy on the mixture formation and combustion characteristics in a DISI (direct injection spark ignition) optical engine. Energy 15(93):1758–1768
Song H, Xiao J, Chen Y, Huang Z (2016) The effects of deposits on spray behaviors of a gasoline direct injector. Fuel 15(180):506–513
Song J, Lee Z, Song J, Park S (2018) Effects of injection strategy and coolant temperature on hydrocarbon and particulate emissions from a gasoline direct injection engine with high pressure injection up to 50 MPa. Energy 1(164):512–522
Stępień Z (2015) Deposits in spark ignition engines–formation and threats. Combust Engines, vol 54
Stiehl R, Schorr J, Krüger C, Dreizler A, Böhm B (2013) In-cylinder flow and fuel spray interactions in a stratified spray-guided gasoline engine investigated by high-speed laser imaging techniques. Flow Turbul Combust 91(3):431–450
Storch M, Hinrichsen F, Wensing M, Will S, Zigan L (2015) The effect of ethanol blending on mixture formation, combustion and soot emission studied in an optical DISI engine. Appl Energy 15(156):783–792
Tang Y, Deng W, Liu B, Hu TG, Wang X, Yang Q, Jiang B, Lin L, Zhan ZS, Min L (2018) The new Chang An inline 4 cylinder 1.6 L gasoline naturally aspirated GDI engine. SAE Technical Paper, 3 Apr 2018
Toulson E, Watson HC, Attard WP (2007) The effects of hot and cool EGR with hydrogen assisted jet ignition. SAE technical paper, 5 Aug 2007
Tree DR, Svensson KI (2007) Soot processes in compression ignition engines. Progr Energy Combust Sci 33(3):272–309
Trimbake S, Malkhede D (2016) Investigations of Port Dual Injection (PDI) strategies in single cylinder SI engine fueled with ethanol/gasoline blends. SAE technical paper, 5 Apr 2016
Turner D, Xu H, Cracknell RF, Natarajan V, Chen X (2011) Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine. Fuel 90(5):1999–2006
Velji A, Yeom K, Wagner U, Spicher U, Roßbach M, Suntz R, Bockhorn H (2010) Investigations of the formation and oxidation of soot inside a direct injection spark ignition engine using advanced laser-techniques. SAE technical paper, 12 Apr 2010
Von Bacho PS, Sofianek JK, Galante-Fox JM, McMahon CJ (2009) Engine test for accelerated fuel deposit formation on injectors used in gasoline direct injection engines. SAE technical paper, 20 Apr 2009
Wada Y, Nakano K, Mochizuki K, Hata R (2016) Development of a new 1.5 L I4 turbocharged gasoline direct injection engine. SAE technical paper, 5 Apr 2016
Wang C, Xu H, Herreros JM, Wang J, Cracknell R (2014a) Impact of fuel and injection system on particle emissions from a GDI engine. Appl Energy 1(132):178–191
Wang Z, Liu H, Song T, Xu Y, Wang JX, Li DS, Chen T (2014) Investigation on pre-ignition and super-knock in highly boosted gasoline direct injection engines. SAE technical paper, 1 Apr 2014
Wang Z, Qi Y, He X, Wang J, Shuai S, Law CK (2015) Analysis of pre-ignition to super-knock: hotspot-induced deflagration to detonation. Fuel 15(144):222–227
Wang Z, Liu H, Reitz RD (2017) Knocking combustion in spark-ignition engines. Prog Energy Combust Sci 1(61):78–112
Wei H, Zhu T, Shu G, Tan L, Wang Y (2012) Gasoline engine exhaust gas recirculation–a review. Appl Energy 1(99):534–544
Welling O, Collings N, Williams J, Moss J (2014) Impact of lubricant composition on low-speed pre-ignition. SAE technical paper, 1 Apr 2014
Whelan I, Timoney D, Smith W, Samuel S (2013) The effect of a three-way catalytic converter on particulate matter from a gasoline direct-injection engine during cold-start. SAE Int J Engines 6(2):1035–1045

Wolfgang S, Sorger H, Loesch S, Unzeitig W, Huettner T, Fuerhapter A (2017) The 2-Step VCR conrod system-modular system for high efficiency and reduced CO_2. SAE technical paper, 28 Mar 2017

Xing J, Shao L, Zheng R, Peng J, Wang W, Guo Q, Wang Y, Qin Y, Shuai S, Hu M (2017) Individual particles emitted from gasoline engines: impact of engine types, engine loads and fuel components. J Clean Prod 15(149):461–471

Xu H, Wang C, Ma X, Sarangi AK, Weall A, Krueger-Venus J (2015) Fuel injector deposits in direct-injection spark-ignition engines. Progr Energy Combust Sci 1(50):63–80

Yamazaki D, Mori A, Murase E (2018) The development of a new V6 3.5 L turbocharged gasoline engine. SAE technical paper, 3 Apr 2018

Yiqiang P, Hao CH, Jing Q, Jianwei Z, Xiang L, Bin L (2015) Effect of GDI engine injector coking on spray. J Tianjin Univ, vol 48

Yu RC, Shahed SM (1981) Effects of injection timing and exhaust gas recirculation on emissions from a DI diesel engine. SAE Trans 1:3873–3883

Yu CH, Park KW, Han SK, Kim WT (2009) Development of theta II 2.4 L GDI engine for high power and low emission. SAE Technical Paper, 20 Apr 2009

Zaccardi JM, Escudié D (2015) Overview of the main mechanisms triggering low-speed pre-ignition in spark-ignition engines. Int J Engine Res 16(2):152–165

Zahdeh A, Rothenberger P, Nguyen W, Anbarasu M, Schmuck-Soldan S, Schaefer J, Goebel T (2011) Fundamental approach to investigate pre-ignition in boosted SI engines. SAE Int J Engines 4(1):246–273

Zhao H (2010) Overview of gasoline direct injection engines. In: Advanced direct injection combustion engine technologies and development 1 Jan 2010, Woodhead Publishing, pp 1–19

Zhao F, Lai MC, Harrington DL (1999) Automotive spark-ignited direct-injection gasoline engines. Prog Energy Combust Sci 25(5):437–562

Zhao H, Peng Z, Ladommatos N (2001) Understanding of controlled autoignition combustion in a four-stroke gasoline engine. Proc Inst Mech Eng Part D J Automob Eng 215(12):1297–1310

Zhuang Y, Qian Y, Hong G (2017) The effect of ethanol direct injection on knock mitigation in a gasoline port injection engine. Fuel 15(210):187–197